# Room Acoustic and Modern Electro-Acoustic Sound System Design during Constructing and Reconstructing Mosques

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*Dedicated to*

*MY FAMILY*
*And*
*ALL MY WELL-WISHERS*

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# Chapter 1

## Introduction:

## 1: General definition of the topic:

This work includes the study of the acoustics including existing or newer computer-supported sound reinforcement systems in all main worship rooms especially in mosques. Furthermore, the principle concepts and input parameters for sound radiation in such rooms are described. Typical cases of application are considered. The main focus of this work is the development and optimisation of control algorithms of such systems using DSP (Digital Signal Processing) controlled electro-acoustic devices and computer-based systems to achieve desired radiation properties for any important worship room spatially mosques.

## 1.1: Development of worship buildings:

### 1.1a: Architectural Development of Christian Churches:

The architecture of Christian worship space grew out of the regular meetings of the followers of Christianity in private houses and synagogues, and occasionally in catacombs (the word catacomb comes from Greek kata kumbas (L. ad catacumbas), "near the low place" and originally it meant a certain burial district in Rome) when necessary. When either the size of the community outgrew the space or the complexity of the uses of the space outs paced the architectural adaptation of houses, buildings began to be built specifically for worship. This became much more feasible and common when the Roman Emperor Constantine stopped the persecution of Christians by issuing the Edict of Milan in 311 C.E. The "Edict of Milan"[1] declared that the Roman Empire would be neutral with regard to religious worship.

The first Christians were former Jews resident in Palestine who worshipped on occasion in the Temple in Jerusalem and weekly in local synagogues. Figure1 shows 53 provinces of the Roman Empire and the location of Jerusalem within the former Empire.

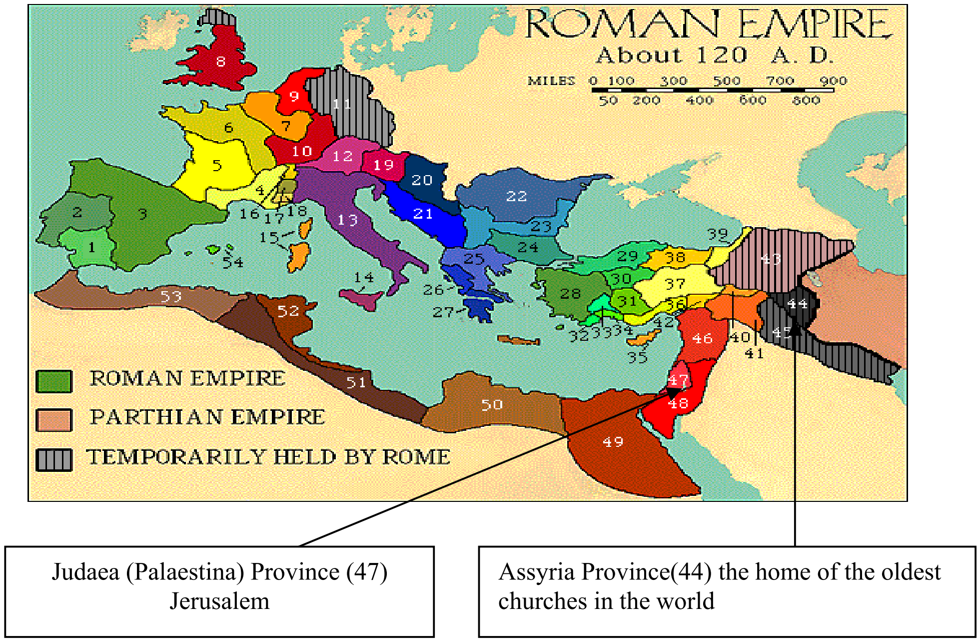



*Figure 1.The borders of the Roman Empire and the location of Jerusalem within the former Empire*

The word **Temple** is derived not from the Hebrew but from the Latin word for place of worship, **templum**. The name given in Scripture for the building was Beit Adonai or "House of Adonai" (although this name was also often used for other temples, or metaphorically).

The First Temple (old form of al-Aqssa Mosque) was built between 15$^{th}$ -10$^{th}$ century BC 40 years after the holy mosque in Makkah which have been built by the Prophet Ibraheem. Due to the relatively short period (40 years) between the constructions of the two Mosques, some historians and Muslim scholars hold the view that Prophet Ibraheem built both of them and it replaced the Tabernacle of Moses. It was destroyed in 568 Century BC by the Babylonians. The second worship space (temple) was rebuilt at the same location after obtained it back from the Babylonians Captivity in 536 BC. The rebuilding process was completed on March 12, 515 BC. Huge blocks of stones were prepared for the walls and the foundation of the temple. All these stones were reshaped by the master builders at that time. To get the required height of the Temple huge walls of solid masonry at a height of 60m above the mount level where the Temple was built were constructed cross the southern and the eastern side of the temple. In the space between arches and pillars were created, thus elevating up the general level surface to the required level. Timbers were also needed at some parts of the temple and it was supplied from the forest of Lebanon. See Figure2 for an overview of the temple.

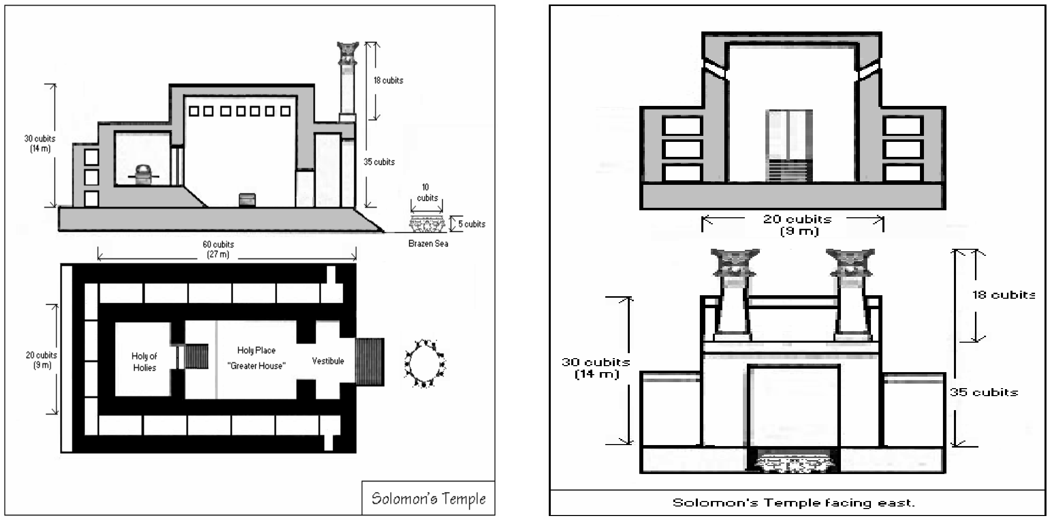



*Figure 2 the first Solomon's Temple in Jerusalem.*

The second temple went through a massive expansion and renovation of the Temple and the area around it. After the expansion process, it was named Hyrodas's Temple and not the Third Temple referring to the Roman Ruler Hyrodas who have ordered the expansion. It was eventually destroyed too, this time by the Romans in 70 AD. In 135 AD Emperor Adriano cleared the ruins and constructed a temple in its place for idol worship. He called it 'Jupiter', which is the name of one of the Roman gods.

When Christianity became widespread in Palestine at the beginning of the fourth century CE, Emperor Constantine, who established Christianity there, demolished the Jupiter temple and constructed another structure in its place for worshiping purposes. This structure went through many renovations processes and reconstruction from that time through out the Christian and the Muslim ruling of Jerusalem until now days, but the main shape of the mosque was kept the way it is until now days.

A third Temple project was turned down by the Roman Emperor Julian (331-363 AD) preventing the Jews from building a third temple. It is believed that he wanted to rebuild a Third Temple for his own apotheosis (the process of creating a waxen image of the Julian after his death to be worshiped) instated of worshiping the Jewish God.

The historical temple today is represented by al-Aqssa Mosque the third holist site in Islam .To its north west located the Dome of the Rock where it is believed the Prophet Mohammed started his journey to the heaven. Figure 3 shows the former location of the Temple where the Dome of the Rock and Al-AqsFsa Mosque are located now.

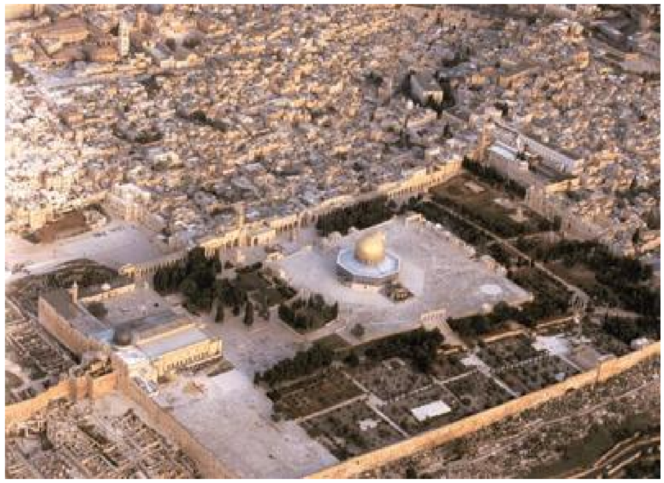


*Figure 3 the Dome of the Rock and Al-Aqssa Mosque.*

Until the 70 AD, the followers of Jesus and the Jews shared places of worshiping. After the destruction of the Solomon Second Temple in 70 AD by the Roman, the Christianity and the Judaism movements became much more separated and gaining different identities. Catholic Christianity became more flexible religion what enhanced its popularity until it became the official religion of the Roman Empire.

The Roman Catholic construction style affect the design of the churches built at that time. A common architecture for churches dated at that time is the shape of a cross (a long central rectangle, with side rectangles, and a rectangle in front for the altar space or sanctuary). They also often have a dome or other large domed space in the interior to represent or draw attention to the heavens. Other common shapes for churches include a circle, to represent eternity, or an octagon or similar star shape, to represent the church's bringing light to the world. Another common feature is the spire, a tall tower on the "west" end of the church or over the crossing. All these Roman Catholic details were added to the design of churches what gave them a distinguished outlook compared to the orthodox churches (as we will discover later) and the early dated worshiping Temples.

Some of the first and oldest churches ever built were found in the Syrian city of Dura-Europos on the West bank of the Euphrates (see Figure 1). It was an outpost town between the Roman and Parthian empires. The were dated back to before 257 AD .These churches were converted from private building to public churches, but they are not more existing. A living example of such Roman Catholic Church is The Church of Nativity in Jerusalem. It contains all the above mentioned featured of the Roman Catholic Church and it is considered the oldest survived church in existence.

The construction of The Church of Nativity in Jerusalem started in 330AD fifteen years after St. Peter church in Rome was ordered to be built and was finished before St. Peter Church was finished in 349AD. See Figure 4 for the interior and the layout of the church.

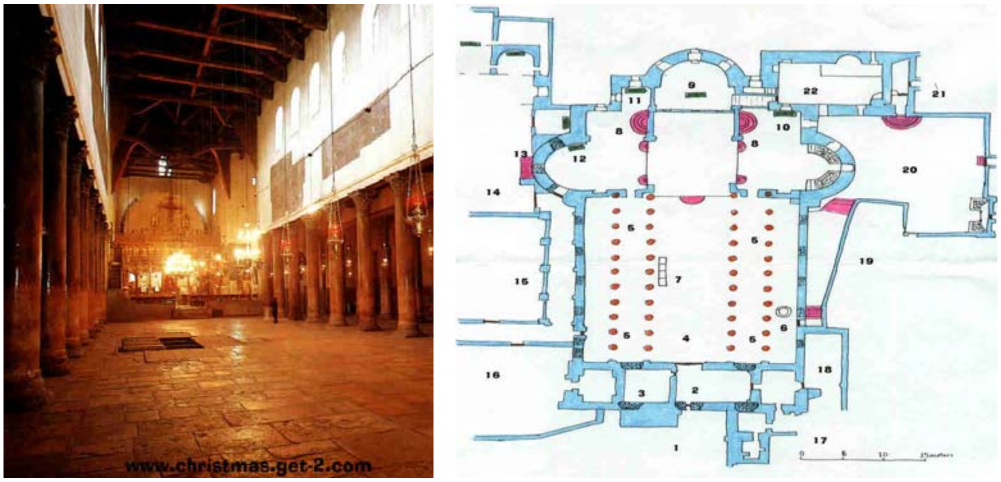



*Figure 4. for the interior and the layout of The Church of Nativity in Jerusalem*

In AD330, Emperior Constantine's Empress Helena built a church over the cave where Jesus is believed was born. The church was rebuilt in the 6th century and Parts of the original church are still standing today. It is considered by the Christian scholars to be one of the most authentic holy sites in the holy land. It is under administration of the Greek Orthodox, Franciscan and Armenian churches. The spread of the catholic designed churches continued as a default construction style until after the built of Hagia Sophia by Constantius in the 6$^{th}$ century.

Generally speaking, separately defined architectural identity for the current catholic, orthodox and Ottoman Mosques (Ottoman Mosques will be discussed later) was a result of the division of the Empire and masking the identity of Hagia Sophia to a mosque at the Fall of Constantinople by the Ottoman Turks. The division of the Empire began with the introduction of Tetrarchy System (The Tetrarchy was a system of government created by the Roman Emperor Diocletian in order to solve serious military and economic problems in the Roman Empire) in the late 3rd century AD. According to this system the Emperor Diocletian split the empire in half, with two emperors ruling from Italy and Greece, each having a co-emperor of their own. This division continued into the 4th century until 324 when Constantine the Great managed to become the sole Emperor of the Empire and then he decided to found a new capital for himself and selected Byzantium (original name of the city of Istanbul) for that purpose. Byzantium went through rebuilding; this process was completed in 330 AD.

In the early 6$^{th}$ century Hagia Sophia, the cathedral of Constantinople, was built by Constantius (the son of Constantine the Great). It was built with the help of mathematicians and engineers. Its design became a model of eastern Orthodox churches and mosques in the Ottoman ruling while the western part of the empire adapted the Catholic construction style introduced earlier. The building design was affected by the Greek architects because of its geographical position in Greek region and Roman architects because of the background of the mathematicians and engineers who participate in the construction and designing of the church. For this reason, we can see that the construction is a combination of a main square shape (inherited from the Roman Catholic Church) mounted by a main central doom covering the majority of the building (inherited from the Greek design style). The church became an ideal model for the design of all orthodox churches.

The building was rebuilt in 532 – 537 AD under the personal supervision of emperor Justinian I. It is a prime example of Byzantine architecture. Of great artistic importance was its decorated interior with mosaics and marble pillars and coverings. The temple itself was so richly and artistically decorated that Justinian is believed to have said Νενίκηκά σε Σολομών [Solomon(the third king of Israel and the builder of the great temple of Jerusalem)], I have surpassed you!). The interior of the Hagia Sophia in Istanbul was designed by Isidore of Miletus, Anthemius of Tralles , professors of geometry at the University of Constantinople. The central dome was 102 feet (31 m) across, slightly smaller than the Pantheon's (the main square shape). The dome seems rendered weightless by the unbroken arcade of arched windows under it, which help flood the colourful interior with light. The dome is carried on pendentives. These four concave triangular sections of masonry solved the problem of setting the circular base of a dome on a rectangular base. In Hagia Sophia, the weight of the dome passes through the pendentives to four massive piers at the corners. Between them the dome seems to float upon four great arches. At the west (entrance) and east ends, the arched openings are extended and by great half domes carried on smaller semi domed exedras. Thus a hierarchy of dome-headed elements build up to create a vast oblong interior crowned by the main dome, a sequence unexampled in antiquity. In fact, "its first dome fell after an earthquake May/7/ 558; its replacement in 563, had a higher profile than the original. It also had to be repaired after additional partial collapses. All interior surfaces are sheathed with polychrome marbles, green and white with purple porphyry and gold mosaics, encrusted upon the brick. On the exterior, simple stuccoed walls reveal the clarity of massed vaults and domes. For over 900 years it was the seat of the Orthodox patriarch of Constantinople and a principal setting for imperial ceremonies. In 1054 the Church in Rome break with the church in Constantinople and then the city became the centre of Christian Orthodox and Hagia Sophia becomes an orthodox church.

Masking the identity of Hagia Sophia to a mosque at the Fall of Constantinople by the Ottoman Turks under Sultan Mehmed II in 1453 AD contributes in giving mosques separately defying identities. Its rich figurative mosaics were covered with plaster and four additional Towers (Minarats) were added to each corner of the church as an Islamic touch to its design. It was for almost 500 years the principal mosque of Istanbul. Hagia Sophia served as model for many of the great Ottoman mosques of Constantinople such as the Shehzade Mosque, the Suleiman Mosque, and the Rustem Pasha Mosque.

After continuing as a mosque into the early years of the republic of Turkey, in 1934 under Kemal Atatürk it was secularized and turned into the Ayasofya Museum.

Nevertheless, the colourful mosaics remained largely plastered over. A 1993 UNESCO mission to Turkey noted falling plaster, dirty marble facings, broken windows, decorative paintings damaged by moisture, and ill-maintained lead roofing. Cleaning, roofing and restoration have since been undertaken. The exceptional floor and wall mosaics which had been cemented over in 1453 AD are now being gradually excavated. Figure 5 shows the current condition of the interior and the exterior of Hagia Sophia.

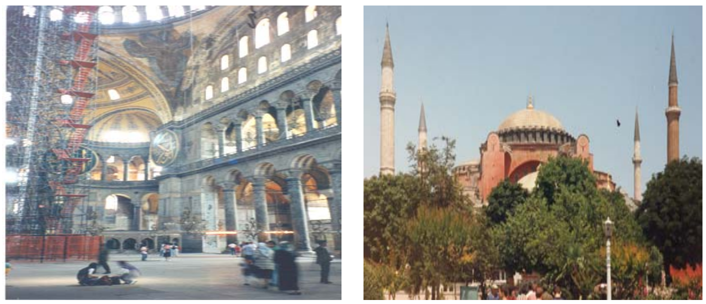


*Figure 5. The interior and the exterior of Hagia Sophia.*

### 1.1a: Christian Churches Classification:

In term of size and design, churches range from the small parish church of simple construction—just large enough to hold a small village congregation—to the huge and complicated cathedral, a church that is the seat of a bishop. Because many branches of Christianity exist, no single type of church building predominates.

Some Christians worship with little ceremony, some with complicated ceremony; some make use of drawings and panting, some do not. Thus, churches vary in appearance, having been planned to suit one or another kind of religious practice. All churches types comes under two major basic plans categories. They are:

- *Basilica with a Transept:*

It is a cross like church with a long axis running from a doorway centered at one narrow end to the altar at the other end. The nave of the basilica with is separated from the side aisles by two ranks of columns which in general also surround the transept. The transept comes in a rectangular or a circular form. The cathedral of Saint Sernin (c. 1080-1120), in Toulouse, is an example of the basilica form. It is shaped like a cross, the long nave intersected at one end by a transept. An overview of the interior and the exterior and all mentioned church features (apse, nave, aisles, transept and ambulatory) are pin pointed in Figure 6.

- *The centralized church:*

It is circular or polygonal in plan, with one large central space, usually with a dome overhead. Santa Costanza (c. ad 350), in Rome, an example of the centralized plan, consists of a domed cylindrical core surrounded by a circular ambulatory, See Figure6.

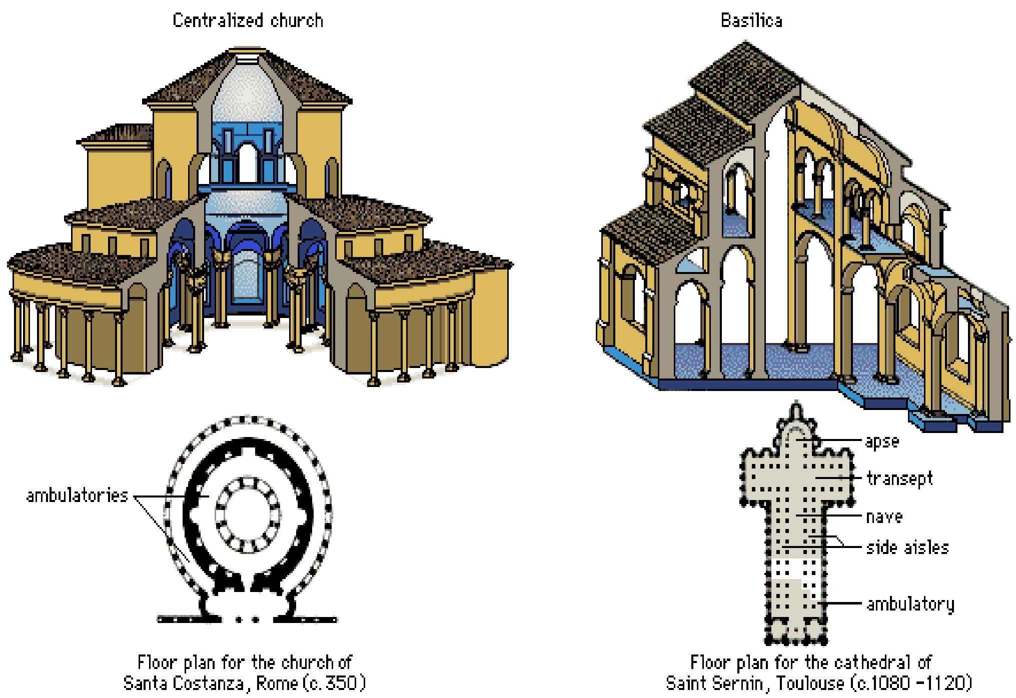



*Figure 6 Two examples of Centralized Church and Basilica Church.*

The above mentioned two types of churches represent extremes. The two basic shapes sometimes are combined in many different ways in new and medieval churches, and either one can be modulated to a cross like form by the addition of projecting wings or combination of the two basic shapes. Cross comes in a shape of a Greek cross (with arms of equal length) or a Latin cross (with one longer arm, the nave). Highly structured churches may have separate rooms for baptism, for treasures and leftovers, and for administration. They may also have more than one altar and auxiliary chapels.

A further classification can be made to subgroup churches in to six [2] different categories. All these subcategories represent the above mentioned two major types. These sub categories are provided below.

The first sub division is called **Romanesque Architecture Churches**. The **term** Romanesque was introduced in the $19^{th}$ century to describe the evolution of the Roman architecture that was introduced between the collapse of the Roman Empire in 500 century and the rise of the Gothic architecture(will be discussed next ) in the 1200 century, but now it is used to refer to the introduced architecture between $11^{th}$ – $12^{th}$ century. Romanesque Church exterior is highlighted by a tower located at the intersecting point of the two arms of the cross shape looking church and a twin towers at the front of the church. The interior of the church is marked by a wood made vaulted aisles over a wide the semicircular shape tunnel vaults. A wood roof as a construction material for such a vaults domination design was chosen to avoid any structural problems. Fire proofing, aesthetic and acoustic consideration played a rule in experimenting with masonry vaults at some regions. To support this, a thicker wall was required and vaulted galleries were often placed over the aisles to make thicker.

A second type is called **Gothic Architecture Churches.** It was named by Italian artistes of the Renaissance (will be discussed later), who considered it so barbaric (defined in idols attached to the surface of the Gothic churches) that it might have been created by Goths (people who have ravager Rome in the $5^{th}$ century). It was designed by Abbot Suger [2] in the $12^{th}$ century and it replaced the local Romanesque by 1250 century in most of west Europe. The basic elements of this design are a pointed arch, rib vault (groin vaults with diagonal arches over each bay like the ribs of an umbrella) and a flying buttress. The advantages of the basic elements go beyond their aesthetic outlook. For example, flying buttresses contribute to the visual impact of the cathedral exterior as well as allowing the side walls to become visually panels and wide allowing windows to be enlarged and contain more stained glass. So, light inside the cathedral will be improved enhancing the felling that the cathedral is an image of the truth communicating a vision of haven. Rib vaults were partly aesthetic and, mainly, they had a great structural advantage of simplifying the building technique of the tunnel like cathedral.

A third major subgroup is called **Italian Renaissance Architecture Churches.** This style represents the high peak level of the growing secularism and the renewed interest in the classical Roman civilization in the $14^{th}$ century. This architecture design is represented by two plans. First, Alberti plan in designing churches (Alberti is the first architecture theorist) and the Latin cross design plane, both made more sophisticated by adding chapels along the side walls sometimes as a substitute for aisles. The two plans are based on squares and circles and there was a fascination with domes and circular surfaces.

**Baroque Architecture Churches** is one of these main subgroups. The word “Baroque” originally meant deformed. It was represented in 1620-60 in Rome. Speared Square and circle surfaces were neglected in these design, instead, they were brought together and orchestrated to toward central vocal point.

**Neo-Classicism Architecture Churches** is more architecturally simple than the other subgroups. It emerged after 1750 century as a return to simplicity, grandeur and antique. The idea of this subgroup was to eliminate any complexity in the design of the church that was presented in the previously presented churches designs. For example, canceling the rounded spaces presented in Baroque Architecture Churches and replace it with start surface plan was considered. Also, eliminating the barbaric look that defined in idols attached to the surface of the Gothic churches was also considered to give the church more classical look.

Finally, **Modern Architecture Churches** was introduced by the end of the 19th century as a untraditional design began to be built in Europe and the United States. They bore no similarity to past designs. They have Plain geometric shapes and free of all historical associations. The technology of building was changing rapidly, and steel and concrete made new shapes possible. The centralized church was revived, with its altar placed in the middle of the congregation. By the end of the 20th century, churches in contemporary architectural modes had become commonplace. This acceptance has included a new interest in church art, and modern carving, mosaics, stained glass and wall weaving have taken their places in the new buildings.

## 1.1b: Architectural Development of Mosques:

### 1.1b.1: First Mosques:

Historically, the first mosque was build ever in Islam as such was The Mosque of Quba (covered hypostyle type) in 622 AD during the prophet journey (Hejra) form Makkah to Madinah when he camped with his companion in the mosque current place before he entered Madinah [3]. It is located in 5km south–east of Madinah city, Saudi Arabia. The mosque was rectangular in shape built of mud bricks and covered with a roof supported by date/palm trunks. Its dimensions were 26m length,30m width and 4m height.

In 623 AD the prophet built his house in Madinah and it was the first gathering and communal prayer place in Islam. It was built of mud-brick consisted of a square courtyard where communal prayer were held with two rooms in the south-east. A portico (zullah) was built of palm/trunks and branches on the north side of the courtyard perpendicular to qibla wall and extended few meters through the courtyard. Also, a lower elevated shed roof (suffa) than the zullah where built to protect visitors who spent the night there from the hot sunshine. The zullah served as place for prayer, community affairs talks and political debates. In 624 AD the zullah and the suffah changed places when the qibla was changed toward Al-Qaba in Makkah. Figure 7 illustrate the old former structural configuration of the Prophet mosque in Medina described above.

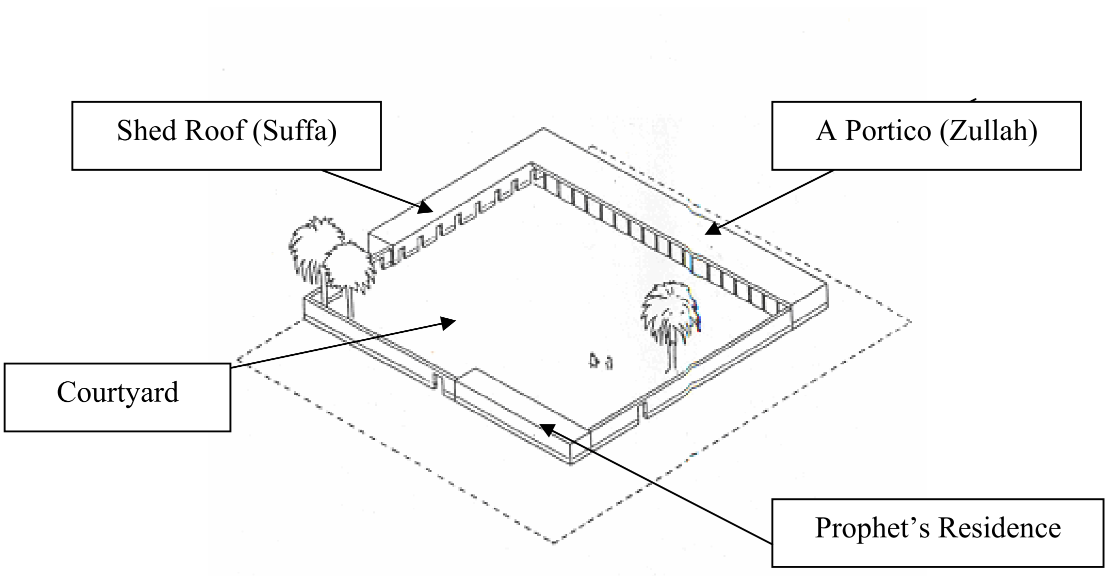



*Figure 7 The old former structural configuration of the Prophet mosque in Medina.*

The Holy Mosque in Makkah was not converted to a mosque at that time. It was an open air temple for the Quraysh triple and the people of Makkah who forced the Prophet to leave Makkah.

## 1.1b.2: Emerging of Basic Elements of Mosques:

Mosques are places of worship used for prayer, public speaking, preaching, lecturing, and *Quran* recitations. All activities performed in mosques are related to speech audibility and intelligibility. Compared to Churches, a good understanding of the speech and Quran recitation is required. Therefore, the design of their acoustical features and basic elements that are related to the acoustical behavior requires careful consideration if good listening conditions are to be achieved. In old churches, intelligibility of sound was not important while all the activity inside the church was carried in Latin language and the worshippers was asked only to repeat the prayers but not forced to understand. On the other hand, Quran recitation in prayer, public speaking, preaching and lecturing all require high level of intelligibility while all these activity are carried in Arabic language and have to be understood by the worshippers.

The prophet mosque formed a model for the subsequent mosques throughout the Islamic world in its combination of basic elements (Qibla wall, Mihrab, Minaret, Minbar). These mosques have been influenced by the subsequent civilizations in respect of architectural form, space, construction system, and building materials. These materials have evolved and developed to a significant and variable extent in different parts of the Islamic world. The main functions of each of the basic element are still the same up to nowadays.

***Mihrab*** literally means “praying niche”. It is the most important feature in the mosque and it’s the center point of the qibla wall. It is semicircular in plan having a semicircular arched top all inserted in the qibla wall. It indicates the direction of prayer and its idea and design were inherited from the prophet mosque when after his death people marked the place where he used to stand to lead prayer by a stone afterward the stone was replaced by a Mihrab. The second important feature is called ***Qibla Wall*** literally means “facing wall”. It is the wall facing Makkah and it’s the most decorated part of any mosque. This wall contains a Mihrab in its center and a the third element called ***Minbar*** ,commonly an elevated floor to the right of the *Mihrab*, as illustrated in Figure 8 and Figure 9.Unlike in Holy Haram in Makkah, worshippers form parallel lines to the qibla wall while they are in Group prayer mode as will be described later. The qibla wall perpendicular to the imaginary line that point to Al-Qaba in Makkah. Such a wall is not exist in The Holy Haram in Makkah where worshippers surrounding and praying facing Al-Qaba. The last important feature is called Minaret. ***Minaret*** literally means “slender tower with balconies”. It was added to the basic element to ensure that the voice of the Muaddin (The person making the call for prayer (adhan)) could be heard at far away distances. This remarkable addition was in 673 AD when Umayyad the governor of Egypt demolished the first mosque of Amr at Fustat which could no longer accommodate the growing number of worshippers and replace it with a new design with four minaret that were inherited from the Syrian church towers according to the wishes of Califa Muawiya as mentioned in “*THE MOSQUE HISTORY, ARCHITECTURE DEVOLPMENT & REGONAL DIVERSITY” [*3*].*

No Mihrab or Minaret where provided in the original construction of the prophet house, but a wooden Minbar with three steps where added later to the main construction features where the Prophet can deliver the Friday speech (kutba) and daily speeches and be more visible and audible to the worshippers when they are in large number. It was an important feature replacing the traditional way of leaning on one of his house palms to deliver daily speeches. Minbar became an essential piece of acoustical and visual tools to make the Imam voice heard better and to be more visible for a lager number of audience. The house was kept as mosque (courtyard type) where the prophet was buried after his death.

*Figure 8 Mihrab of the Imam.*

All these basic elements (*qibla* Wall, *Mihrab, Minbar, Minaret)* are important in the mosques construction and design throughout the Islamic world. Figure 9 shows the above mentioned basic elements of the mosque and their orientations within the mosque (Minaret will be an external feature constructed as a square tower).

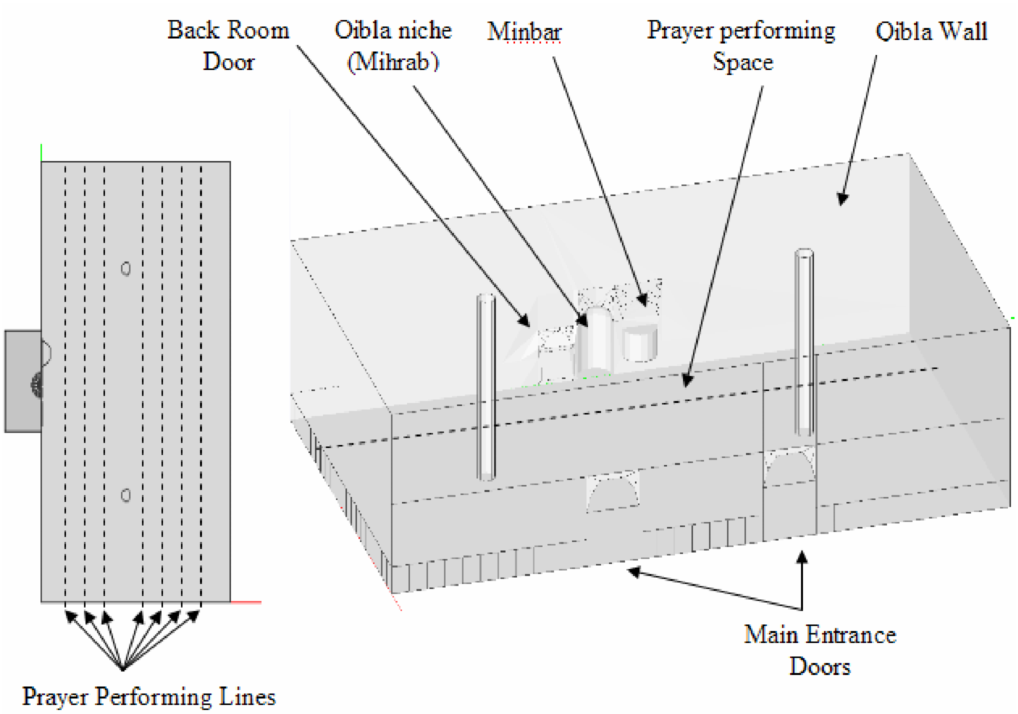



*Figure 9.Basic elements of a mosque and there orientations within the mosque space (constructed using EASE Software).*

### 1.1b.3: Mosques Classification:

One set of criteria can not be used to make a general classification for mosques and churches in the same time. While Churches can be classified architecturally to two mean groups and 6 subgroups, Mosques may be classified primarily according to their construction style to two main types. The reason for that is a different acoustical requirement as a result of different religious activity. Mosques might be classified as follow:

- *Traditional Mosques:*

Traditional mosques are classified according to their architectural form and configuration [3,4,5] .Some of these mosques have an important religious value and their internal and external construction can not be manipulated to optimize the sound behavior. Traditional mosques come in three different styles as they were also presented in the life time of the prophet. First, covered ***Hypostyle Hall*** with a roof supported by trees palms. Hypostyle mosques usually built in modest dimensions for Daily prayer, local Friday prayer and local occasions. The second type called ***Courtyard Mosque*** with sheltered *Haram which means "Protected portico"* and a *Sahn* which means "Courtyard". This type is used for Daily prayers, Friday Prayers and political debates to be held under the covered haram roof. Finally, the third style is called a ***Marked out Open Area*** used for a big congregational prayers and important Islamic occasions.

(a)

(b)


(c) (d)

*Figure 10 (a)Old Airport Market out open Area Mosque in Jeddah, Saudi Arabia.(b)The Prophet's Mosque in Madinah ,Saudi Arabia, Represents a Courtyard Mosque(c,(d)) Al-Abbas Mosque Restoration in Asnaf, Yemen , Represents a covered Hypostyle Mosque*

- *Contemporary Mosques:*

This type can be classified according to their size and location in the community to four types each of them have additional separated area for female worshipers in the same floor or mezzanine floor[6].

The first subtype is called ***Major landmark structure.*** This type is architecturally designed to provide a "landmark" fulfilling their social function(s).It dominates the townscape and affects the order of space in the urban environment. They can occupy more than 3000 worshippers and it is usually built by a government or a significant figure in the country like kings or princes.

The second subtype is called ***Large state Mosque***. This type of mosques are usually located in large cites as public landmarks area and can occupy between 1500-3000 worshippers. They are usually built by the state government expressing the commitments of the government to Islam.

The third subtype is called ***Communities Mosques***. These mosques are distributed through out the urban and the rural communities and they are used for Friday Prayers and Daily Prayers. They may accommodate additional faculties like a library, meeting rooms, clinic, etc. They also can accommodate minimum 300 worshipers and maximum 1000 worshipers.

Finally, the last subdivision is called **S*mall Local Mosques.*** They are of modest dimensions and relatively small number of worshipers (<300 worshipers).An example of each mosque will be introduced with photos in the up coming section under "Modern Designs of Mosques".

## 1.1c.4: Modern Designs of Mosques:

This section will give the reader a more detailed picture about some of the modern designs ”contemporary designs” for each of the contemporary mosques that have been introduced earlier. It will also introduce five different Architectural Approaches that are been used to design Modern Mosques.

These different broad approaches are been used by mosques designers in order to give mosques the intended identity. Each of these approaches can be exemplified by contemporary mosques. The first approach is called ***popular approach***. It is identified by the use of a traditional indigenous language of the place of construction with a construction work made by a local design and community replacing an architect in the modern sense of the word. Figure 11 shows the interior and the exterior of The Mosque of PUSDAI Islamic Center Located in Bandung, Indonesia and built in the 20th century [7]. Its design is a prime example of *large state mosque* where implementing the *Popular Approach* to give the mosque its identity is obvious. The mosque external outlook represents a modern 20th design merged with pyramid roof like style taken from former Indonesian construction style.

*Figure 11. The interior and the exterior of the mosque of PUSDAI Islamic center; a prime example of a large mosque subtype from contemporary mosques type implementing a Popular Approach.*

The second approach is called ***Populist Approach.*** It is similar to the popular approach but implementing a wider range of popular formal references and indigenous images. This popular formal references and indigenous images represented in the windows style, entry doors style, and the internal and external general construction identity of the mosque. Figure 12 shows the interior and the exterior of The Great Mosque of Riyadh and the Old City Located in Riyadh, Saudi Arabia and built in the 20th century. Its design is a prime example of *large state mosque* where implementing the *Populist Approach* to give the mosque its identity is obvious.

*Figure 12. The interior and the exterior of the great mosque of Riyadh and the old city; a prime example of a large mosque subtype from contemporary mosques type implementing a Populist Approach.*

Another approach is called ***Modernist Approach***. This approach is usually uses modern, original characteristics, form and technology at the fore to give the mosque its new modern identity. Figure 13 demonstrates a contemporary *community mosque* where the *Modernist Approach* is been used. This mosque was built in the 20th century and it is called Aramco mosque, located in Dhahran, Eastern Region of Saudi Arabia.

*Figure 13. The interior and the exterior of the of Aramco mosque in Dhahran, Eastern Region of Saudi Arabia; a prime example of communities mosques subtype from contemporary mosques type using a Modernist Approach*

Another approach is called ***Traditional approach***. It is made by a trained and registered architect who chooses to work with either the vernacular or historical relevant traditional architectural language. Figure 14, The interior and the exterior of Hassan(II) mosque in Casablanca, Morocco; a prime example of a Major landmark structure subtype from contemporary mosques type using a traditional approach in the mosque interior identity. Using the historical Moroccan traditional architectural language in decorating the interior and the exterior of Hassan (II) Mosque in Casablanca gives a good example of a *Major landmark structure* subtype from contemporary mosques that implements a *traditional approach* as provided below.

*Figure 14. The interior and the exterior of Hassan(II) mosque in Casablanca, Morocco; a prime example of a Major landmark structure subtype from contemporary mosques type using a traditional approach in the mosque interior identity.*

Figure15 illustrate a forth example called ***Adaptive Modern Approach .***This approach in designing mosques implements traditional characteristics into a modern approach. This technique is clear in designing the window of the illustrated mosque. This 20$^{th}$ century mosque is called_Azizeyah mosque. It is located in small neighborhoods in Jeddah, Western region of Saudi Arabia.

*Figure 15. The interior and the exterior of Azizeyah mosque in Jeddah, Western Region; a prime example of Small Local Mosque subtype from contemporary mosques type using An adaptive modern approach.*

### 1.1d: Conclusion:

To conclude, in part two of this introduction a historical background has been giving of the development of worship spaces starting with Solomon Temples as a first congregational place of worshipping in the history of Christianity and Judaism and passing through some of the most important historical like The church of Nativity and Hagia Sophia.

In the introduction stated two defining moments in the history that gave the current catholic, orthodox and Ottoman Mosques separately defined architectural identity. First, the division of the Empire that began with the Tetrarchy in the late 3rd century AD. The second defining moment in the architectural history of Hagia Sophia was masking the identity of Hagia Sophia to a mosque at the Fall of Constantinople by the Ottoman Turks under Sultan Mehmed II in 1453 AD.

Two different styles of Christian churches were mentioned. These types are: *Basilica with a Transept and The centralized church* and examples of such churches were provided. On the other hand, two main classification of mosques *Traditional Mosques* and *Contemporary Mosques* with their subdivision were introduced. In case of the subdivisions of the Traditional Mosques, three different types were mentioned. They are: *Hypostyle Hall, Courtyard Mosque and Marked out Open Area.* Five different Contemporary mosques subdivisions were also included and they are: *Major Landmark, Large State Mosque, Communities Mosques and Small Local Mosques* .An Example of each type and subtype was provided.

## 1.2: Acoustics in worship spaces:

### 1.2a: Acoustics in Christian Churches:

Acoustics in churches has got a great attention in the last 100 years. In fact, church community led the way in the sound reinforcement in the late1940's and early 50’s. Also, the work done in the 50's are the sound system standards that all high quality sound systems use today. In our case it might be efficient to introduce the sound system development in churches, so we can see the different in sound system development in the field of acoustic between Mosques and Churches. So, **what happened throughout the history of acoustic in the church?** [8].

In the early days, construction of the churches was done in remote places away from cities to avoid high background noise and they were designed so that the sound can be projected uniformly in all directions without a need for amplification and to flow in a smooth path without being obstructed by walls from listeners [9]. As the time goes, people realized that the need for sound amplification is a fact while the background noise increased due to increasing number of noise sources like airplanes, cars and trains etc. The reason why old churches need to treat the acoustic of the place to accommodate the new environmental conditions is no sound proof in older churches was provided because of the quit environment they were built in. In 1940's, builders of new churches suggested that they could save the church large sums of money by making a few changes. They suggested copying existing building designs and cutting all costs related to acoustics, acoustical materials and acoustical consulting and making up the rest with a proper sound system. So, attention was diverted from treatment the acoustic of the church passively by adjusting the wall martial, changing carpet and adding or removing padded pews to active treatment by adding high quality sound system. By doing this they saved up to 10% from the total cost while the cost of the high quality sound system is very low compared to the construction materials. The high quality sound system that was used at that time could not overcome the poor acoustic of the church. So, ignoring the architectural acoustic of the church and relay only on the sound system to enhance and improve the acoustical characteristics of the church was a big mistake.

In the 1950's architects started to test new construction models with a good sound system but the acoustical result were often poor while the sound system could not overcome the poor acoustical behavior of the place. They implemented newer construction technique and lower cost building material to lower the cost of older type of churches including all of the acoustical work they have done in the past.

In the mid to late 1950's two techniques were introduced *Rock and Roll* and Cheaper *Professional commercial Electronics.* No good care were given to the acoustical behavior of the church were Rock and Roll music team was performing. Speakers placed to the left and to the right of a built-in platform for one night stand giving the scene that the sound is coming direct from the stage where the musicians are performing. The other technique that was happing concurrently is called cheap professional commercial electronics. Both techniques were not meant to be functioning in a church environment which required high quality equipments to satisfy its purpose and produce high intelligible sound and reasonable reverberation time (RT).

In the early 1960's, the construction and design of the new churches were not suitable for lively congregational singing. Also, in term of cost the sound system which the church group was expecting was a lot more expensive than what they were spending on it. So, the result was a week sound system that does not meet the expectation of the worshipers and the church group.

Nothing significant happened in the 1970's. Architects were implementing the same old designed building without talking any acoustical considerations into account. Architects community had been committing implementing the same designs from the begging of 40's up to the end of the 70's. They were seeking acoustical knowledge at that time to fix the old church design but there wasn't any. The only group that has this knowledge was busy designs more acoustically efficient models.

Unintentionally, one step in the right direction was taken in the 1980's. It was emerging of a new administrative technique in the construction of churches. All the construction services, lighting services and other services people were hired at once. The final result church was called "Package church", so called in *"why is the Church Sound So Confusing" [7]*. Unfortunately, the acoustical requirement of the church was ignored at this step. The high quality package church had an inexpensive price compared to other old design churches built up to that time. Such a church was affordable and convincing financially. There were big concerns about the acoustic of the church while it was not convincing and the design did not meet the requirement of the congregational singing. Some people were describing these churches as warehouses or funeral parlors. Some effort were done for the seek of optimizing the sound performance in the package church and it was suggested that increasing the ceiling level , doubling the thickness of the drywalls to increase the reverberation time and sloped walls or different carpet will make the church sounds better. Acoustical consultancies and audio experts were not working with architects at early design process of churches models, but they were analyzing the acoustics of the old designed churches and they were trying to educate the public and the church group about the importance of hiring the acoustical expert at the same time an architect is hired. They were also showing statistics which prove that consulting an acoustical expert before design the church model and implementing his recommendation throughout the construction process costs less, more efficient and less disturbing for the worshipers than repairing the acoustical problem after constructing the church with out the acoustical consultancy. Early acoustical consultancy has saved a lot of fixing and reconstructions fees even in the low cost churches like package church. Simply, acoustical design of the church and the sound system need an acoustical expert not architect and noise control experts been hired by the Architect or the church group to make it sounds right.

In the last 50 years, a lot of events have happened caused a tremendous amount of confusion and uncertainty in the church community in many ways. Poor acoustic of these churches from the 40's to the 80's had a negative psychological effect on people attending the church ceremony. People can be divide upon there response to the acoustic of the church. The first group is people with some degree of hearing loss but can have a normal conversation in short distances. They often have problems in not recent acoustically treated church that have been built in the last 50 years because of the bad acoustical behavior in such churches. Some of this group will insist in attending the church ceremony because they are spiritually connected to the church and they want to practice their faith in **anyway**. The second group will come if you provide them with hearing helping system or they will attend other church. They are the group who want to practice their faith in **proper way**. The last group who does not need hearing assistance because they can hear well will stay at home and watch the ceremony live because they think T.V sounds better. They are the ones who want to practice their faith in a **perfect way**.

Designing a good church with a high quality sound system means people with hearing helping instruments will have no problem hearing and interacting with environment around them. People with severe hearing loss will anyway have problem listen in churches no matter how good is the system. Church's sound system must satisfy the need all different people attending the ceremony. Young people also have hearing taste in the church. They were exposed to different era of music with high quality sound and high quality radio as well. So, sound system of the church should satisfy their need. In fact" if a sound system satisfies the need of old people, it will satisfy the hearing requirements of young people and vice versa".

In 1990's after the introduction of personal computers a lot of simulation software, Array loudspeaker and computer controlled equipments have been developed. So, all these modern equipments and softwares helped solving acoustical problems in worship spaces. Simulation softwares such as EASE; Odeon and in 1995 Auralisation by means of computer models, for example, EARS Auralisation have been developed. Simulation software gives the designer a general sense of different acoustical parameters value in the developed model and how can he manipulate the sound system to optimise the functionality of the designed system and get better acoustical parameters like SPL,RT,D/R ratio,$D_{50}$ ,etc. Also, Auralisation is very useful tool that give more sensible information about how the room will sound in real life. Array loudspeaker has been developed to concentrate the directivity pattern of a number of loudspeakers assigned together in a vertical manner to cover the audience area specifically. So, as a result D/R ratio in the audience area can be higher and a better intelligibility of sound can be accomplished. Some of these arrays are controlled by computers where the user can manipulate the directivity pattern of the loudspeaker array.

These modern techniques mentioned earlier are well known and can be implemented only by acoustical expert or an audio engineer. Other people involved in this business do not have the proper knowledge of how do these new products and techniques can help solving acoustical problems in churches. So, as a result these people with a weak knowledge of the modern techniques are avoiding using them. For this reason, usually a sound system project for a church pass through 4 different designed sound systems stages before it gets to the final designed system that will last life long. The first sound system would be installed when the church is built by the cheapest offered proposal. The second sound system is usually installed by local low quality expert who has strong relation with the church community or from a local music or electronic store. The third sound system is insulted by the Professional sound engineering expert company who does all types of sound systems. This system is almost the right final system for the churches but usually the church community has concerns about the quality of their system. This is why a forth and a last system will be permanent and satisfactory for worshippers and the church community. These final systems are designed and installed by a few who have a true understanding of churches needs. They educate the members of the church about the importance of their system and how will it solve the acoustical problem of the church before a proposal is even submitted.

Due to this confusion in the sound system of the church very well known statements have been emerged. One of these statements says *"There is never enough money to do the job right in the first place but there is always enough money to do it four times" [8].*

# 1.3b: Acoustics in Mosques:

## 1.3b.1: Modes of Worshipping in Mosques:

Before start exploring the acoustic of mosques, it would be very useful to introduce the different worshiping activities in such spaces, while they might be needed (in a future analyzes and research in the coming chapters) to adjust the acoustical parameters of mosques by being fully aware of the different activity inside it.

Worshiping activities within mosques are quit different than any other worship space what makes it require different spatially designed sound system and constructional acoustical considerations. There are two different modes of worshiping in mosques *Prayer mode* and *preaching mode* as shown in Figure 16 [10]. *Prayer mode* comes in two different types called *Group prayer* and *individual prayer. Group prayer* is performed in four different consequent worshiping positions and they are standing, bowing, prostrating, or sitting behind the *Imam* all looking toward the qibla wall , on the same floor level, aligned in rows parallel to the *qibla* wall with distances around 1.2 m apart between each line. Individual prayer can be described as having the same worshipping acts as the *Group prayer*, but performed individually.

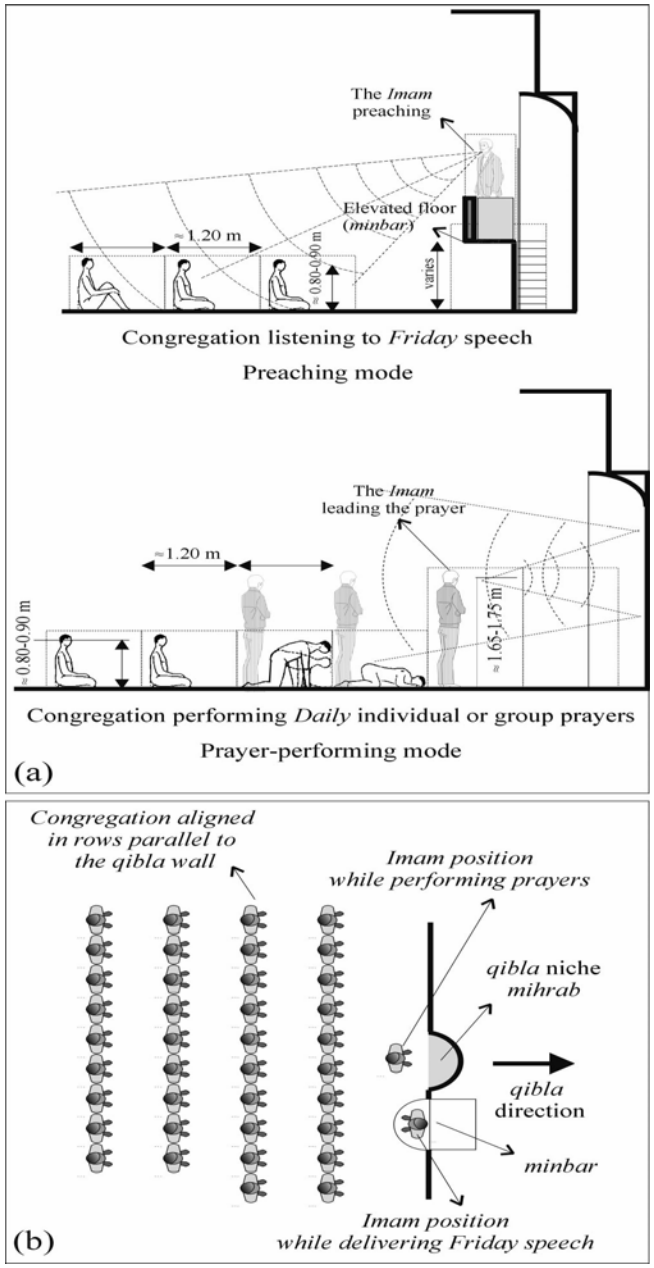



*Figure 16.Two different religious modes, (a) sections showing congregations listening to the Friday speech (i.e. the preaching mode) and performing Daily individual or group prayer (i.e., the prayer-performing mode), and (b) is a top-view plan showing the source–receiver path (i.e. Imam worshippers in group prayer performing)*

The second mode is *Preaching mode* where worshippers are seated on the floor in random rows listening to the *Imam* preaching or delivering the *khutba (Friday Speech)* while standing on the elevated *Minbar* floor. The *Minbar* floor height varies from one mosque to the other but usually is in the range of one to three meters above the mosque floor. The listening domain for seated worshipers is believed to be 0.8 m.

### 1.3b.2: Room-Acoustic Parameters in Mosques:

The study of mosque acoustics, with regard to acoustical characteristics, sound quality for speech intelligibility, and other applicable acoustic criteria, has been neglected in the last 50 years. Unfortunately, dealing with acoustic in mosques comes in a later stage after finalizing the construction of such buildings.

There are some work have been done in the field of evaluating the acoustical parameter of mosques and former Byzantine churches in Turkey called CHARISMA project (Conservation of the Acoustical Heritage by the Revival and Identification of the Sinan's Mosques Acoustics) and they are dated back to the last 6 years[11,12]. In this project, acoustical measurements by means of objective identification and evaluation (measurements, calculations) , subjective identification and evaluation (psycho-acoustical surveys) and Acoustical simulation for three Mosques and three Byzantine Churches, namely the Sokullu, Selimiye, Süleymaniye, Ss. Sergius and Bacchus, Saint Irene and Hagia Sophia have been conducted. Furthermore, Comparison between In-situ recordings and Auralizations for some of these Mosques and Byzantine Churches was, also, within the context of this project. Also, an investigation of the effect of the Byzantine churches architecture on the Sinan’s structural design was one of the main aims in this project. Some other research papers have been conducted in evaluating and treating the acoustical characteristics of individual mosques. A remarkable work has been done in evaluating and treating some acoustical parameters in King Abdullah Mosque in Amman, Jordan. The treatment pressure involved changing the wall material, carpet and doubling the window thickness to block the outside noise and increase intelligibility. Almost all of these last mentioned works and others that have been done in the field of evaluating the acoustical parameters of mosques (Traditional and contemporary mosques) evaluated the following parameters: **RT60** (Reverberation Time for 60dB reduction of sound energy), **STI** (speech Transmission Index to evaluate intelligibility), **EDT** (Energy Decay Time to evaluate lack of absorption treatment and volume), **S/N** (Signal to noise ratio to get a better view of the background noise), **Articulation index** (to evaluate the intelligibility), **D/R** (Direct to reverberant ratio is another way to evaluate intelligibility) and **Sound pressure Distribution** (evaluating the installed sound system).

All of these research papers concluded that the acoustic of contemporary mosques have to be dealt with in an earlier stages of the design to reduce the cost and time of the acoustical treatment and to get better acoustical characteristics in mosques.

### 1.3b.3: Sound System in Mosques:

In literature, no series of development of acoustic in mosques that can be mentioned or traced back throughout the last century as it is the case in churches as have been mentioned earlier. Three techniques were used and worth mentioning in the field of mosques acoustics; the addition of the ***mihrab*** which has concaved shape to ensure a more efficient sound reflection of the Imam voice toward the worshippers in the Group Prayer mode. The use of the Imam ***Minbar*** was in order to improve the maximum sound coverage distance inside the mosque. Also, the ***Minaret*** was introduced in 673 AD to ensure that the voice of the Muaddin (The person making the call for prayer (adhan)) could be heard at maximum distance possible in the area around the mosque.

Nowadays, after the rise of new modern Electro-Acoustical techniques good designed mosques by an acoustical expert are benefiting from them. Also, computer-based programs were helping in designing, analyzing and simulating the sound system behavior of mosques in a more efficient way. Although, these assisting tools have appeared, some mosques with an important religious and spiritual values are not benefiting from them the way they are suppose to. The People responsible about sound system insulation in mosques think that it will take only couple of speakers, wires and amplifiers and it will sound “RIGHT”. That is why in most mosques designs we notice some common mistakes like using sphere speakers while the mosques is suffering from low level of intelligibility and/or a long reverberation time , insulting speakers in two row distribution without using delay boxes what results in echo and low level of intelligibility. Also, because of the wrong placing of speakers and microphones the phenomena of feedback is common in mosques. Furthermore, Mosques are, in general, rectangular in shape with a lot of parallel walls and a central dome with several smaller ones; such a construction system is very problematic where generating of standing waves (as a result of parallel walls) is a fact and sound focusing (as a result of the domes) is possible [13]. Both of the last mentioned design features are not dealt with as an acoustical concerns yet (and as a main cause of a non even distribution of sound level) in most of the newly installed sound systems.

Also, most of the modern designed mosques and some of the old “Traditional” large untreated volumes have sound-reflecting finish materials on all surfaces, except the floor area which is usually carpeted. They have wooden doors and large single glazed windows. Noise level is high due to environmental noise such as: traffic noises, overhead aircraft, automobiles, air conditioners, fans and machinery noises from industrial areas [14]. All these features and environmental noise factors contribute in some way or another in decreasing the intelligibility level inside mosques .A field measurements in 30 mosques in Amman, Jordan have concluded after conducting RASTI, Reverberation Time, Background noise level, EDT and Signal to Noise Ratio measurements that there is not a single mosque were the articulation index is good or excellent and the reverberation time is usually high and affecting the speech intelligibility considerably [15].

## 1.3c: Conclusion:

As have been illustrated in section three of this introduction, in worship spaces like churches much work have been done in studying, analyzing and optimizing the sound system of such places. Also, there is a considerable amount of acoustical data in such spaces in order to help designing a new space or improvement of an older one. **No** comparable efforts have been put in mosques. So, this work is intended to study, analyze and optimize the Sound Systems and the existing room-acoustic parameters in mosques and adding acoustical design of future mosques.

# Chapter 2

## 2: Description of the topic of the thesis:

The effect of each basic element like domes, roof supporting columns and common feature on sound behaviour inside mosques will be investigated once at the time. Different sizes, position and geometrical shapes of these basic elements and common feature will be considered. Points of weakness and strength will be highlighted for different architectural forms. Different acoustical parameters will be tested and simulated for different models at different preaching behaviour, different demands for speech, ensuring of needed intelligibility and other acoustical measurements. Representative mosque model of each group of mosques that have been mentioned earlier will be entered in EASE software and simulated results will be compared to a measured data. The effect Wall's Ornaments as sound diffusers will be investigated. Weaved surfaces and non cylindrical columns will also be considered.

Nowadays, background noise increased due to increasing number of noise sources like airplanes, cars and trains as sources located outside the mosque and air-conditioning and roof fans inside mosques. All these noise sources affect the intelligibility and audibility of sound with in mosques. This work will suggest the minimum acceptable sound parameters inside different volume of mosques. Traditional mosques with an open courtyard will also be investigated since they are more exposed to environmental noise. Since no random placement of treatment material "Passive Treatment" for the different mosques types is recommended, controlled system algorithm will be provided to minimize the effect of the environmental noise on the intelligibility level and to improve the audibility of sound especially in open space and courtyard mosque. Effective places and materials of treatments with minimum deformation of wall characteristics, especially the Qibla wall, will be carefully selected.

Also, a study of the acoustic in existing worship rooms and the use of modern developments in the field of DSP- and computer-based systems for sound reinforcement in such rooms will be investigated. Furthermore, development of optimised algorithms to create most flexibly programmable radiation characteristics in worship rooms will be considered. Derivation of the physical (location) and technical (control of loudspeaker's control setting) background for the control mechanisms by constructing the corresponding computer models will also be provided. Test and verification of the algorithms in practical applications preferentially in a mosque will also be considered. Test and verification of the algorithms in practical applications preferentially in mosques will also be considered. Optimisation to achieve the desired coverage of sound pressure level on audience areas will be demonstrated and analysis will be provided for the resulting coverage when using optimised and non-optimised systems. Also, compensation of the developed optimised radiation will be used to suit another additional consideration of the local environment parameters for open and closed spaces. Furthermore, a discussion of the advantages and the disadvantages of the developed algorithms compared to conventional concepts to create guidelines of sound reinforcement engineering (including acoustical treatment) in exiting worship rooms will be within the main aim of this work.

# Chapter 3

Mosques, as all halls or rooms where people gather, may be studied according to their primary and secondary structures. Primary structures are determined by their volume, shape and specific dimensions of a mosque. Secondary structures are based on wall shape and acoustical treatment of a mosque surface part. Let us start with the Primary Structure:

## 3.1: Primary Structure of Mosques:

### 3.1a: Dimensions:

Categorizing Mosques according to their volumes will be the approach used in this section. As mentioned earlier in chapter 1, mosques shall be classified according to their volume into six different groups. In another work of Adel A. Abdou, 21 mosques have been investigated to show the relationship between mosques volume and their effect on the acoustic parameters of mosques [9]. See Table 1 for more details about different groups of mosques and their associated volumes.

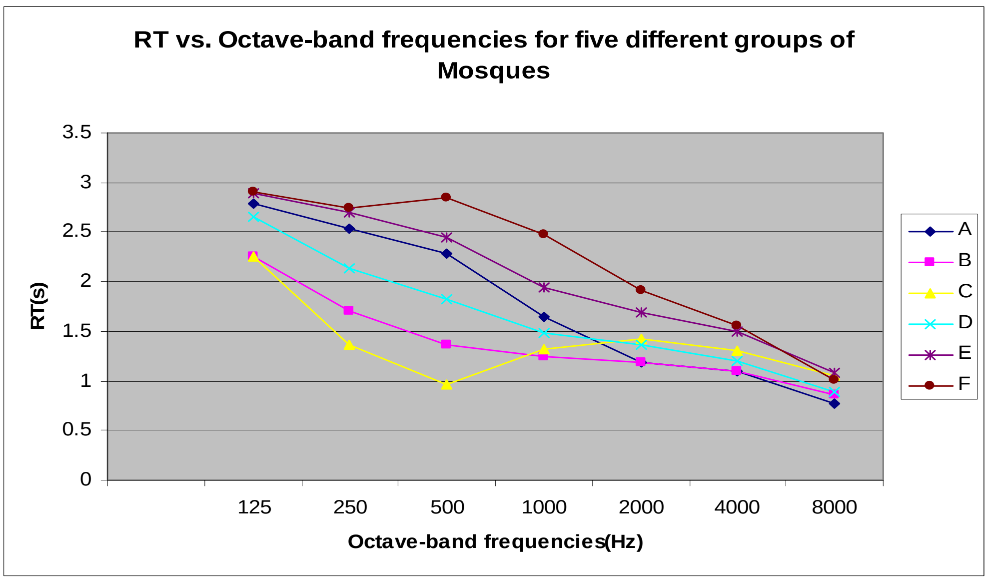
| Group | Associated volume range ($m^3$) |
|---|---|
| A | <1000 |
| B | >1000<1500 |
| C | >1500<2000 |
| D | >2000< 3000 |
| E | >3000<10000 |
| F | >10000 |

*Table 1. Different groups of mosques and their associated volumes*

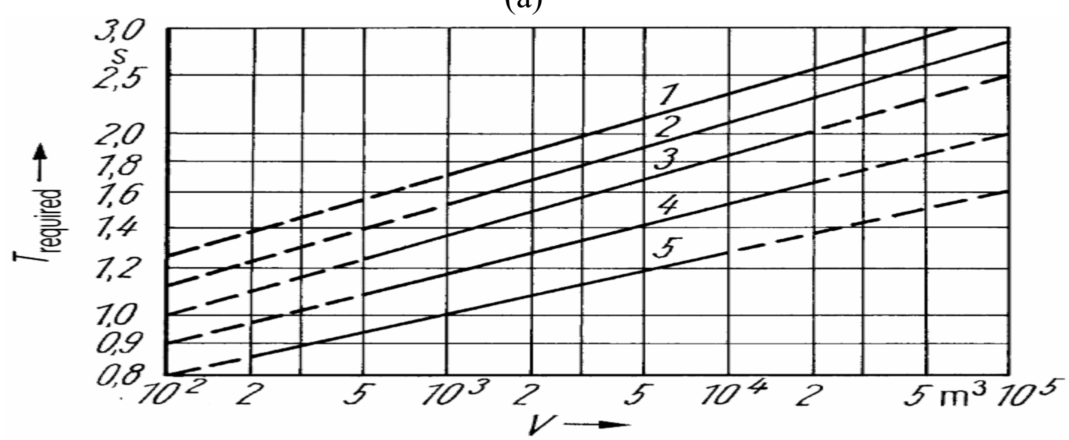
A relationship between volumes and the associated reverberation times and other acoustic parameters will be investigated. The RT has been compared to the reverberation time used as standard values for the same room size. Let us start with the RT as an important acoustical parameter in mosques.

### 3.1a.1: Reverberation time:

The relationships between volume and RT for the six different groups are shown below in fig. 17a as it was measured in earlier mentioned research paper. Additionally, the internationally recommended RT for different acoustical application is shown in fig. 17 b.




(a)




(b)

*Figure 17(a).RT Vs. Octave-band frequencies for five different groups of Mosques(b).Recommended RT for: 1.organ of a church 2. Symphony music 3. Multipurpose Hall 4.Speech 5. Halls equipped with a Sound reinforcement system*

A measured RT of all mosques is a single value at a certain position and changes slightly from position to position inside the mosque. These values imply what might be the influence of domes, rounded surfaces, carpet and other common features. Compared to optimal target reverberation time for speech (curve 4, Figure 17b), the selected 21 mosques were more reverberant. They did not meet the expectation of having the presented relationship in fig. 17b between RT and the mosque's volume. In contrast, some mosques with smaller volumes had more RT compared to bigger volumes mosques. The reason is certainly the influence of the earlier mentioned features and elements of mosques on the RT behaviour.

EASE Models representing the mentioned different volumes of mosques, but simple in design, were created to understand more the influence of the primary structure of a more sophisticated mosque on the reverberation time. A sample mosque in design (rectangular in shape) of each group which maintained the same volume was modelled.

Aura Ray Tracing tool provided in EASE was used to take into consideration all architectural features and characteristics inside the different groups of mosques and to investigate their influence on sound parameters. The Aura, **A**nalysis **U**tility for **R**oom **A**coustic, Module is a very powerful EASE acoustical analysis tool. Based on CAESER algorithms developed by Aachen University (RWTH), AURA allows the calculation of all key room acoustical parameters defined in ISO3382. Below in fig. 18 is shown the RT of each model for different band frequencies using Aura Ray Tracing.

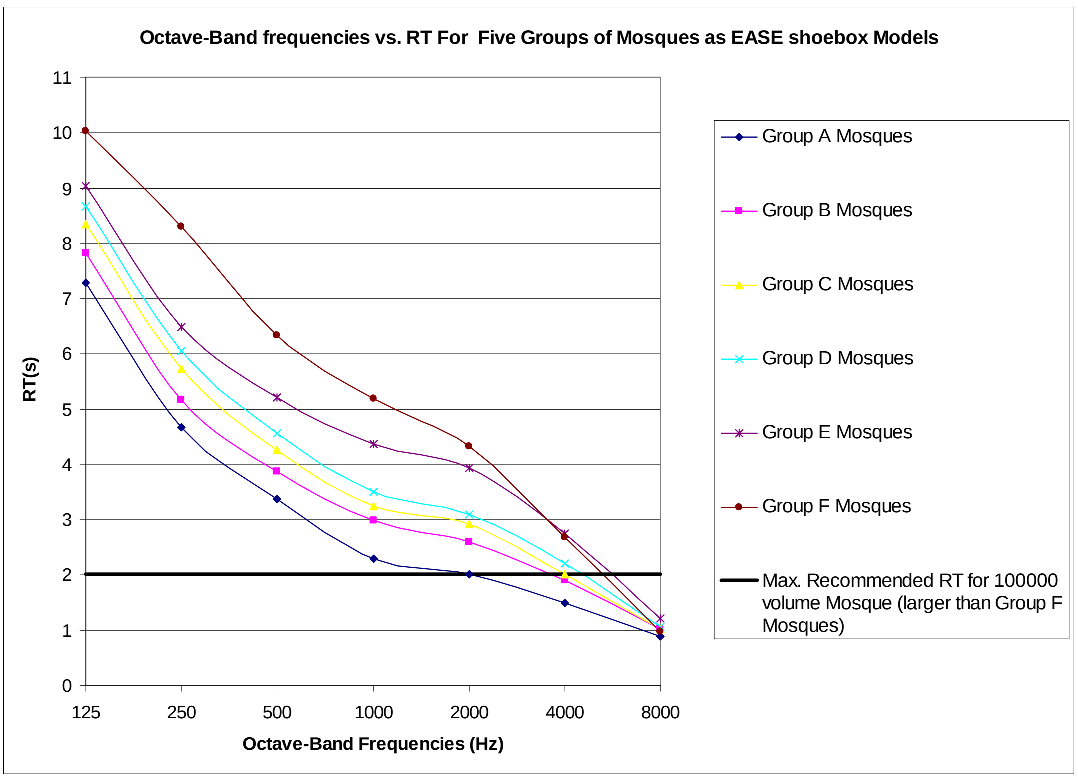



*Figure 18 Octave-Band Frequencies vs. RT for EASE Shoebox Model*

By comparing Fig.17 a and 18, it is clear that the EASE shoebox models behave more as expected compared to the mosques groups presented in Figure 17a. The presence of more mosques features like columns, domes, lowered surfaces and rounded walls make the relation between volume and RT more sophisticated.

Also, it is noticeable from the results provided in the previous figure that the EASE models with its six different groups showed higher values of reverberation time compared to the results provided in fig. 17a. Furthermore, by comparing them to the recommended reverberation times for speech, the EASE models were more reverberant. The Maximum recommended RT of speech for 100,000 $m^3$ structure is 2s as shown in fig.17b and as marked by bolded line in fig.18. It is visible that all the six different groups (even group A mosques with <1000 $m^3$) have RT's more than the RT recommended for 100000 $m^3$ (bigger volume than all the six groups).

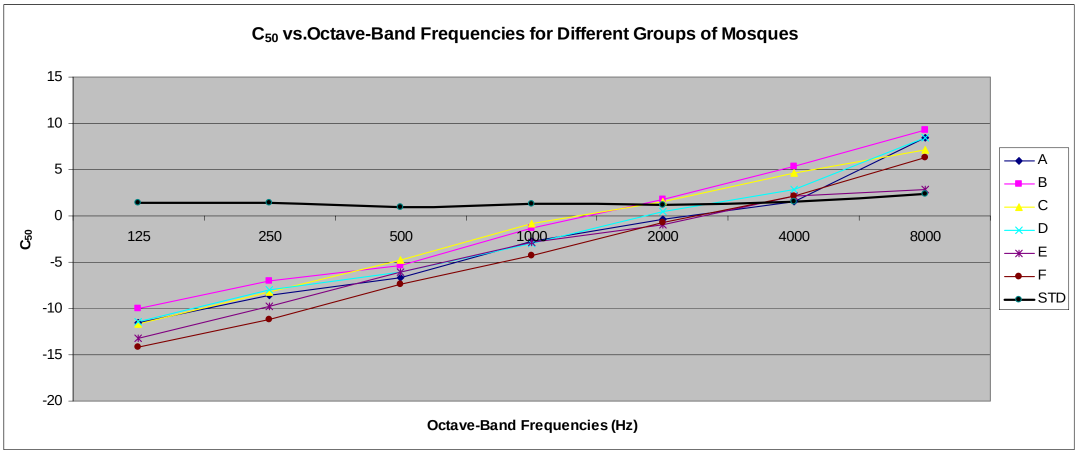
The reasons for this increase can be explained as the result of Flutter Echoes and the lack of sound obstruction objects and surfaces. The reverberation time dramatically increases especially at the low end frequencies as a result of Flutters Echoes bouncing back and forth between parallel walls. Also, the lack of obstruction objects surfaces like roof supporting columns and lowered surfaces (Female worshipping areas) gave more chance for the sound to travel through the mosque space without been obstructed.

Because of the design features of real mosques compared to the EASE simple models, the RT presented in Fig. 17a is not behaving as expected. The increase in the RT as the volume increases was not noticed.

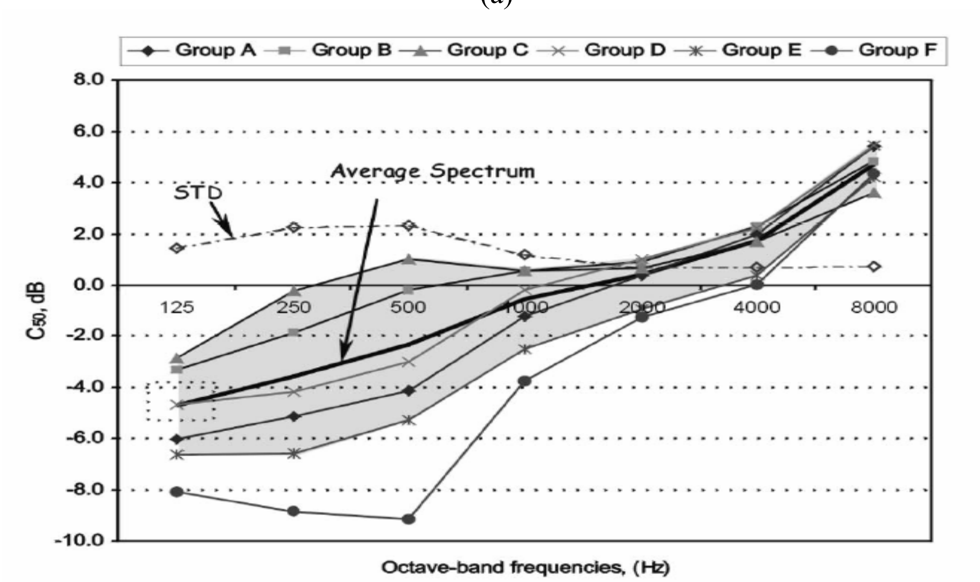
It seems that the presence of different wall structures, material and manipulation of the general layout of the real mosque play a major role in influencing its acoustic behavior compared to shoebox EASE mosques. All these factors made the RT's of the real mosques less independent from increasing the volume. More precisely, the natural increase of the RT associated with increasing the structure volume will not be evident in real mosques. To underscore this result similar investigations follow for the intelligibility.

### 3.1a.2: Clarity of Speech (Intelligibility):

Normally the Speech Transmission Index is selected to describe the Intelligibility of Speech Transmission alone important in mosques. But here the measure $C_{50}$ has been selected to be able to compare it with the mentioned measured values recorded in the 21 mosques. The clarity measure for speech $C_{50}$ for the six different groups as provided in the work of Adel A. Abdou and in the EASE models will be compared to investigate the relationship between increasing RT and the intelligibility in mosques. Figure 19 (a) and (b) presents $C_{50}$ curves for the earlier represented EASE Modeled groups mosques along with the correspondence $C_{50}$ measures taken from the mentioned research paper respectively. The simulation using Aura Ray Tracing Method has taken place in the six different groups A,B,C,D,E and F with 2,4,5,6,8 and 10 positions respectively (grid size 3 and 4m for groups A and B and 5m for C,D,E and F). A comparable number of prayer positions for the measured values were considered. The number of simulation positions in the different groups of mosques was chosen according to the recommendation of ISO3382.




(a)




(b)

*Figure 19(a) Averaged C50 for EASE Shoebox Models vs. Octave Band Frequencies for different groups of mosques, (b) Averaged Measured C50 provided in Adel A. Abdou /ee/ vs.. Octave-Band Frequencies*

By comparing 19a and b one sees that the clarity measures in the EASE Shoebox models show a more linear dependency. The Standard Deviation Curves (STD) in the two figures indicates how the Clarity values at each Octave-Band frequencies fluctuate. If the Clarity values are close to the average of those values, then we may expect to see a low standard deviation and vice versa. It is visible that the STD in the shoebox models is more constant compared to STD curve of the measured clarity curves. The presence of structural details in the real mosques like domes, Roof supporting Columns, lowered and curved surfaces, all have contributed to prevent flutter echoes travelling between parallel walls to degrade the measured clarity values at low frequencies Octave-Bands, see fig. 19 b. On the other hand, according to the influence of fine wall structural details like wall Ornaments in the real mosques which scatter high frequencies, lower clarity levels were experienced compared to the EASE modelled mosques.

Factors other than dimension and volume played a major role in inflecting the clarity of sound. Travelling low frequency sound waves between parallel walls degrades the clarity of sound in the absences of waved surfaces and obstructing objects like columns. The presences of wall ornament and other wall decoration which scatters and diffused sound waves at correspondences wavelengths to their dimensions degrades clarity of sound as have been noticed. All these factors will be closely investigated in a later section.

### 3.1a.3: Sound Level in the Direct Field:

Sound intensity in the areas covered with direct sound can be described with following equation:

$$I_{dir} = \frac{\gamma_L P_{ak}}{4\pi r^2} \text{.............}(1)$$

Where,
$\gamma_L$ - the effective front-to-random factor
$P_{ak}$ - the acoustic power of the source ($P_o$=$10^{-12}$ W)
r - distance source – receiver point

Thus, in levels notation we get:

$$L_{dir} = L_w - 20 \log r + C - 11dB \text{.......... ...}(2)$$

Front-to-random factor $\gamma_L$ characterises the relationship between the acoustical power that would be radiated into a room by an omnidirectional radiator having the same free-field sensitivity and the same acoustical power as the actual radiator to be assessed. In the above equation $C=10 \log \gamma_L$ is the front-random-factor index. By assuming that sound power level of a human loud voice at 1m is 80dB and C=2 (at 1 KHz), thus:

$$L_{dir} = 71dB - 20 \log r \text{.......... ...}(3)$$

The following Figure depicts the line represented by equation 3. Here the sound pressure level in the direct field as a function of the distance from the source is drawn.

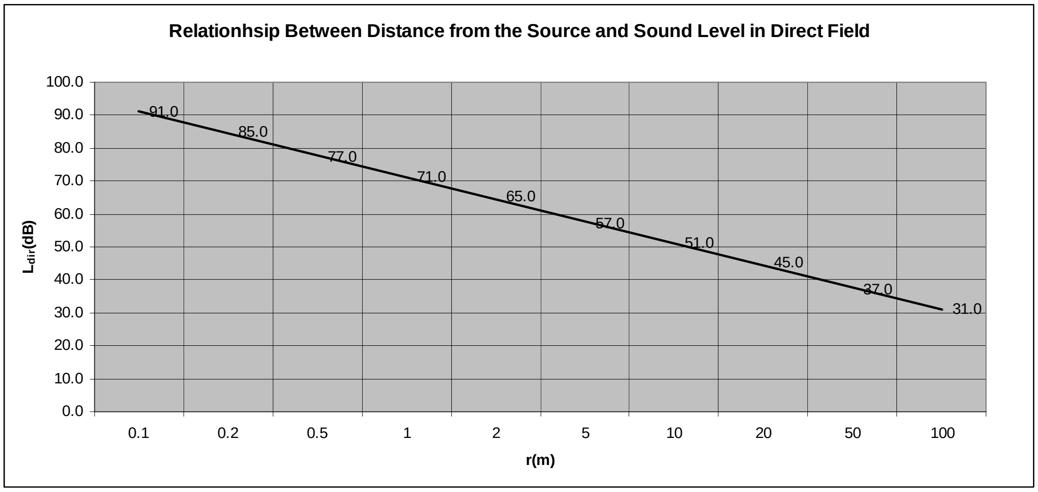



*Figure 20 Sound level in the Direct Field as function of the distance from the source*

Fig. 20 shows that in a distance of 10m the direct sound level is already dropped to 50 dB and will soon be below the noise floor. The intelligibility of the speech of the Imam is gone under these circumstances.

## 3.1a.4: Maximum Achievable Sound Level in Diffuse Field:

In the presence of a sound source (Loudspeaker) or a human voice (Imam Voice) in a mosque, the homogeneity of the diffuse field is more or less steady. The shape and size of a mosque both affect the reverberance and the spaciousness of the diffuse sound field in this mosque. Our interest in this work is focussed to a relationship between volume of a mosque, the usable acoustic power radiated into the space and the sound pressure level in the diffuse sound field you may get and all these tasks as a function of different reverberation times inside the mosques. Investigating the maximum sound level in the diffused field that can be achieved will draw a maximum border line of the maximum possible RT which can occur in such a diffuse sound field. This may be applied later to our above mentioned six different groups of mosques. Thus, by developing a relation between the maximum attainable sound pressure level in the diffuse field ($L_{diff}$) and the ratio V/RT you get limits of the diffuse sound field level vs. the maximum RT that can occur. An equation to start with is the Intensity level in the diffuse field:

$$I_{diff} = \frac{4P_{ak}}{A} \quad \text{.............(4)}$$

Since the A=0.163V/T and $P_o$=$10^{-12}$ W, the final equations that relate the diffuse sound field level to the V/RT ratio is:

$$L_{diff} = L_w + 14dB - 10\log\frac{V}{RT}dB..........(5)$$

By assuming that sound power level of a human loud voice at 1m is 80dB:

$$L_{diff} = 94dB - 10\log\frac{V}{RT}dB............(6)$$

The following Figure depicts the line represented by equation 6. Here the sound pressure level in the diffuse field as a function of the ratio between volume and the Reverberation time is drawn.

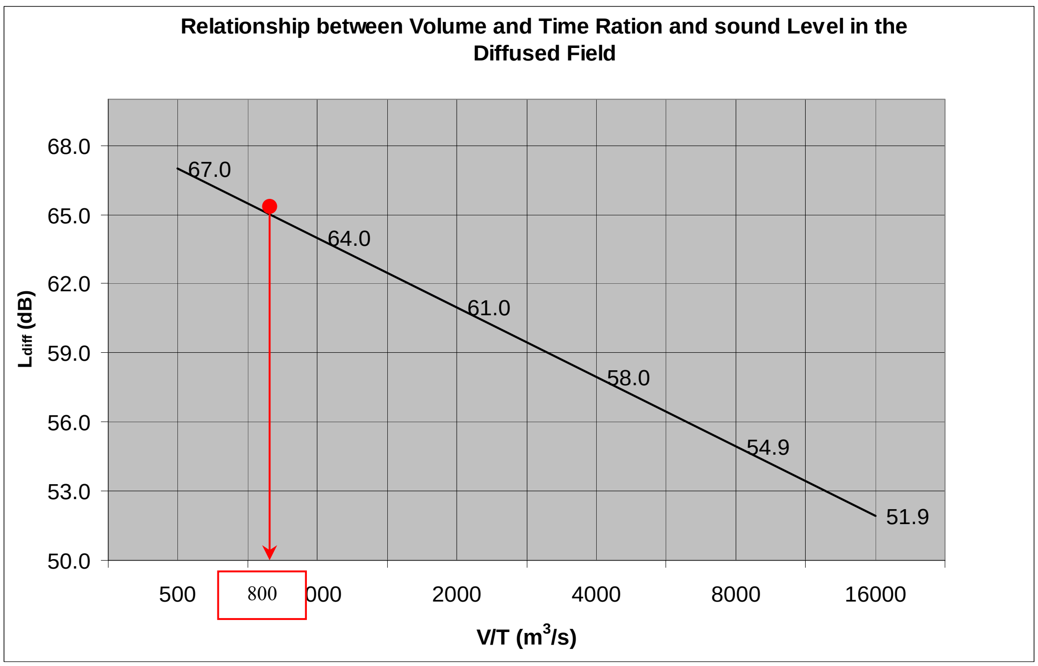



*Figure 21 Sound level in the Diffuse Field as function of the Ration V/RT*

The above Figure depicts, beside the relationship between $L_{diff}$ and V/RT, the assumed minimum acceptable diffuse field level $L_{diff}$ (65dB) without the need for Sound Reinforcement System (SRS) to boost up the SPL in the diffuse field. This level is influenced by the existing noise floor inside the mosque. From chapter 2 we know that noise inside mosques has been increased in the last 20 years caused by the increasing number of noise sources like airplanes, cars and trains as sources located outside the mosque. Also, air-conditioning and roof fans as sources of noise inside mosques can not be neglected. All these noise sources affect the intelligibility and audibility of sound within mosques.

So from fig. 21 we conclude, that all mosques with a volume/RT ratio < 800 $m^3/s$ can be handled pure acoustically (using only the Imam voice) without the need for SRS. On the other hand, all mosques with a volume/RT ratio ≥ 800 $m^3/s$ needs SRS to get a reasonable SPL in the diffuse field to overcome high background noise in mosques. If for example, an Imam ($L_w$= 80dB as was assumed before) deliver his speech in a group E mosque (V/RT≈2900 $m^3/s$, see Figure 21), level of approximately 60dB would be realized in the diffuse field which is less than the assumed minimum acceptable $L_{diff}$ (65dB). Thus, the diffuse sound pressure level caused by the Imam will be lower than the noise floor and will not be audible anymore.

Referring to Figure 17b, the maximum recommended RT for a 10,000 $m^3$ Speech hall is 1.8 s. Initially, assuming that 1.8 s is the no border cross line for the RT as a matter of fact for any mosque volume, thus, mosques with a volume/RT ratio of V/RT= 800 $m^3/s$ should have a volume of no more than 1440 $m^3$ (1.8 s × 800 $m^3/s$) to maintain 65dB at the diffuse field. Accordingly, all group A, B mosques can be handled pure acoustically with out the need for a sound system. Applicable sound systems must be applied for the other groups of mosques to maintain the required SPL level at the diffuse field.

### 3.1a.5: Total Sound Level of Direct Field and Diffuse Field levels in real Mosques:

In sound field of rooms, the resulting sound pressure from the Direct and the Diffuse sound is additive. The resulting total energy density is:

$$w = w_d + w_r \text{..........(7)}$$

Where $w_d = \dfrac{\gamma_L P_{ak}}{4\pi r^2 c}, w_r = \dfrac{4P_{ak}}{cA}$ ;

thus, the total energy density is:

$$w = \frac{\gamma_L P_{ak}}{4\pi r^2 c} + \frac{4P_{ak}}{cA} \text{...........(8)}$$

Thus the total intensity is:

$$I = \frac{\gamma_L P_{ak}}{4\pi r^2} + \frac{4P_{ak}}{A} \text{..........(9)}$$

Where, I=w.c (c is the sound velocity), A=0.163V/RT and by multiplying the nominator and the dominator by $P_o$:

$$L = L_w + 10\log\left(\frac{\gamma_L}{4\pi r^2} + \frac{25 * RT}{V}\right) dB .......(10)$$

or by introducing the critical distance $r_R$ (here $w_d = w_r$) and with

$$r_R^2 = \left(\frac{0.163V}{16\pi RT}\right) \times \gamma_L$$

the levels notation equation is:

$$L = L_w - 20\log r_R \, dB + C + 10\log\left(\left(\frac{r_R}{r}\right)^2 + 1\right) dB - 11 dB .........(11)$$

Figure 22 depicts the overall energy density level ($w=w_d+w_r$) depicted by equations 10 and 11. For direct sound field, as also represented in Figure 20, the decrement of 6 dB per distance doubling is visible. In the open air (A→∞) the direct field behaviour would continue (marked by dashed line). In realty, beyond the critical distance a constant diffused field (10 log $w_r$, *eq. (5)*) dominates. The curved line represents the total Sound level of the two fields combined together in the area around the critical distance $r_R$.

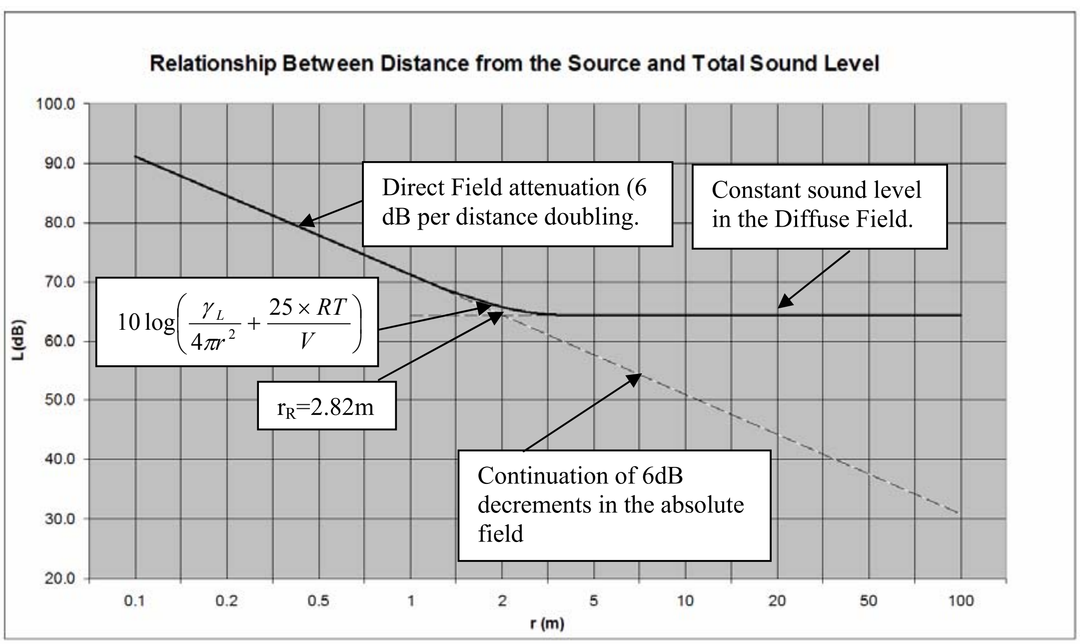



*Figure 22 Total sound level as function of the distance from the source*

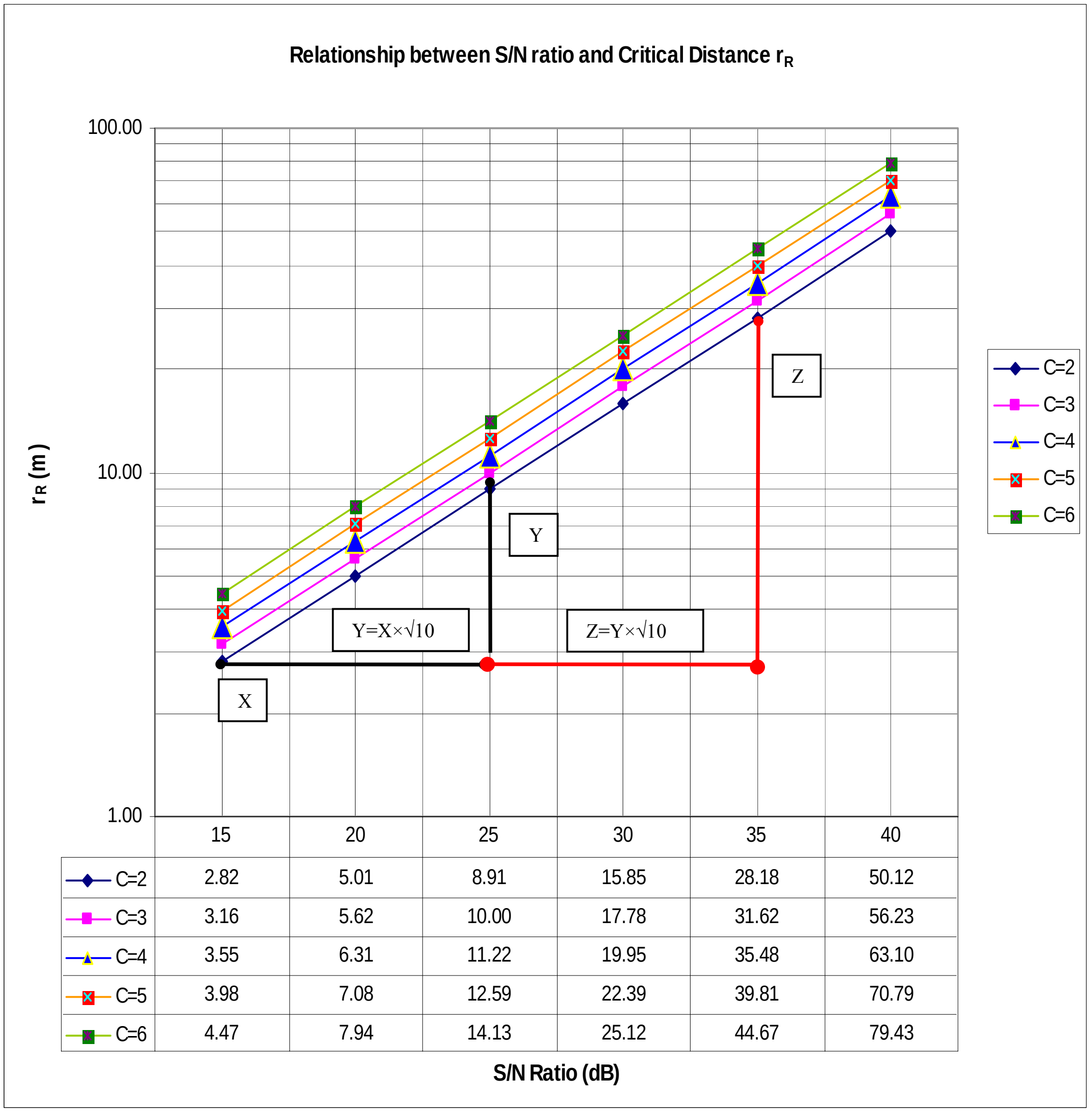
The critical distance $r_R$ of a loud man voice have been, also, concluded graphically in Figure 22. It is the intersecting point of the bolded curved line with a diffused level of 65dB ($r_R$=2.82m). Mathematically, when $L_w$ =80dB and C=2 for loud human voice at 1 KHz and $L_{diff}$=$L_{dir}$=65 *dB*, thus, by substituting in equation (11):

$$65dB = 80\,dB - 20\log r_R + 2 + 10\log 2\,dB - 11dB$$

$$\boxed{r_R = 2.82\text{ m}}$$

If the critical distance were to be calculated using equation 8, $r_R$ would be 2m (given that the sound power level of the Imam voice at 1m is 80dB and C=2(at 1 KHz)). In figure 23 $r_R = 2m$ is the intersecting point of the direct field attenuation line (the dashed line of 6 dB decrements per distance doubling) and the line which represents a constant sound level in the diffuse field (65dB). The different between the calculated $r_R$ using equation 11 and 2 (0.82m) is the distance it takes the sound to decrease gradually in a smooth transition (represented by the curved part of the bolded curve) until it reaches a level of 65dB in the diffuse field. A sudden decrease of the sound level to 65 dB as it enters the diffuse field from the direct sound field is not valid in real application. A gradual decrease of the sound level takes place where the sound filed is still a mixture of direct and diffuse field before a constant diffuse field is maintained.

In general, in any structure used for speech purposes good intelligibility is our main task, i.e. the worshippers should be covered with the direct field of the imam, but in any case getting a SPL higher than the noise floor is important. It turns out that the volume/RT ratio must be increased (higher absorption) and of course the noise floor should be decreased in an existing mosque to improve the situation. By decreasing the target level by 10dB (i.e. 55dB instead of 65dB, because of higher absorption at lower noise floor) the critical distance is increased to a factor $\sqrt{10}$m. In open air (very high absorption) the limitation is the final level of the noise floor alone. See the following figure for a better illustration for the relationship between S/N ratio in the diffuse field and the critical distance $r_R$ for a different source's Front to Random indices C derived from equation 11.




| | 15 | 20 | 25 | 30 | 35 | 40 |
|---|---|---|---|---|---|---|
| C=2 | 2.82 | 5.01 | 8.91 | 15.85 | 28.18 | 50.12 |
| C=3 | 3.16 | 5.62 | 10.00 | 17.78 | 31.62 | 56.23 |
| C=4 | 3.55 | 6.31 | 11.22 | 19.95 | 35.48 | 63.10 |
| C=5 | 3.98 | 7.08 | 12.59 | 22.39 | 39.81 | 70.79 |
| C=6 | 4.47 | 7.94 | 14.13 | 25.12 | 44.67 | 79.43 |

*Figure 23 Relationship of reachable critical distance $r_R$ vs. S/N ratio in the sound field. Parameter: different directivity values C of the source.*

So, high absorption and low noise floor will lead to increase the direct field range in real mosques. Accordingly, the influence of reverberance and noise floor is pushed to lower values. Thus, especially in small mosques the Imam could under these circumstances pray without sound reinforcement. Of course in big mosques with big dimensions, he needs SRS to increase the S/N ratio represented in fig. 23 to increase the critical distance which correlates with the increase of intelligibility.

### 3.1a.6: Conclusion to dimension considerations:

The expected increase of RT related to the increase of mosque's volumes as shown with corresponding EASE shoebox models was not noticed in the volume-related real mosques. The existence of more sophisticated wall structures, shape and general layout of mosques degraded the dependence of the RT on Mosque's volumes.

By using the acoustical measure of Speech Clarity $C_{50}$, the intelligibility was evaluated for EASE shoebox models and their associated real mosques. Features and structural details of mosques like Domes, Roof Supporting columns, Lowered Surfaces and Wall Ornaments have degraded the measured clarity values especially between 500-2000 Hz Octave-Bands. Also, parallel walls lowered the clarity level at lower Octave-Bands according to the resulting Flutter Echoes. The presence of fine wall structural details like wall Ornaments which scatter higher frequencies (4000-8000 Hz) degraded the clarity levels at these Octave bands.

Furthermore, it was found that volumes of mosques should be between 1500 to 2000 $m^3$ to maintain a certain Signal/Noise ratio giving a certain assumed values for natural voice of the Imam (80dB Sound power level assumed) and the reverberant sound or the noise floor (Here a level of 65dB in the diffuse sound field or as a noise floor has been assumed normally exist in real mosques). Thus, group A, B mosques can be handled pure acoustically without the need for a sound system. But in any case, sound systems must be applied for the other groups of mosques with bigger volumes to keep the needed direct/reverberant field ratio. The target is to increase the critical distance of the used sound sources to bring the worshippers into the direct field to assure good intelligibility.

## 3.1b: Shape:

A lot of mosques constructional features have an effect on the sound behaviour inside mosques. Different sizes and designs of domes and columns manipulate the acoustical parameters inside mosques constructions. Also, parallel walls play a major roll in causing Flutter-Echoes phenomena. Moreover, in open court yard mosques where worshippers are exposed to delayed sound arriving from the Minarets sound system measures show a poor Intelligibility level. The important constructional features in real mosques will be now discussed and acoustically investigated by using hypothetical and real existing mosques both modelled in a computer.

## 3.1b.1: Traditional Hypostyle Mosque:

### 3.1b.1.1: Columns Effect:

An EASE computer model of the Former Quba Mosque in Madinah, Saudi Arabia is created as shown below. This mosque with its simple rectangular shape and large number of columns supporting the roof was chosen to investigate the effect of the columns and parallel walls on sound parameters.

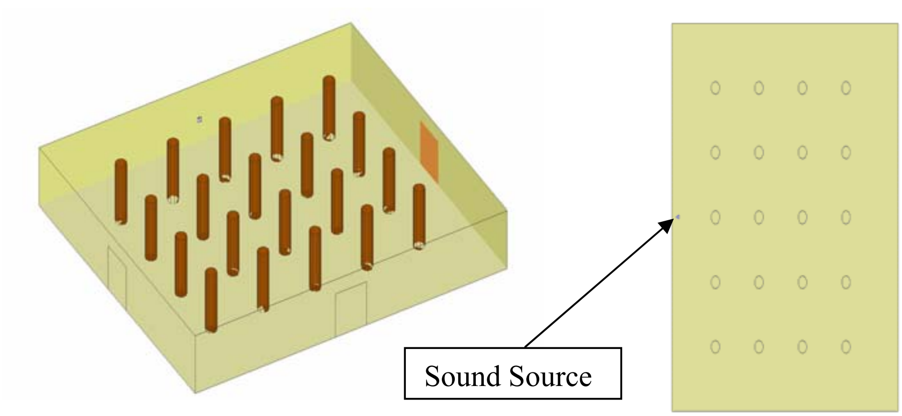



*Figure 24. Former Mosque of Quba (covered hypostyle type)*

As mentioned already in chapter 1, the mosque was rectangular in shape and built of mud bricks and covered with a tress leaves roof supported by date/palm trunks. It has had a sandy ground space and dimensions of 26m length, 30m width and 4m height. A man raised voice representing an Imam voice was placed in the center of the Qibla wall as shown in Figure 24 to investigate the acoustic behavior of the mosque. Acoustic Area Mapping and Ray Tracing Methods were carried out as shown below to investigate the effect of the roof supporting columns and other structural features on the sound parameters.

Direct sound Mapping was carried out as illustrated in Figure 25. One can see clearly the lack of direct sound in almost 35% of the audience areas.

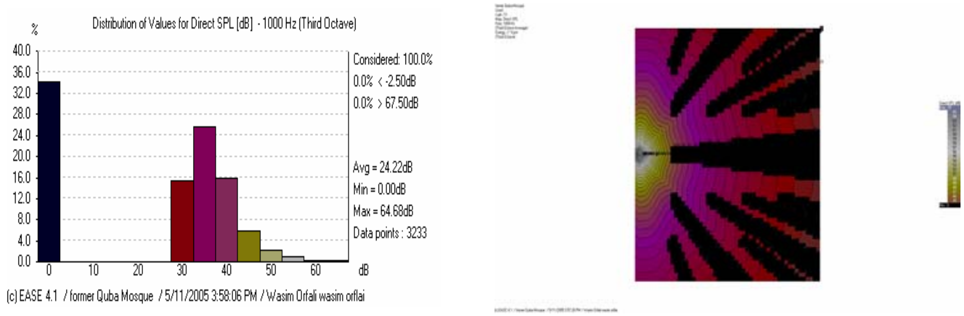
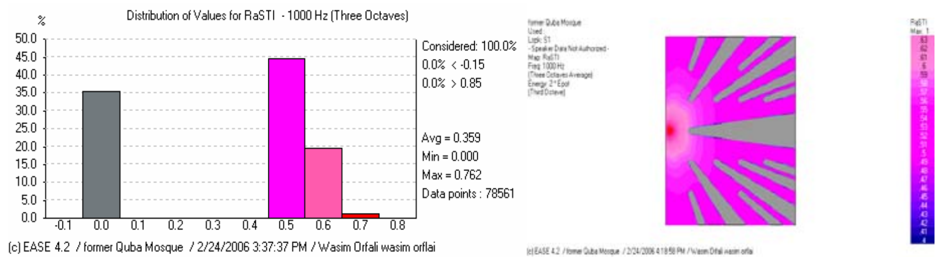
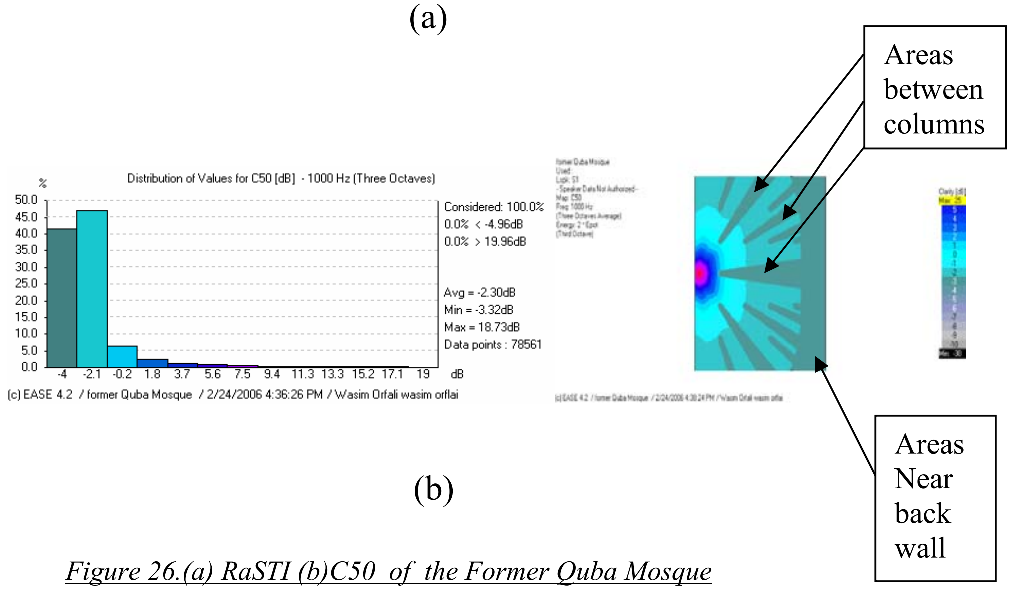



*Figure 25. Direct SPL of the Former Quba Mosque*

Intelligibility of sound was, also, evaluated using the simulated raised voice of an Imam as a sound source. The big number of roof supporting columns played a major role in obstructing the direct sound from reaching almost 35% of the worshiping area. See Figure 26a for detailed illustration. To show more the influence of blocking the direct sound by the columns, the simulations were conducted considering only the direct sound (no reflections were considered in the simulation). For this reason we notice the existence of 0 STI level in fig. 26a. In reality, there are reflections from the neighboring surfaces which boost up the intelligibility level. Also, $C_{50}$ map in Figure 26b shows the clarity levels measures for the investigated mosque. Any value above 0 dB is a good indication for sound clarity. The result of the Audience Area Mapping shows very good clarity level throughout the mosque. As we go forward away from the Qibla Wall and through the columns rows the clarity level decreases dramatically. Within the region between the Qibla Wall and the first row of columns clarity measure $C_{50}$ was at very good level, since no columns blocks the sound in this region. Even between the last row of columns and the back wall the clarity level was as low as -4 which still imply a clear sound.



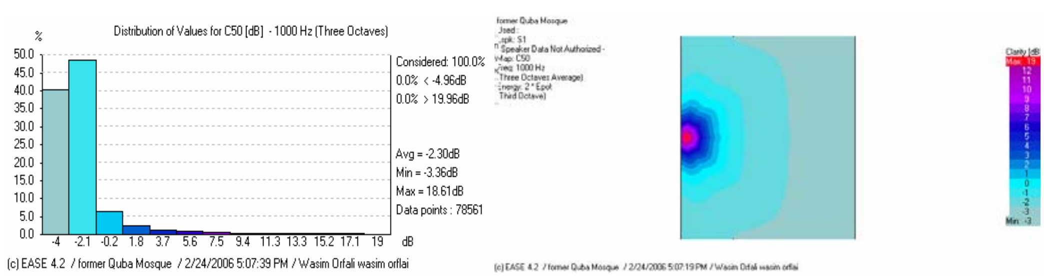

(a)



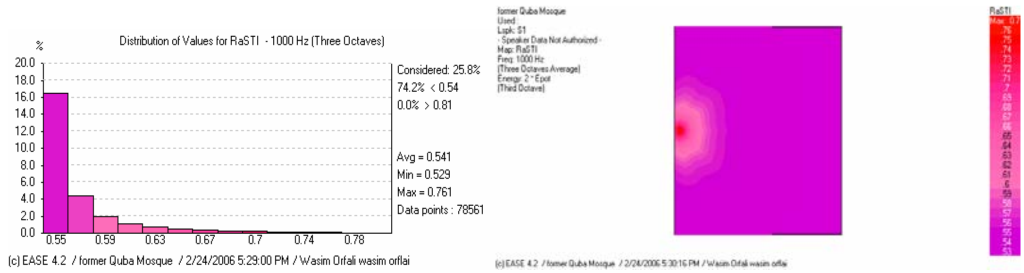

(b)

*Figure 26.(a) RaSTI (b)C50 of the Former Quba Mosque*

There is no doubt, the effect of the number of columns and their size inside a mosque can not be ignored. Assuming that the mosque presented in Figure 24 would be build without columns supporting its roof. Fig. 27 depicts the improvement in the sound intelligibility and clarity when the columns are eliminated. The poor clarity and intelligibility is still evident, since the mosque is relatively big to be covered only with an Imam voice without the help of SRS, but in any case the shadow caused by the columns is eliminated.




(a)



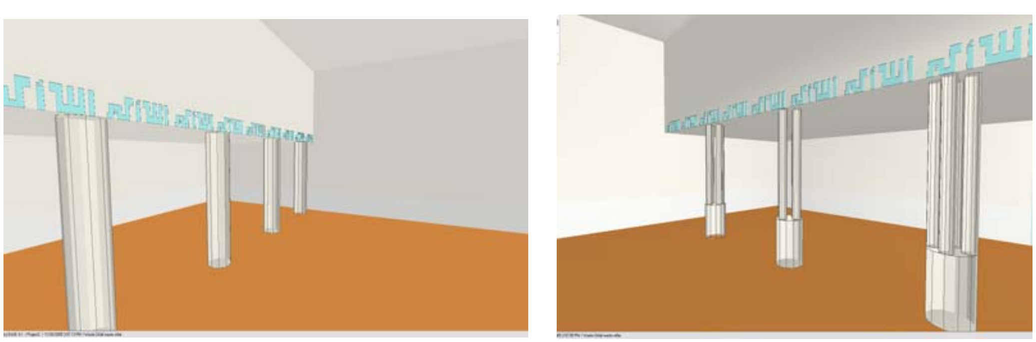

(b)

*Figure 27. (a)C50 of the Former Quba Mosque(no columns)(b) RaSTI of the Former Quba Mosque*

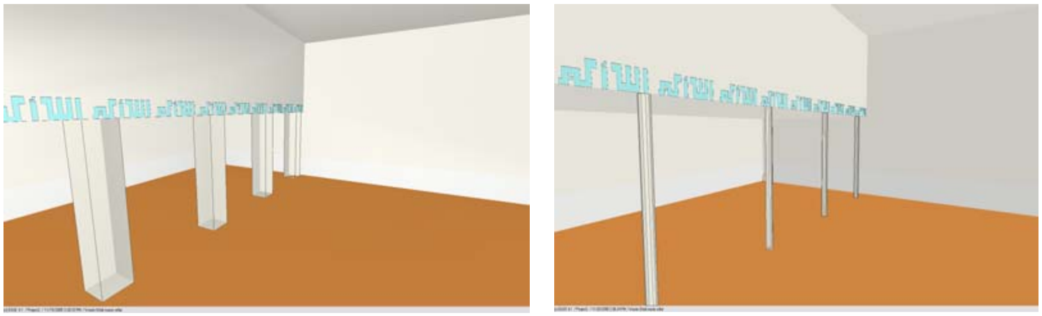
The influence of columns on the sound clarity and intelligibility was shown in this section. Eliminating the columns from a mosque structure will result in a better coverage of the direct sound through out the audience area. Accordingly, an increase in the sound intelligibility and clarity will be evident. Also, the size and the spacing of columns will have such an effect on the sound quality.

### 3.1b.1.1.1: Columns Size, Spacing and Shape:

Spacing of the roof supporting columns, also, contributes into the percentage of the obstructed direct sound. Today, architects do not give the proper attention to this fact. Quite often they don't have a clear knowledge about its drawbacks on the sound quality of a mosque. In this section, different shapes and sizes of columns were investigated to show their influence on the direct sound coverage. The following Figure 28 gives an overview about the investigated columns sizes and shapes.



***(a)*** ***(b)***



***(c)*** ***(d)***

*Figure 28.(a) 2m diameter circular columns (b)4 in 1 circular columns(c)One by one Square columns(d) 1m diameter circular columns.*

The following Figure 29 depicts a relation between Column Spacing and percentage of areas shadowed from the direct sound in Quba Mosque for a 1m and 2m circular column, 1x1 Square and for 4 in 1 roof supporting column arrangement.

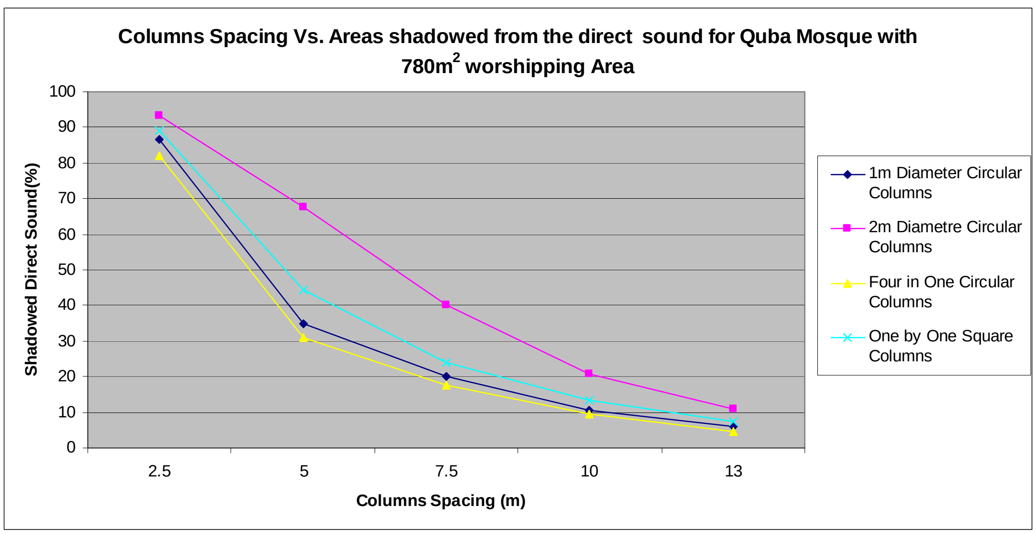



*Figure 29. Relation between columns spacing and Areas shadowed from the direct sound.*

As the distance between columns increases, the percentage of the areas shadowed from the direct sound to the total worshipping area decreases. The percentage of the shadowed area shows a maximum in case of 2m diameter columns. Squared shape columns which contain the same ground area as 1m diameter circular columns and four in one circular columns obstruct more the direct sound as these two last column types. Consequently, using such often designed columns to support the roof will have a negative influence on sound intelligibility and clarity.

Both decreasing the spacing between columns (or increasing the numbers of columns per area) and increasing the diameter of the roof supporting columns had an evident effect in increasing the obstructed area for the direct sound, compare Figure 29. Consequently, the intelligibility and clarity of the sound will be reduced. Also, increasing the spacing between columns (consequently, decreasing the number of columns to support the roof) give more chance to the low frequency sound rays to form Flutter Echoes between parallel walls.

### 3.1b.1.2: Parallel walls effect:

Not only the roof supporting columns have an effect on the sound quality of a mosque; Also, parallel walls cause the phenomena of Flutter Echoes. Flutter Echoes play a major rule in reducing the speech intelligibility inside a mosque. A long-delayed reflection pattern of the direct sound rays bouncing forth and back between the side walls degrades the intelligibility values. See Figure 30 to get a better understanding of such ray behaviour.

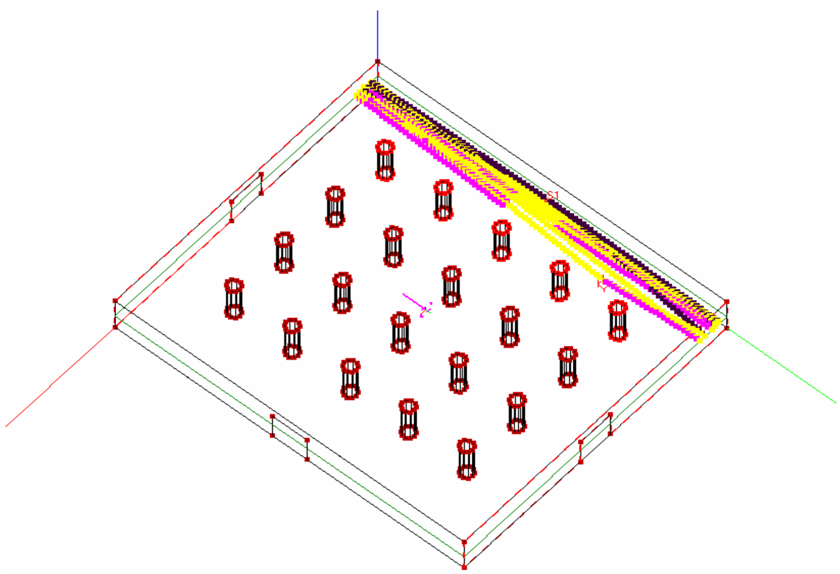


*Figure 30. Sound Ray Bounces between the side walls (Flutter Echoes)*

Unfortunately, no treatment of wall constructions or wall materials like scattering elements superimposed on parallel walls or increasing the absorption of such walls, respectively, has been done until now to break the influence of this behaviour. Today, most of the constructed mosques have two parallel walls perpendicular to the Qibla wall and a roof supported with columns. Thus, the formation of Flutter Echoes rays in front of the Qibla wall and the first row of columns will be evident in most of theses mosques. On the other hand, the formation of such Flutter Echoes rays between the Qibla wall and the opposite back wall and between the flat ceiling and the floor will not be less because of the existence of the columns and the carpet respectively. On one side the columns scatter the sound rays between the Qibla and the back walls but don't prevent Flutter Echoes rays between them. Also, the carpet floor tends to absorb most of the sound energy rays before they reflect from the floor toward the roof forming the Flutter Echoes rays.

### 3.1b.2: Hypothetical Design of a Domed Contemporary Mosque:

Contemporary Mosques have in common what is so called mosque's features like Domes, Carpet, and wall writing ornaments. A Hypothetical design of a Domed Contemporary Mosque was modelled in EASE as shown in Figure 31 to study the effect of these features.

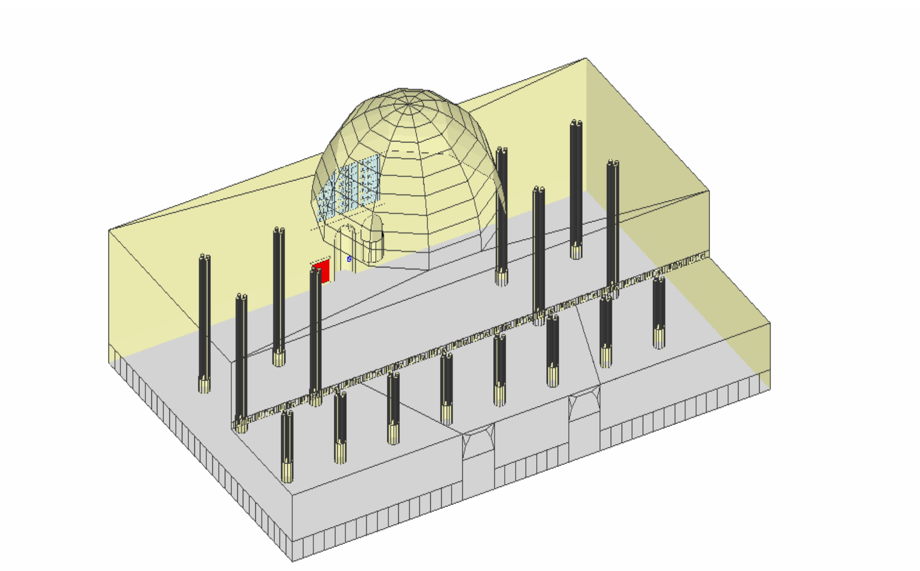


*Figure 31. Hypothetical Domed Contemporary Mosque*

#### 3.1b.2.1: Dome and Curved Surfaces effects:

#### 3.1b.2.1.1: Dome Effect:

Domes in mosques became a fixed structural identity. It gives the designed mosque an extended architectural dimension compared to Traditional Mosques with its simple design. Most of mosque's architects have not paid to much attention to the influence of domes and curved surfaces on the radiation of sound in a mosque. The focus of the following section is to investigate the influence of different kinds of dome structures, their deepness and their height from worshipper's area level on sound behaviour in mosques.

A relationship known in optics and applied for lenses rules of physics, relates and governs the interaction of domes with the sound being directly radiated to its centre:

$$\frac{1}{s}+\frac{1}{e}=\frac{2}{r} \text{.......... ...(12)}$$

Where, (see figure 32 for a better understanding)
*s:* is the distance from the centre vertex point of the dome to the source,
*e:* is the distance between the focal point and the centre vertex point of the dome ($e= r/2$)
*r:* is the radius of the dome.

When $s = r/2$ (the radiating source in the middle of the radius length at the focal point) all the reflected sound rays are parallel as seen in Figure 32a. In case $s > r/2 < r$ as in 32b sound rays concave and intersect at a point farer than the focal point of the surface. When the sound source is located at position closer in distance to the reflecting surface than the radius middle point ($s<r/2$) reflected sound rays start to convex as shown in Figure 32c. Moving the radiating source around the radiating axis will cause the radiating sound to be reflected in the opposite direction as shown in Figure 32d. Figure 32e shows the source at farer distances compared to the focal point $s > r$. Sound rays concave at points less than the distance (***r)***. It can happen that the distance from the centre vertex point of the dome to the source **(*s*)** is equal to the radius of the dome **(*r*)**. Consequently, the focal point **(*e)*** will be located at the same position as **(*r)*** and **(*s)***, see figure 32f. This situation must be avoided to avoid focusing, specially, when the focal point is at the hearing level of the worshippers (1.7m from the ground floor).

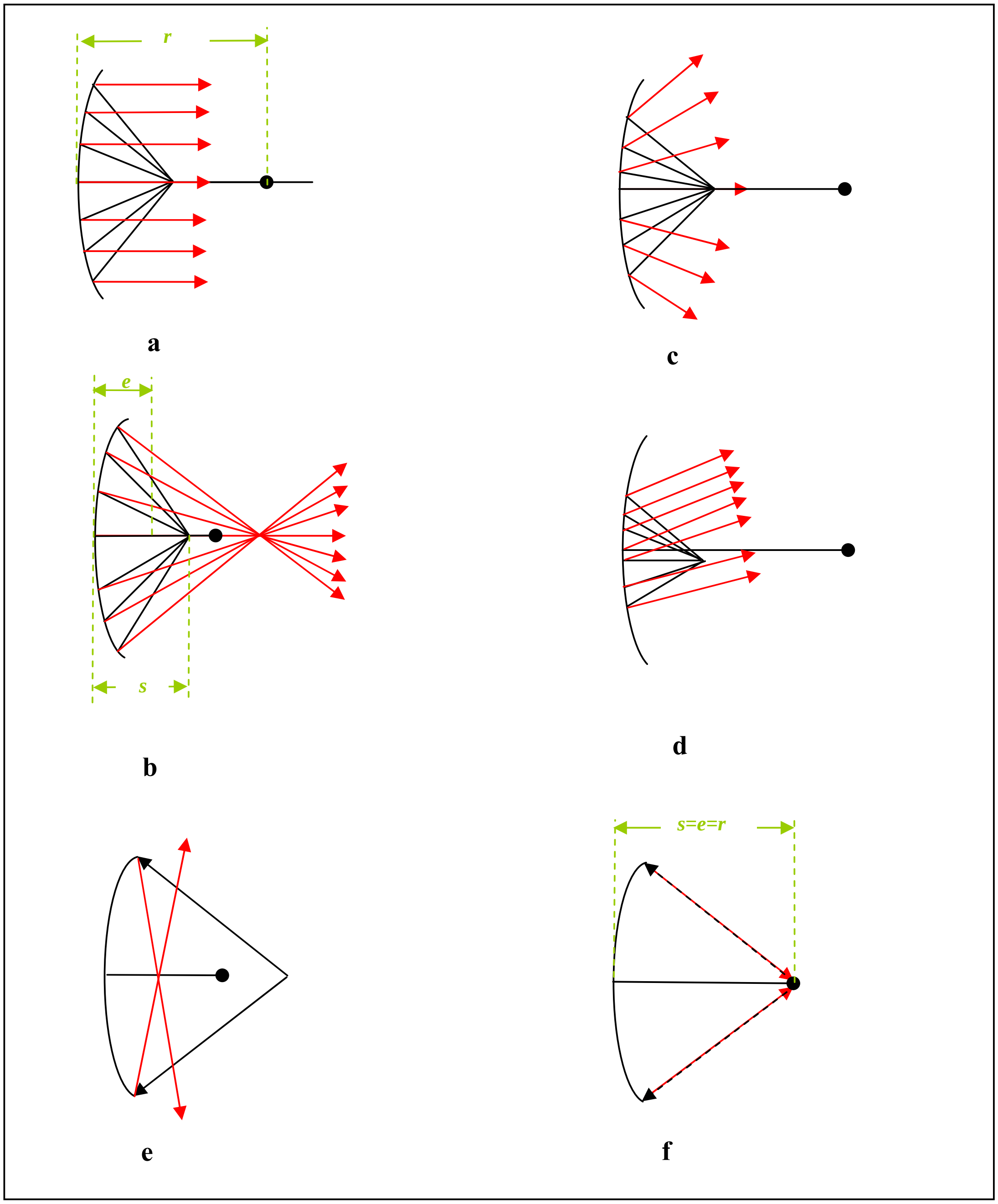



*Figure 32. Different radiating behaviour*

In the Hypothetical design of the Domed Contemporary Mosque shown in Figure 31, one sound source placed directly under the dome is used in different height levels. The interaction of every source, once at the time, with the 8m radius dome will be simulated in the mosque's EASE model.

In a case of a full excitation of the dome represented by a sound source pointed toward the centre of the dome, different source positions are considered. The results of a Ray Tracing Simulation are shown in the following Figure. Sound source placed at r/2 shows a parallel reflection lines bouncing back toward the carpet. One source location located at s>>r/2 =1.7m from the ground floor (r=8, s=16.3 all from the dome highest point) which represents speaking human height level shows a concentration of sound rays at the dome height level (concentration at e=14.8m from the ground level) far from the worshippers hearing surface levels and more distributed sound as reflected sound rays travels toward the audience level (Figure 33 a, b and c). The dome structure starts at 10m from the floor level.

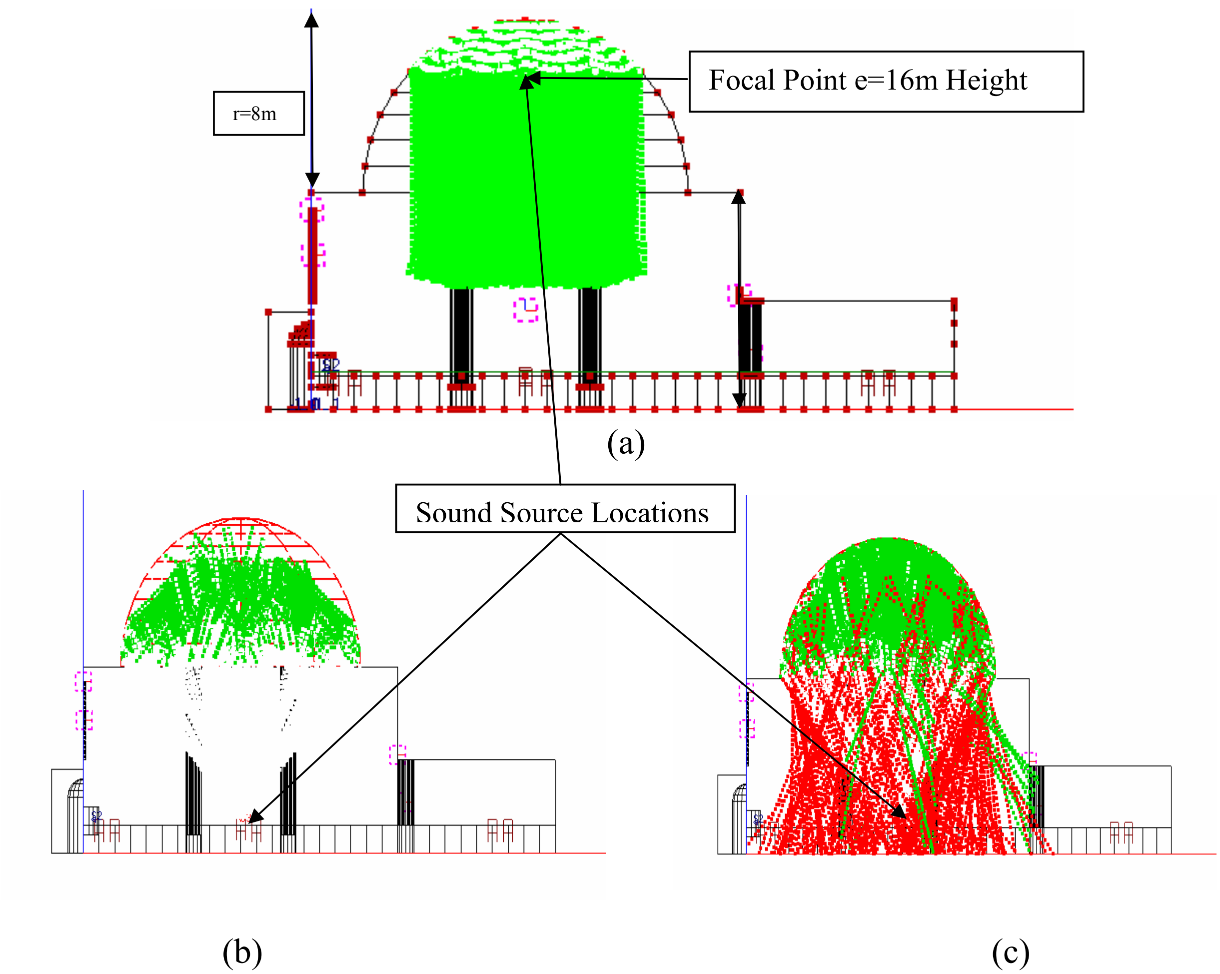



*Figure 33.(a) parallel reflection,(b) concentration of sound rays within the dome level ,(c)concaving of sound rays after concentration within the dome level*

In the hypothetical mosque shown in Figure 31 seven different test point location were chosen to represent the whole structure. Aura Ray Tracing Method was conducted to calculate the RT at seven different Octave Bands. Afterward, the average reverberation time was obtained with and without a dome. Also, the floor material was changed between marble and thick carpet floor to observe their effect on the excitation of the Dome. The volume of the mosque was maintained to be the same before and after eliminating the dome. As a result six different RT curves were obtained and shown in Figure 34.

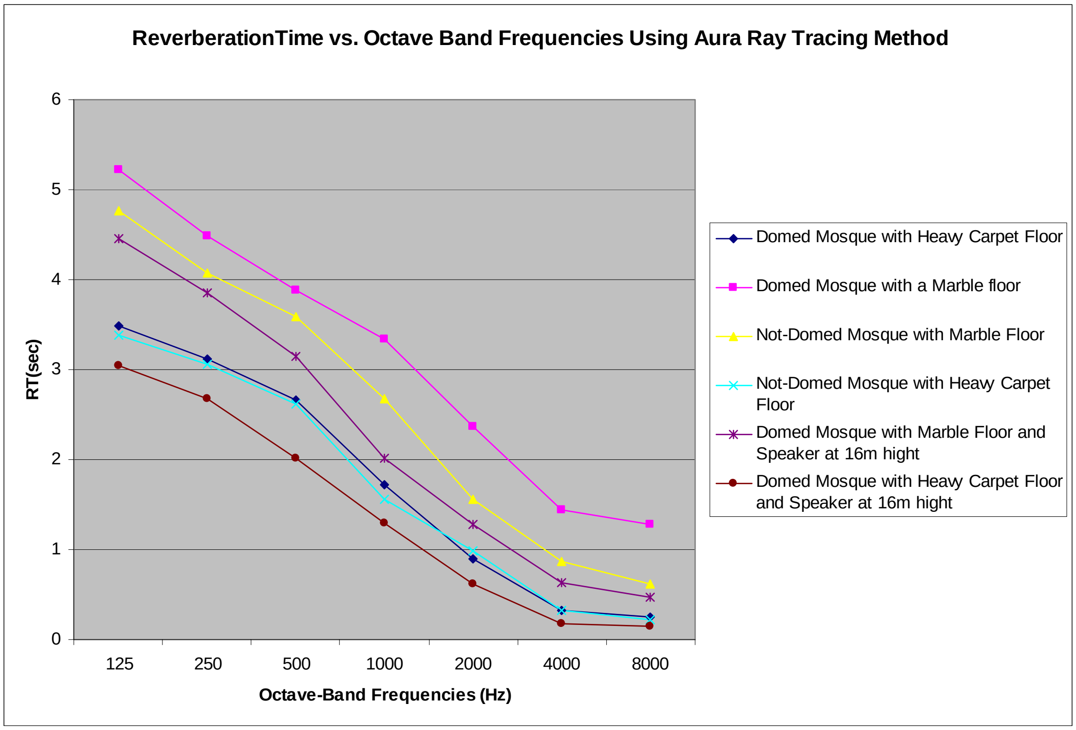



*Figure 34. RT for Domed and Not-Domed mosque at different source height levels*

First, in case of using a marble floor the mosque showed higher RT level values, since the marble floor is highly reflective compared to the thick carpet. Adding a Dome to the mosque structure increased the RT compared to a Not-Domed Mosque with a marble floor (while maintaining the volume unchanged). The reason for this increase is the location of the sound source in the domed mosque placed at human speaking height (1.7m) from the floor level. Placing the source at this height causes the dome's reflected sound rays to be more distributed through out the mosque structure as shown in Figure 33 b and c. Accordingly, this increases the overall RT.

In case of placing the sound source at the focal point of the dome (16m from the floor level) in a marble floor mosque decreased the RT dramatically as shown in Figure 33a and 34 respectively (this source location is only interesting from a theoretical point of view). The reason for this reduction is that the sound rays travel in parallel manner forth and back between the dome and the marble floor. So the reflected sound is less radiated through the mosque structure; so in consequence, this will not contribute in increasing the total RT.

Secondly, in case of placing a thick carpet over the floor (as usual in mosques), sound rays interactions between the dome and the mosque's floor are decreased. When it is compared to the marble floor, the carpet absorbs most of the radiated energy before it reflects back toward the Dome. Accordingly, RT values did not show a big difference with and without the dome.

Placing the sound source at the focal point of the dome (in our example 16m from the floor level) in a heavy carpet floor mosque decreased the RT as shown in Figure 33a and 34 respectively. Placing it at this level causes a continuous bouncing of the sound rays between the dome and the heavy carpet surface. As a result, possible reflections of sound rays from the neighbouring surfaces after been reflected from the floor are somehow been eliminated according to the high level of absorption of the carpet and the continuous parallel bouncing of sound rays.

The effect of dome's focusing and the change of the intelligibility measures according to the change in the radius of the dome is investigated next. A middle size mosque with simple shape and a 2m radius dome were modelled in EASE, see Figure 35. According to eq. (12), such a dome will have a focusing level at 5.8m from the floor level (s=1.47m, r=2m). Figure 36 shows the simulated impulse responses at the focusing level and at point outside the dome domain and more inside the mosque's structure.

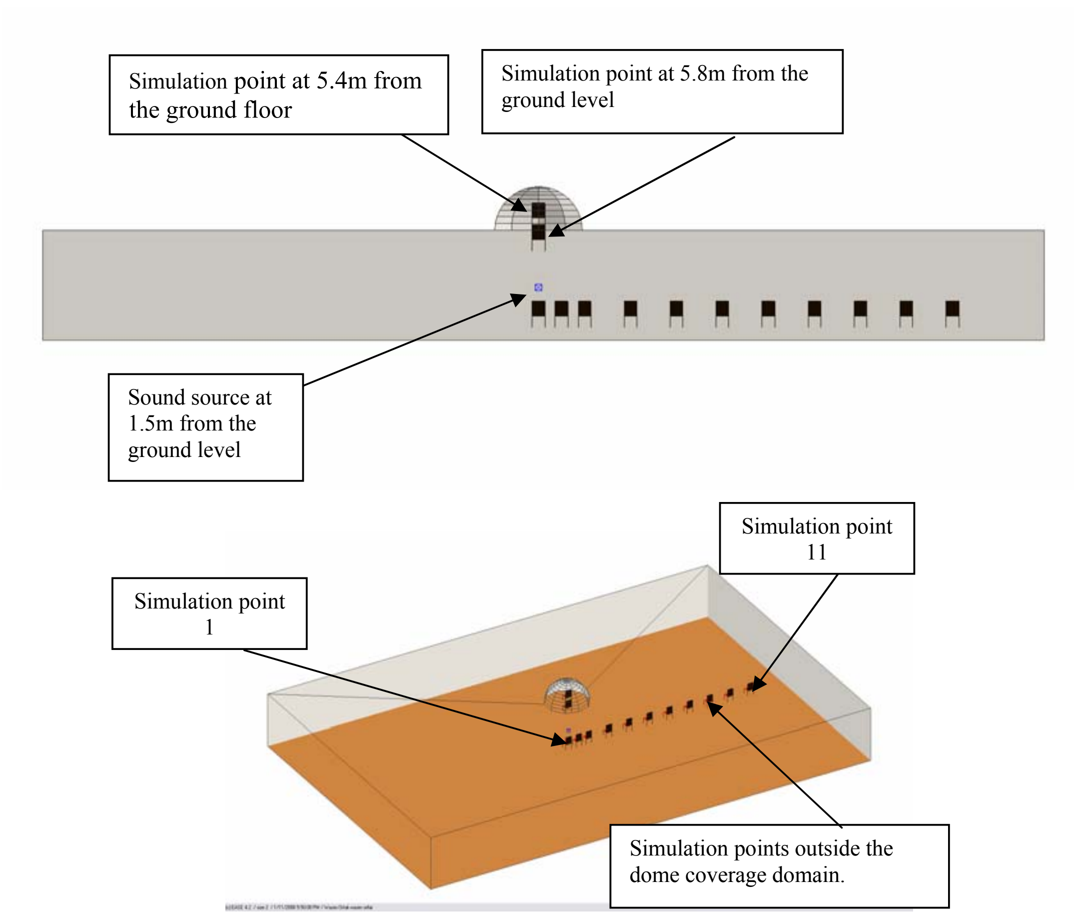



*Figure 35. The simulated impulse responses at the focusing level (left) and at point outside the dome domain (right)*

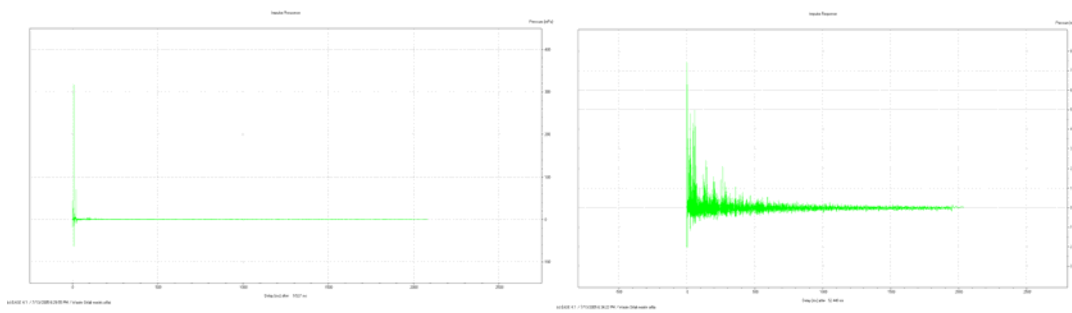


*Figure 36. The simulated impulse responses at the focusing level (left) and at point outside the dome domain (right)*

It is clear that the impulse response at the focusing point lacks late coming reflection compared to the other impulse response.

Intelligibility measures in form of STI numbers (Speech Transmission Index) at different locations under the dome and away from it were derived see Figure 38.At the focusing point (at 5.8m from the ground level) the STI level was the highest (0.991), while at the focusing point no late reflections degrading the intelligibility. STI level at a closer distance to the source should be higher (at 5.4m from the ground level); nevertheless, a lower STI level was noticed (0.813). When the focusing point is located at the hearing height level of the worshippers, the domes focusing effect must be dealt with. For example, a mosque dome with 2m radius and a sound source placed at 5.84m from the ground level will result in focused sound at 1.7m from the ground level, i.e. at the hearing height level of the worshippers. Placing the sound source in the dome domain is not practical; it was only introduced in the previous example to show the influence of the dome at different source levels.

Another example of 3m radius dome and sound source placed at 2.46m from the ground level, the focusing point will be at 6.03m from the ground level. The following Figure demonstrates the AURA impulse responses at the focusing point and at a point outside the dome domain and more inside the mosque's structure.

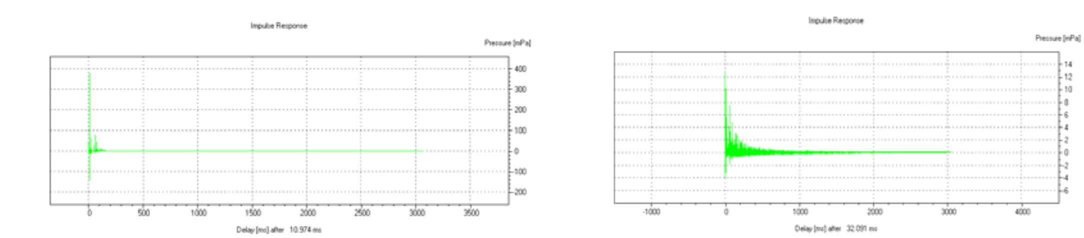



*Figure 37. The simulated impulse responses at the focusing level (left) and at point outside the dome domain (right)*

The **STI** measures for mosques with different domes radius (but with a fixed volume) and different sound source positions are investigated (refer to the appendix to look at the EASE models). Source points under the dome domain and more inside the mosque structure see Figure 38, were compared to investigate the effect of the dome radius on the sound intelligibility measure STI.

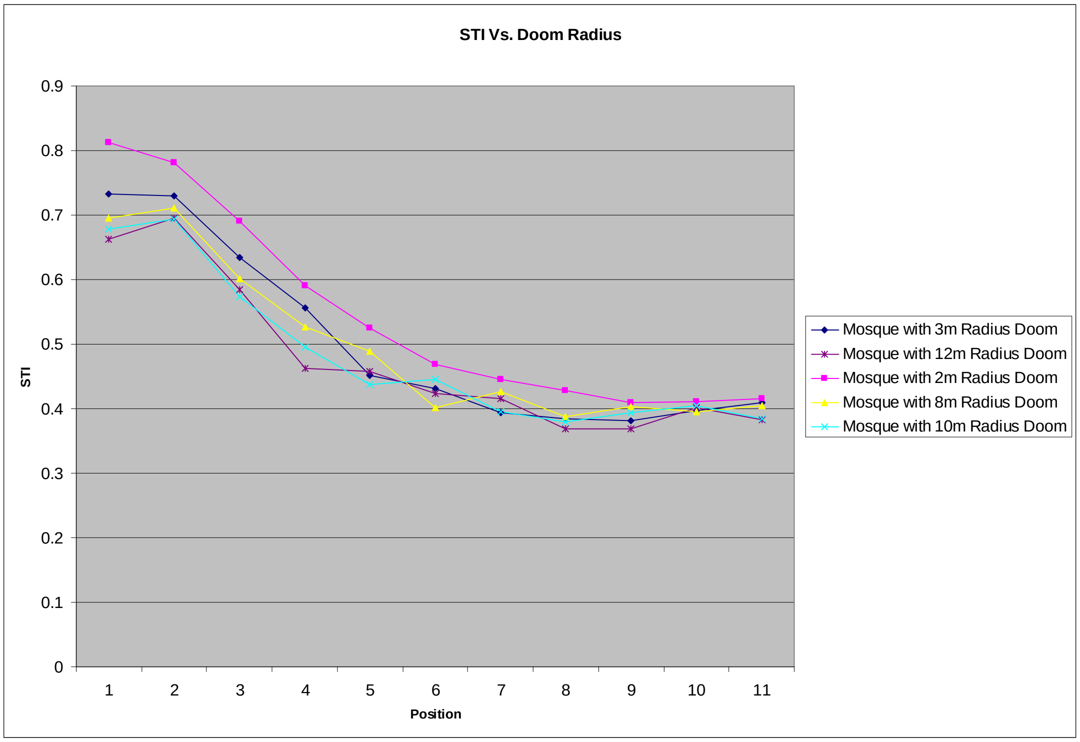



*Figure 38. STI for Different Dome Radius*

A 2m radius dome in a mosque with a volume of 6,000 $m^3$ might not be efficient to be used for comparisons, since the dome's volume is relatively very small compared to the overall volume of the mosque. Consider a mosque with 3m radius dome compared to 12m radius domed mosque will more efficiently reflect the purpose of this investigation. STI measures for 12m radius domed mosque were lower than the 3m radius domed mosque (refer to the appendix to look at the EASE models). At further distances the STI measures for both of them nearly match. We conclude from this that the effect of the dome on the STI values is more evident under the dome area than it is the case far from it.

In great majority of mosques, all sound sources are placed further away from the dome at more than even the diameter distance. Accordingly, the behaviour shown in Figure 32e is more considered in mosques. Generally, the existence of a dome in a mosque with heavy carpet floor did not have a significant change in the RT. On the other hand, the effect on the RT when adding or removing the dome in the existence of marble floor is much more exaggerated, see Figure 34. The effect of the existence of the dome on the STI values was significant on areas located directly under the dome structure. At the far field or on areas which are not located under the dome structure, adding or removing the dome did not make a big difference.

**3.1b.2.1.1.1: Relationship between Focusing Height (e) and sound source height (s):**

As we have experienced in the pervious section, the relation between the source location and the focusing height of the dome must be governed. The architect and the sound system designer must work together to prevent the dome focusing effect. The following figure presents a tool to help both of them making a decision about the dome radius and the height of the sound speakers to prevent sound focusing.

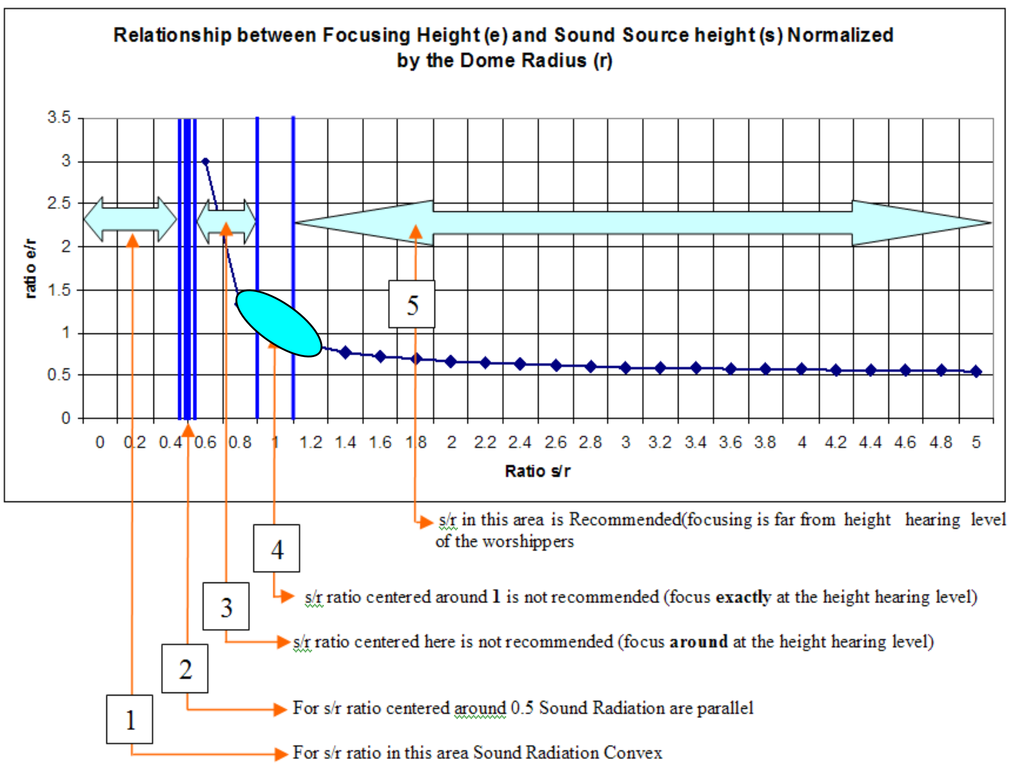



*Figure 39. Relationship between s/r and e/r*

Couple of situations have to be addressed with regards to the above figure. In the area marked by box 1, sound radiation convex. In area 2 where s/r=0.5, the sound radiation is reflected as parallel radiation from the dome. When s/r ratio is located in the area marked by box 3, the focus level is below the height hearing level of the worshippers. This ration is not recommended, since it is still near the worshippers hearing level. At ratio of 1 (box 4), the sound radiation focus at exactly the height hearing level of the worshipper. This means that the focus distance and the source height (represented by the Imam or the worshippers) from the dome centre vertex point are at the same position. Therefore, this ratio should not implemented. Starting from 1.1 to 5 the focus level is far above the height hearing level of the worshippers.

### 3.1b.2.1.2: Rounded Back Wall Effect:

In mosques with rounded back walls, the sound concentration from back walls is very common. In this case sound concentration at any point between the Qibla wall and rounded reflecting wall must be considered. On the other hand, sound concentration in the vertical domain, in a mosque with a dome design in its roof, is not considered a serious matter in the existence of heavy carpet compared to the possible concentration of sound in the horizontal domain in case of the existence of a rounded back wall.

In EASE, a model was constructed which represents a simple shape mosque with rounded back wall, see fig. 40a. Ray Tracing was conducted inside the mosque to investigate the effect of the back wall on the sound energy distribution. Different behaviours of sound rays are represented as a result of moving the sound source toward and a way from the rounded wall. Placing the source at more than r/2 will result in distributed sound rays (b). When the source is located at exactly r/2 then sound rays tend to be reflected in a parallel manner (d). Finally, placing the sound source further away from the rounded surface will cause the sound rays to be concaved as illustrated in (c).

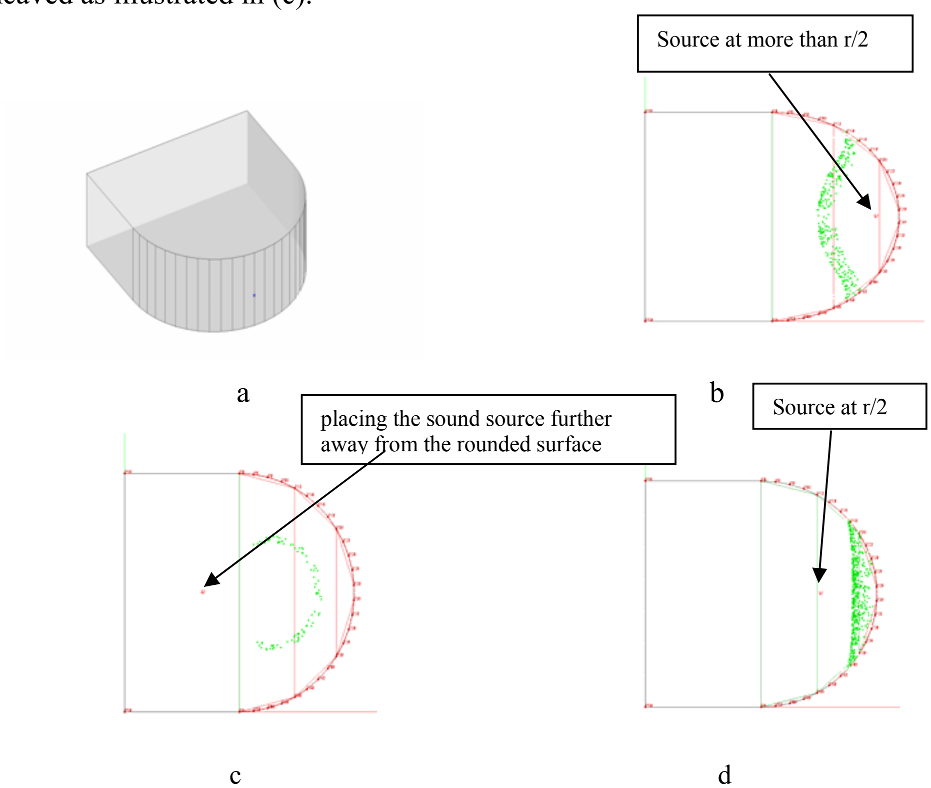



*Figure 40. Mosque with rounded back wall and Ray Tracing results.*

Sound concentration from a back rounded wall are more likely to happen compared to concentration from the dome. The reason is that loudspeakers in mosques are more oriented toward the back wall. Also, most of the sound energy that may be reflected by the dome and cause concentration of sound is absorbed by the carpet before they reflect back toward the dome; unfortunately this will not happen with concentrated back wall reflections.

### 3.1b.3: Open Courtyard Mosques:

Both of the two holiest mosques in the Muslim world can be considered as open courtyard Mosques. The Holy Haram in Makkah and the Prophet's Mosque in Madinah have in common an open air courtyards. The coexistence of the Minarets and the open courtyard has some acoustical drawbacks which shall be addressed in this section. Below in Figure 41 shows a photo of the Holy Haram with some of its Minarets.

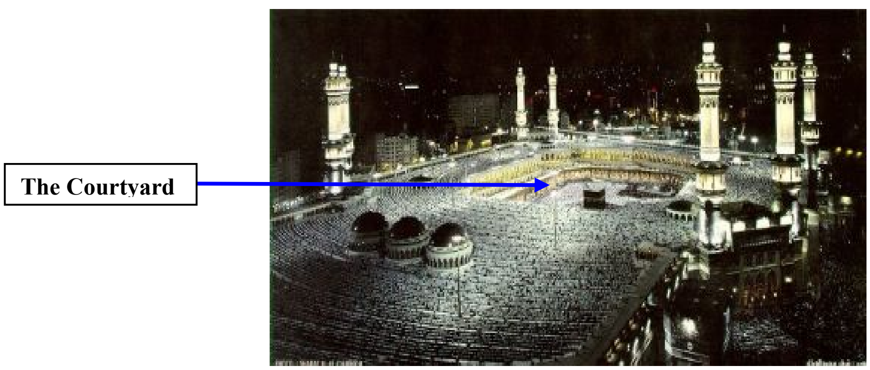



*Figure 41. The Holy Haram and the Kaba located in the middle of the courtyard.*

Nine different Minarets exist in the Holy Haram. Eight of which are equipped with a sound system to radiate the call for prayers into the extended neighbourhood. The sound of the speaker on the top of the minarets produces audible echoes and, consequently, degrading the sound clarity and intelligibility inside the courtyard.

Impulse Responses measurements at several places in the Holy Haram have been conducted using EASERA Software developed by SDA (Software Design Ahnert). A measurement point in the Mattaf area (the courtyard area) has been chosen to investigate the strong acoustic echoes more closely. I found out that the causes for these echoes are the late arriving sound energy reflections coming from the Minaret speakers (see the following figure 42). Point 1,the selected measurement below, represents the position where the Imam stands to lead the prayer in the presence of a high number of worshippers (Results at other position refer to the appendix).

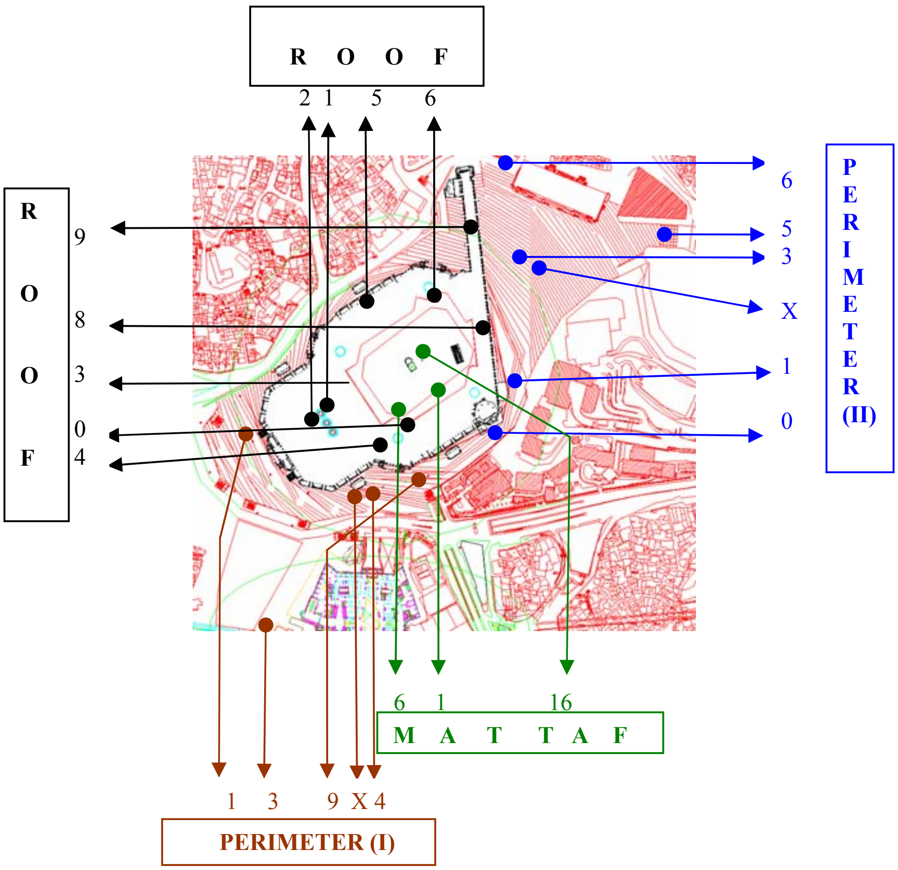



*Figure 42. Measurement positions in the Holy Haram*

The Impulse response at the measurement point 1 is shown in Figure 43.

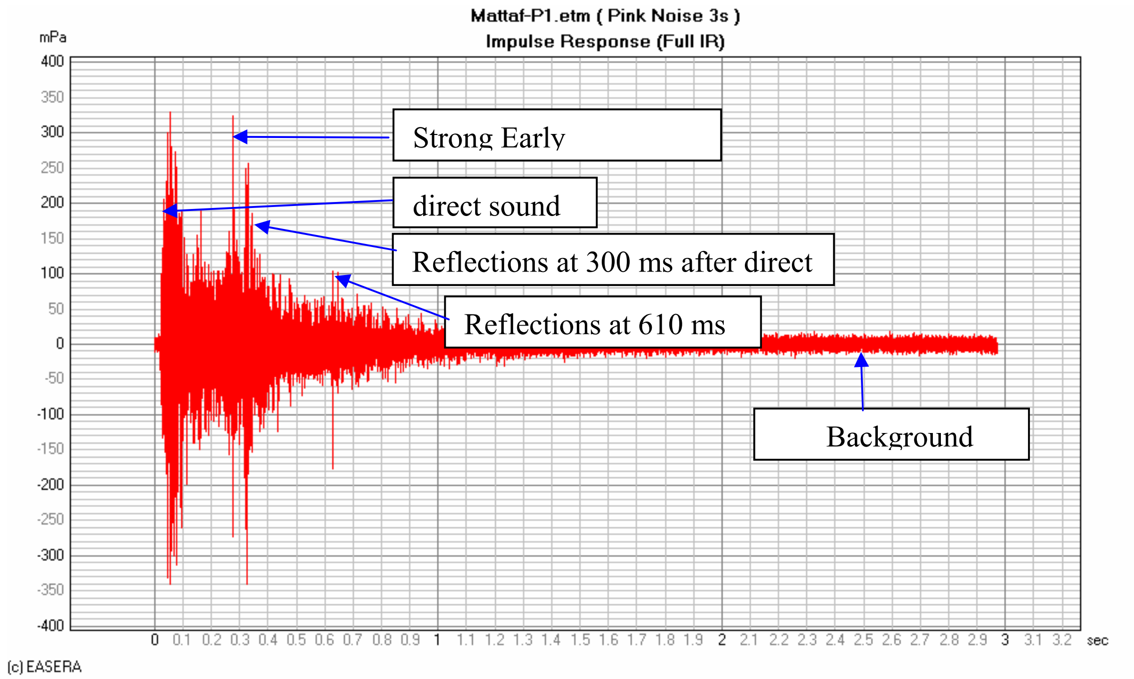



*Figure 43. Impulse Response recorded at position 1 in the Mattaf area*

A couple of late direct sound arrivals from the minaret sound system and late reflections from neighbouring buildings are clearly visible around 300 ms and 610 ms after direct sound. This causes echoes and degrades the intelligibility. Normally, to ensure good intelligibility the early reflections are coming immediately after the direct sound (maybe with a short initial time delay gap after the direct sound) followed by later reflections decreasing in level over time. This is not the case as we can see in Figure 43 and Figure 44 where the ETC curve in dB vs. time is shown. High level of background noise was measured too which plays a major role in effecting the intelligibility of the Haram negatively.

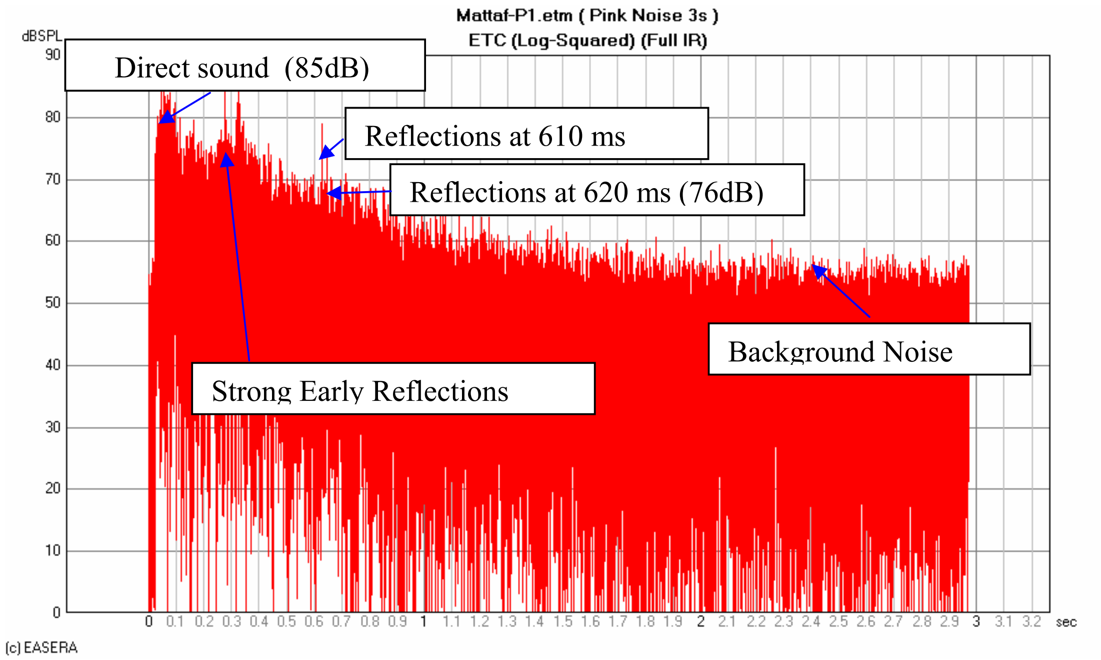



*Figure 44. ETC curve of the reflections at position1 in the mattaf*

The following Figure 45 shows that the echoes are really audible by using a special echo detector implemented in the EASERA software.

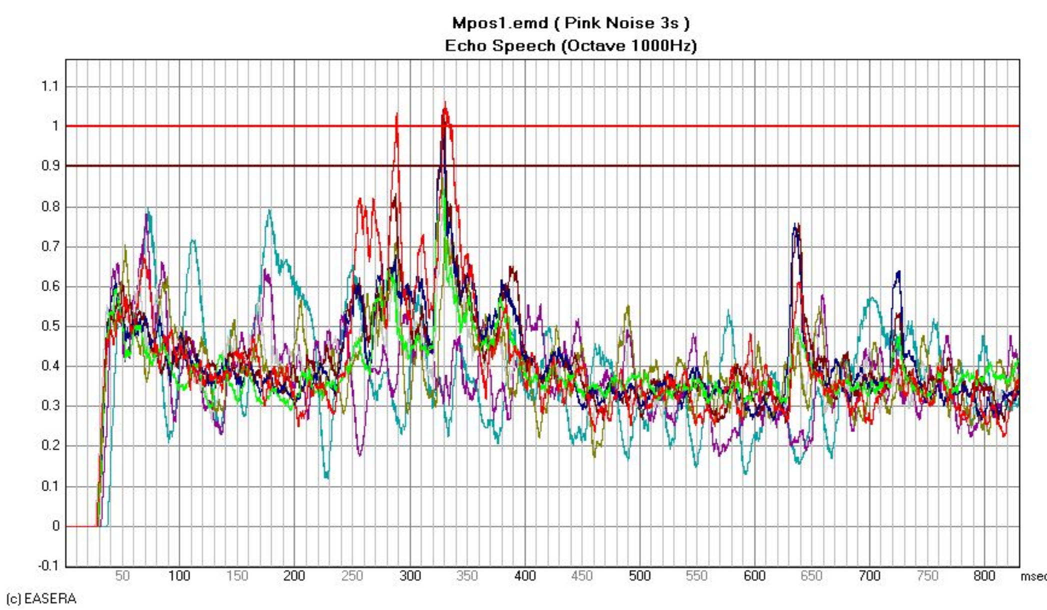



*Figure 45. Echo detection by exceeding the horizontal limit lines*

The frequency-dependant echo curves exceed the horizontal marker (see especially the red marked curve for 1000Hz), so echoes from late arrival of direct sound and reflections from the minarets and the high buildings surrounding the Haram become audible. As a last point, the STI in this location has been examined too. Using EASERA as a measuring tool, we were able to generate the MTF values in form of a graph which will result in calculating the STI, see Figure 46 and table 2.

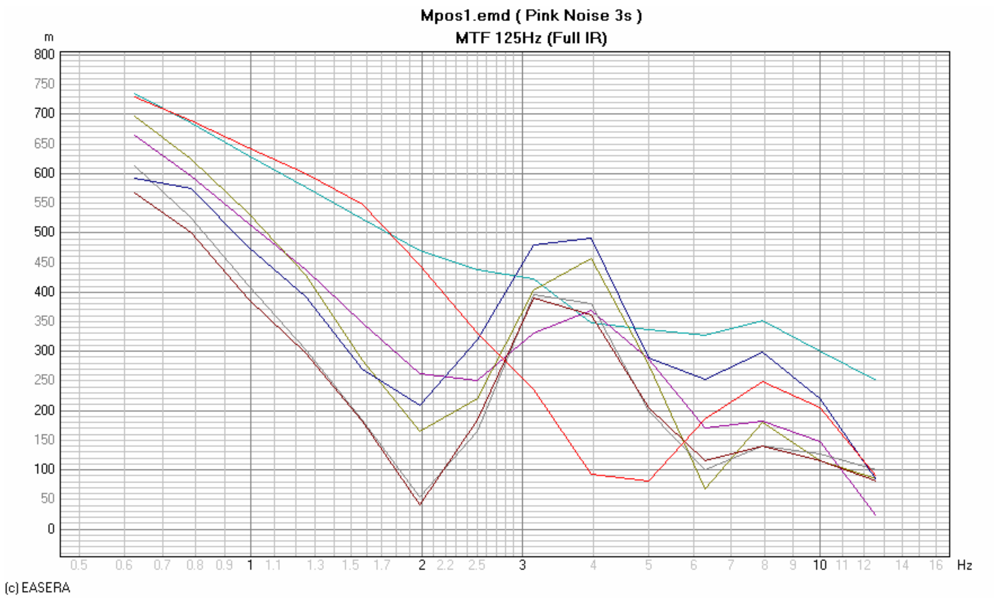



*Figure 46. MTF values for seven octaves vs. modulation frequency*

The lower the MTF values are, the worse is the intelligibility of sound (lower STI). In the following table MTF values and the associated STI value are calculated.

| Easera 1.0, Results of Data: | Mpos1.emd ( 44.1k ) // Full IR | | | | | | |
|---|---|---|---|---|---|---|---|
| STI, MTF, MTI | | | | | | | |
| | | | | | | | |
| | MTF 125Hz | MTF 250Hz | MTF 500Hz | MTF 1000Hz | MTF 2000Hz | MTF 4000Hz | MTF 8000Hz |
| 0,63 Hz | 0,729 | 0,734 | 0,665 | 0,698 | 0,612 | 0,568 | 0,591 |
| 0,8 Hz | 0,69 | 0,685 | 0,596 | 0,624 | 0,525 | 0,501 | 0,575 |
| 1 Hz | 0,644 | 0,63 | 0,517 | 0,533 | 0,411 | 0,388 | 0,475 |
| 1,25 Hz | 0,599 | 0,577 | 0,437 | 0,427 | 0,303 | 0,296 | 0,391 |
| 1,6 Hz | 0,548 | 0,523 | 0,347 | 0,285 | 0,185 | 0,183 | 0,27 |
| 2 Hz | 0,445 | 0,47 | 0,262 | 0,164 | 0,054 | 0,041 | 0,208 |
| 2,5 Hz | 0,331 | 0,438 | 0,25 | 0,22 | 0,165 | 0,184 | 0,319 |
| 3,15 Hz | 0,236 | 0,423 | 0,331 | 0,404 | 0,395 | 0,391 | 0,48 |
| 4 Hz | 0,093 | 0,348 | 0,369 | 0,456 | 0,38 | 0,361 | 0,491 |
| 5 Hz | 0,081 | 0,337 | 0,286 | 0,278 | 0,199 | 0,205 | 0,289 |
| 6,3 Hz | 0,187 | 0,327 | 0,171 | 0,068 | 0,101 | 0,115 | 0,252 |
| 8 Hz | 0,25 | 0,352 | 0,183 | 0,18 | 0,14 | 0,141 | 0,299 |
| 10 Hz | 0,206 | 0,301 | 0,148 | 0,115 | 0,128 | 0,116 | 0,22 |
| 12,5 Hz | 0,088 | 0,25 | 0,023 | 0,085 | 0,101 | 0,082 | 0,083 |
| | | | | | | | |
| MTI | 0,396 | 0,474 | 0,373 | 0,369 | 0,324 | 0,315 | 0,401 |
| STI (Calibrate | 0,374 | | | | | | |
| AlCons [%] | 22,429 | | | | | | |
| STI (Male) | 0,359 | | | | | | |
| STI (Female) | 0,359 | | | | | | |
| RaSTI | 0,359 | | | | | | |
| | | | | | | | |
| Equiv. STIPa | 0,35 | | | | | | |
| Equiv. STIPa | 0,353 | | | | | | |

*Table 2: MTF values and  the associated STI values*

The STI value of 0.374, as been indicated in the above table, indicates a bad speech transmission index at this particular measuring point. Values from 0.45 to 0.5 are acceptable, but value of 0.5 and above are more recommended. So, the acoustical design and the speaker orientation directed at some points should be improved or redesigned.

As a conclusion, construction of mosques with a courtyard and because of the existence of sound systems installed in high Minarets, the problem of potential echo occurrence has to be taken more seriously. The existence of elevated landscape and high buildings around the constructed mosque will cause not pleasant late reflections of sound, which will cause echoes and degrade the intelligibility of sound. The aiming and orientation of the Minaret sound system have to be done the right way to prevent such reflections of sound energy. Constructing movable or fixed tents, roofs and domes over the courtyard area should be recommended to prevent such late reflections, see also chapter 5.

## 3.2: Secondary Shape:

### 3.2a: Wall Material:

Fortunately, Secondary Shape design may be used to solve the acoustical problems resulting from the Primary structure problems of a mosque. Wall treatments or what so called "passive treatments" of the worship space are implemented in most cases to overcome the effect of some fundamental architectural design contradictions, which degrade the sound quality in such a space. This treatment will add more to the total predetermined costs of the mosque, since it may require removing and manipulating some wall parts and, not in all cases, will manipulate some important interior figures of the treated mosque. The main part here is to investigate the effect of the treatment of a Dome, the Qibla wall and Back Wall and the importance of a carpet on the sound quality. It will make the attempt possible to suggest the most preferable sound treatments materials in mosques. These materials should have a good price/result ratio, suitable from Architectural and Islamic point of view, easy to fix and not heavy in weight. An example of a prestigious mosque in Amman, Jordan before and after different types of wall and carpet treatments is considered here to characterise this approach, see Figure 47.

King Abdullah Mosque is located near the centre of the city of Amman, Jordan, with two main streets surrounding it. It has a huge octagonal structure with a diagonal of 45m. The hall structure was covered with a huge dome. It has a diameter of 38m and a height of 32m from the floor level. The dome has eliminated the need to have roof supporting columns. The mosque has 5 (9×3 m) doors and 16 (0.7×6 m) windows. The interior of the mosque originally had hard floor tiles and concrete walls. Also, 64 glass windows (1×1.2 m) are located at the neck of the dome. A (20×4 m) marble wall was build inside the mosque as a Qibla wall. The total area of the vertical surfaces is 2700 $m^2$, the floor area is 1600 $m^2$, the surface area of the dome is 1450 $m^2$ and the total volume of the mosque is 34000 $m^3$.

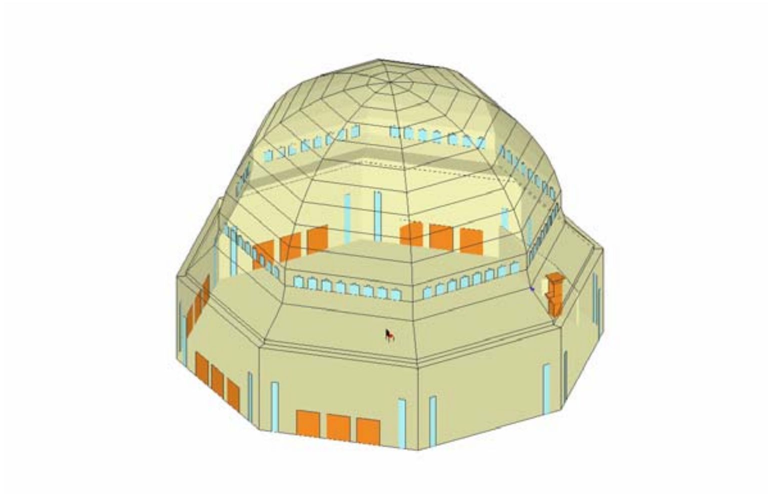


*Figure 47. King Abdullah Mosque in Amman, Jordan.*

## 3.2a.1: Mosque Acoustical Condition before Treatments:

After creating a model in EASE, a couple of simulations have been done. First, the mosque model room was "excited" using one omni-directional source placed 1m away from the Mihrab. The acoustical conditions of the mosque before treatment were estimated to be poor. An average of 18s RT at 1 KHz resulted in poor intelligibility values even within few meters from the source. The recommended RT for such a volume at 1 KHz is around 1.3s, see Figure 17b. Also, ambient noise is an important factor affecting the overall intelligibility of the mosque. The measured ambient noise outside and inside the mosque were 80 and 58 dB (A) respectively [16]. This is due to the poor sound insulation of the structure and the very low absorption coefficients of the mosque interior surfaces. Particularly, 64 windows at the neck of the dome, the 16 wall windows and 5 doors of the mosque were considered as bad insulators.

Outside noise intrusion reduction is not the focus of this work. There are a lot of wall construction standards, which are recommended to minimize the intrusion of the outside noise. The following Figure 47 represents the calculated RT in the EASE model before treatments of walls.

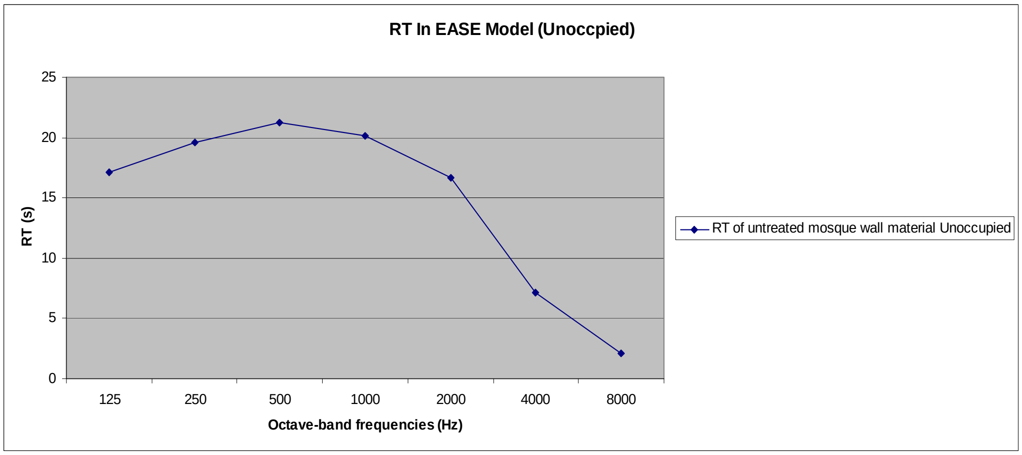



*Figure 48. RT for the Mosque in EASE Model (unoccupied)*

Also, the intelligibility was evaluated by calculating the STI at different measurement lines. The measurements points of Line A are directly aliened in front of the sound source followed by points at 5 subsequent lines separated by 5m and all at the hearing height of the worshippers as shown in the following Figure 49.

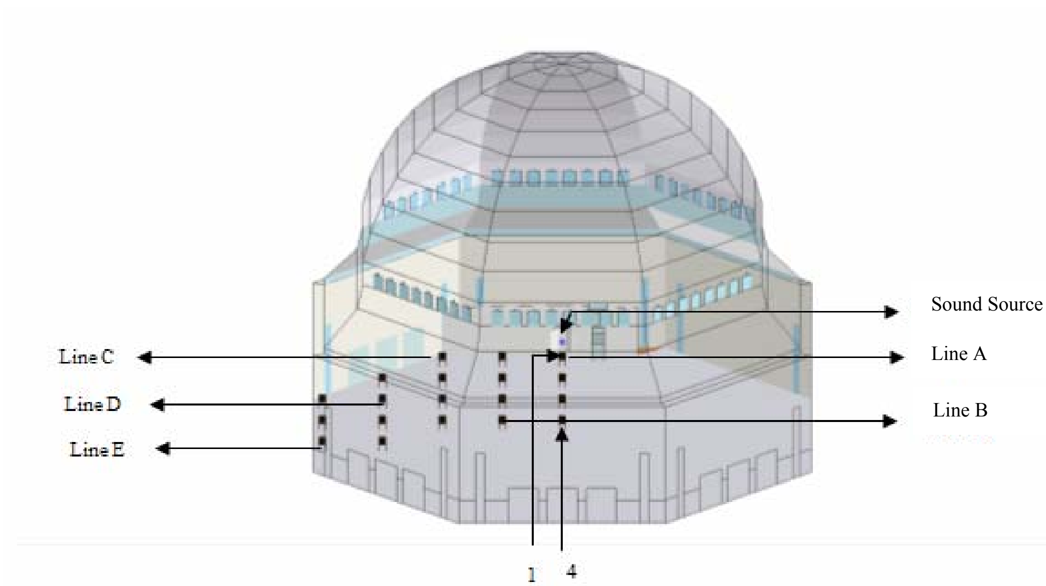



*Figure 49. Layout of listening Lines Positions.*

Generally, the intelligibility in the mosque was poor for the reasons mentioned earlier. The following Figure 50 shows the results of the STI values which was acquired in the EASE model.

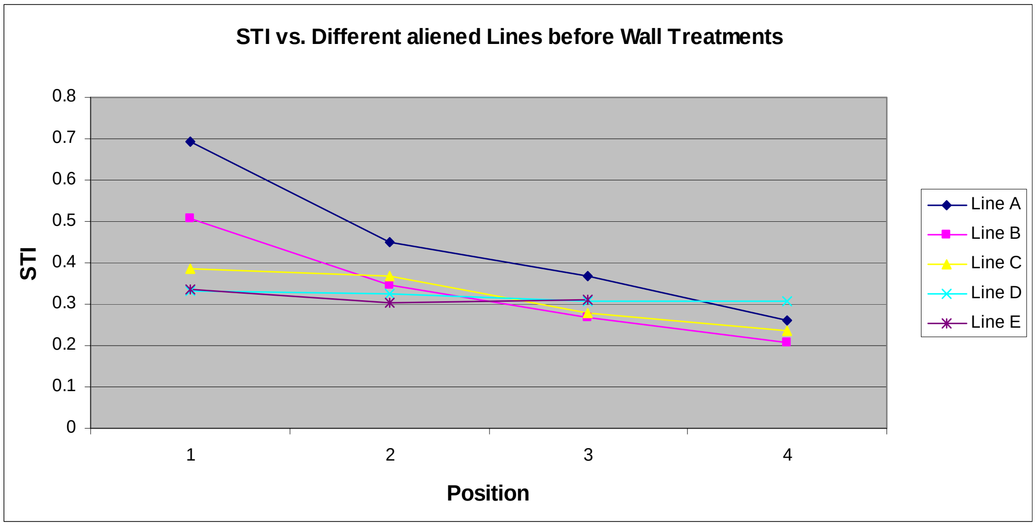



*Figure 50. STI at different measuring lines before wall treatments.*

Distance from the source, the volume and the architectural design of a particular mosque play a major roll in reducing the STI (intelligibility) throughout the structure. In the above Figure 50, in addition to the huge reverberation time which degrades throughout the mosque structure, two major factors influenced the STI values, namely the distance from the source and the rounded shape of the dome.

First, by increasing the distance from the source to the measure point the STI decreases simultaneously. But because of the high RT of the King Abdullah Mosque (18s at 1 KHz), the distance from the source factor might not play a significant role.

Secondly, as we go further away from line A toward line E, the differences in the STI measures within a particular line start to decrease. Consequently, the STI curves for distanced lines start to saturate at far distances. In other words, the dome's focussing effect on the STI decreases as we go further from the imaginary line which passes through the centre point of the dome. Because of the high reverberation a more even distribution of STI values starts to dominate. The reason is that the center point of the mosque works as an accumulation region of sound energy which is reflected back from the dome and the inclined walls as mentioned earlier.

### 3.2a.2: Treated Wall Parts and Mosque Acoustical Condition after Treatments:

Today, treatments of any mosques are usually been conducted for the Dome, the Qibla Wall and a little attention have been given to the treatment of the Carpet. In some other conditions when the mosque needs further treatments the vertical and the inclined walls are included in the treatments procedure. In this part of this work two different treatment approaches will be compared together to emphasis the advantages of carpet treatment upon other parts of the mosque. The first treatment approach was suggested in the literature and already implemented [16]. The seconded approach is presented in this work.

### 3.2a.2.1: Implemented Treatment In the Mosque (suggested in the literature):

#### 3.2a.2.1.1: The Dome and Inclined walls:

The dome and inclined walls reflect most of the sound energy toward the floor. Consequently, the quality of sound is reduced in most of the mosque's areas as already mentioned earlier. The same suggested treatment material in the previously mentioned ASA paper was used in both the Dome and the inclined walls. As they say "The treatment of the Dome surface was the most critical of all other surfaces, since the dome has a huge volume and low absorption Coefficient" [16]. They have chosen 8 mm 24% perforation Plywood material as a treatment solution. It was selected, because it is a well-known material, has a lightweight and can easily be curved and fixed. The 24% perforation Plywood panels were attached to the Dome and the Inclined Walls with 50 mm thick mineral wool and by providing a 50-mm air gap. The absorption coefficients of the 24% perforation Plywood panels are shown in Figure 51.

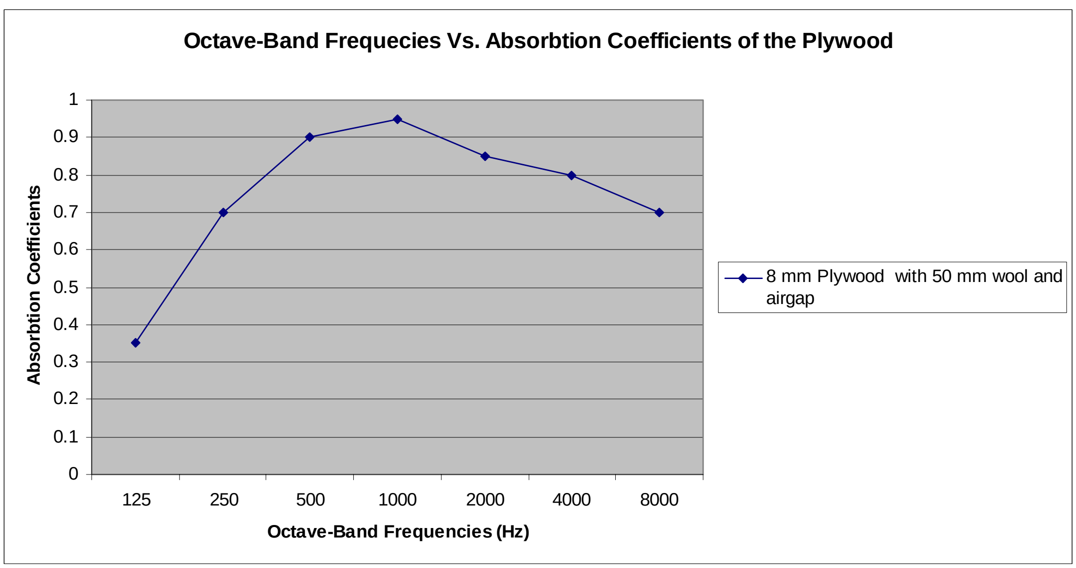



*Figure 51. Absorption Coefficient of the 24% perforation Plywood panels with 50 mm thickness mineral wool and 50 mm air gap*

The treatment of the Dome and the Inclined Walls using the 24% perforation Plywood panels represents 40% of the total surface area of the mosque. This was not only the implemented treatment they went further treating the vertical and the Qibla walls.

### 3.2a.2.1.2: Qibla and vertical wall:

The Qibla Wall is the most decorated part of a mosque. Marble at a height of 2m from the mosque floor which has a reflection coefficient exceeding 0.95 was used as well as in the vertical walls too. The rest of the wall height (with a 750m$^2$ surface area) covered with decorated wood (backed with 50-mm of thick layer of wool and 50-mm air gap). Absorption coefficients of the decorated wood are shown in Figure 52.

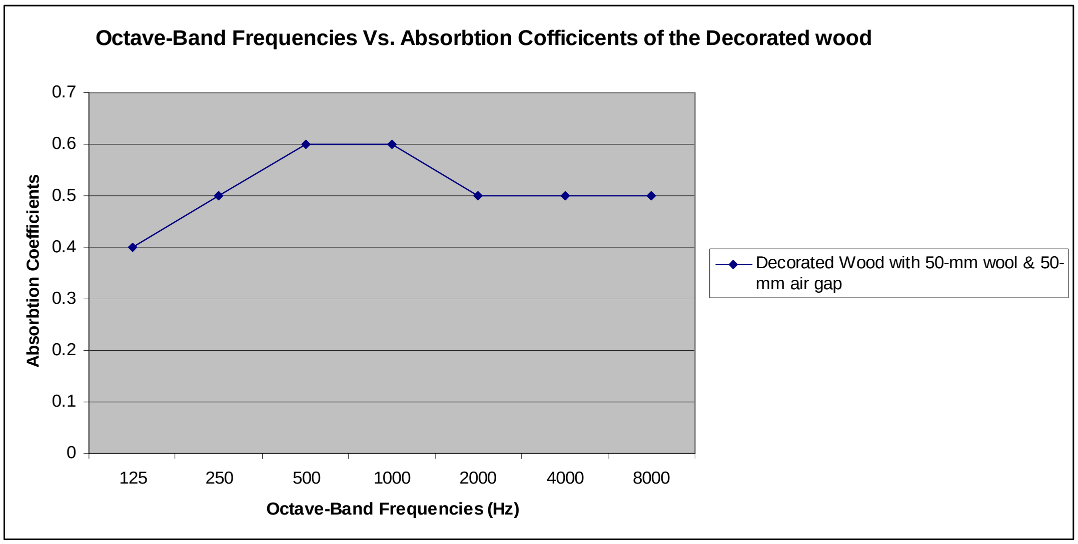



*Figure 52. Absorption coefficients of the decorated wood with 50-mm of thick layer of wool and 50-mm air gap*

The treatment of the Qibla and vertical walls represent another 20% of the total surface area of the mosque. The treated surface area until now is 60% after treating the Dome, Inclined walls and Qibla and vertical walls. They did not give enough attention to the treatment of the carpet especially at the low end frequencies as we can see below.

### 3.2a.2.1.3: Treatments of the Carpet:

In contrast to churches, carpet is very important for the convenient of worshippers, since the prayers involve kneeing and setting on the ground. It plays a major rule in any mosque acoustical condition, since it covers a large surface area of the total surface area. Also, it has (depending on their thickness) an absorption coefficient between 0.4 and 0.75 in mid-frequencies rang. In addition, an acoustical pad was placed under the carpet trying to increase the absorption of the floor area to serve the purpose of the treatments. The Carpet and the padding Material have a variation of absorption coefficient as illustrated in Figure 53.

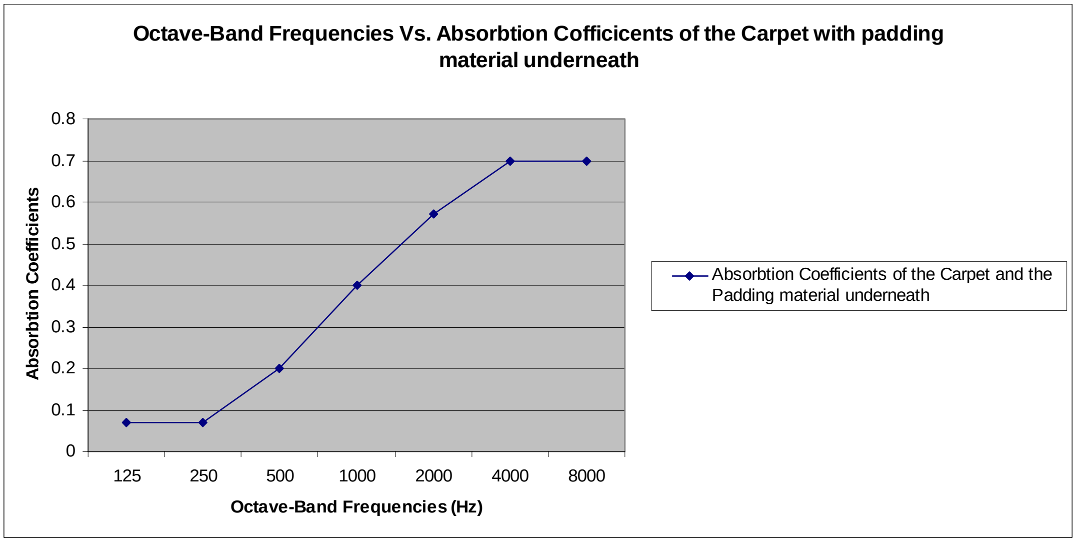



*Figure 53. Absorption coefficients of the Carpet with the Padding Material*

The weakness in absorbing the low end frequencies is quit clear in the above figure. Increasing the absorption at the low end frequencies and the mid frequencies will save a lot of cost and effort treating the other part of the mosque as we will see in the next part.

### 3.2a.2.2: Suggested Treatment In this work:

### 3.2a.2.2.1: Treatments of the Carpet:

In contrast to churches, carpet is very important for the convenience of the worshippers, since the praying involve kneeing and sitting on the ground. It plays a major rule in influencing the acoustical conditions of any mosques, since it covers a large surface area of the total area. In addition to the treatment solution implemented already in the real mosque, Figure 54 illustrates different suggested treatment solutions of the floor carpet presented in this chapter.

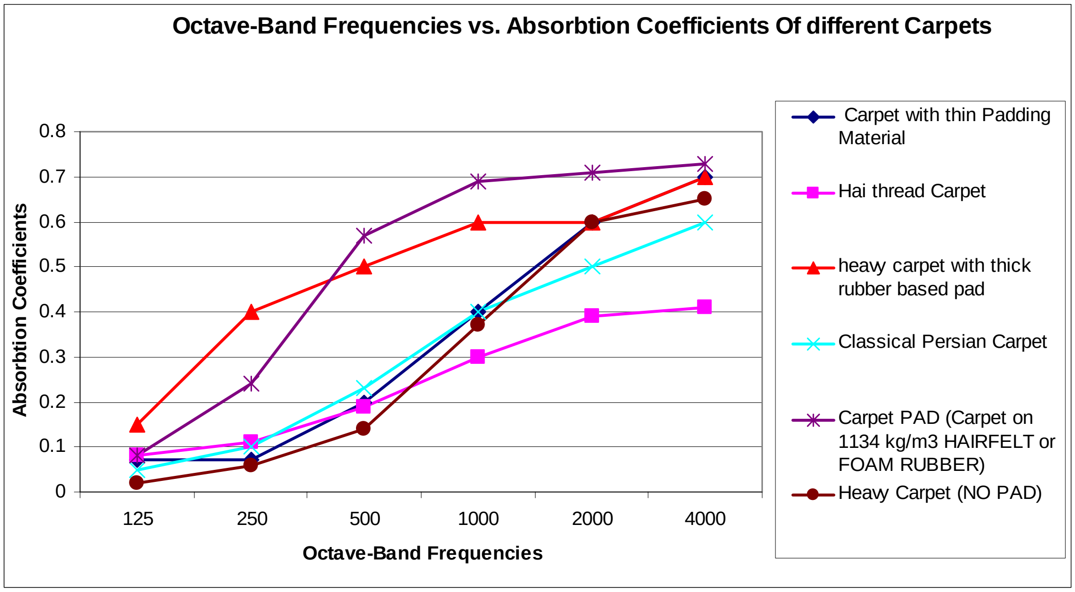



*Figure 54. Absorption coefficients of the Padding Material*

More absorption of sound at lower frequencies is provided by heavy carpet with a thick, rubber based pad and Carpet PAD materials. This absorption characteristic is more recommended for the carpet treatment, since it absorbs more sound energy caused by the low frequencies compared to the other materials. Accordingly, it overall RT decreases to match the recommended RT values for the same size structures. Also, using such materials reduce the necessity, in most cases, to treat some other parts of the mosque structures. Furthermore, lower treatment cost could be saved, since only carpet treatment is needed and no other treatments (or only modest treatments) and manipulations of other surfaces are necessary.

### 3.2a.2.2.2: The Acoustical Condition after Different Carpet Treatments:

AS illustrated in Figure 55, different materials were used to treat the floor surface of the mosque. Also, it shows the final RT results after the treatment of carpet, Dome, Qibla and vertical walls and the inclined walls.

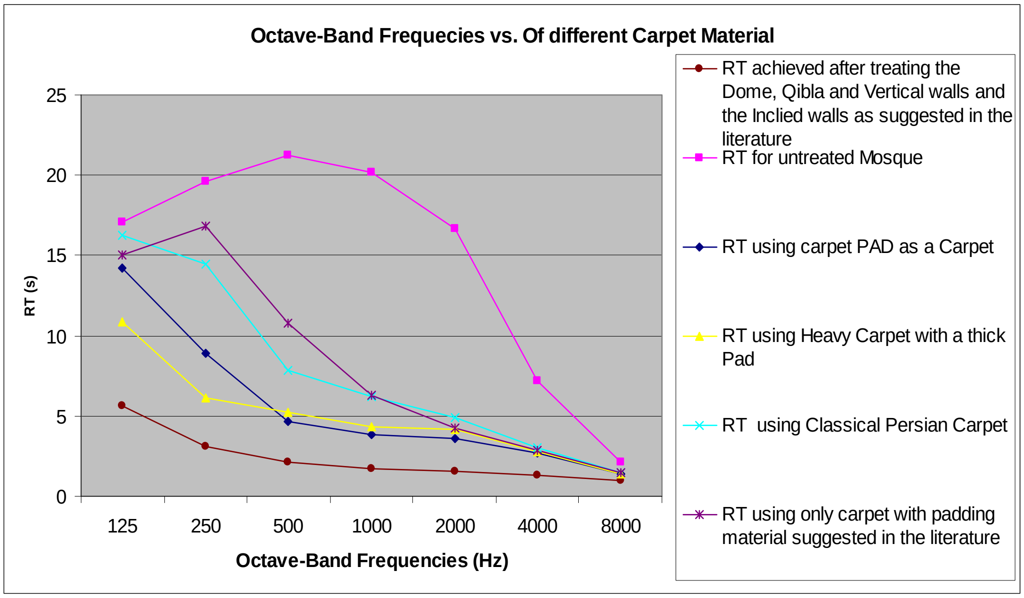



*Figure 55. RT for the Mosque in EASE Model after Treatment (Unoccupied)*

As noticed from the previous figure that the suggest treatment of the carpet with padding material (presented in the ASA research paper) did not succeed in reducing the RT (as it should), especially, at the low end frequencies. Nevertheless, the acousticians went further treating another 60% of the total surface area of the mosque (Dome, Qilbla and Vertical walls and the inclined walls) to achieve their goal. All these treatments have of course increased the total cost of the treatment. If more attention were given to the treatment of the floor carpet which is 20% of the total surface area of the mosque, they could have saved a lot of money and efforts achieving their goal.

Figure 55, also, presents different carpet materials which were more efficient in decreasing the overall RT of the mosque. The heavy carpet with a thick pad worked better than the other carpet materials in reducing the RT. Let us consider this carpet material to investigate how much more surface treatment we have to implement to reach the design goal they have reached?

It turns out that by treating only 22% of the total surface area of the mosque instead of 60% using the same material they have used and implementing the heavy carpet with a thick pad on the floor, their design target could have, almost, been achieved. The following figure depicts the RT of the untreated mosque along with the two treatment approaches.

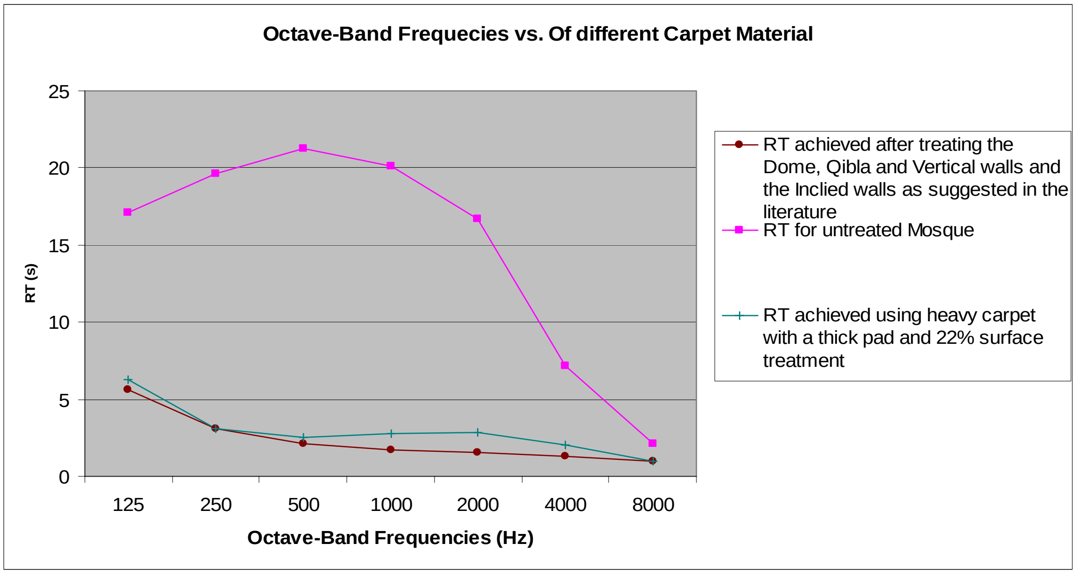



*Figure 56. RT for the Mosque in EASE Model after Treatment with the second approach (Unoccupied)*

The treatment managed to decrease the RT dramatically and made it in favor of the quality of speech. Generally, after treatment the mosque's RT is within acceptable range.

Also, after wall treatments, STI values have been calculated using AURA Ray tracing at the same places considered before the treatment. Figure 57 illustrates the STI values at different measuring lines, starting from line A from the center of the mosque toward line E for treated mosque's wall.

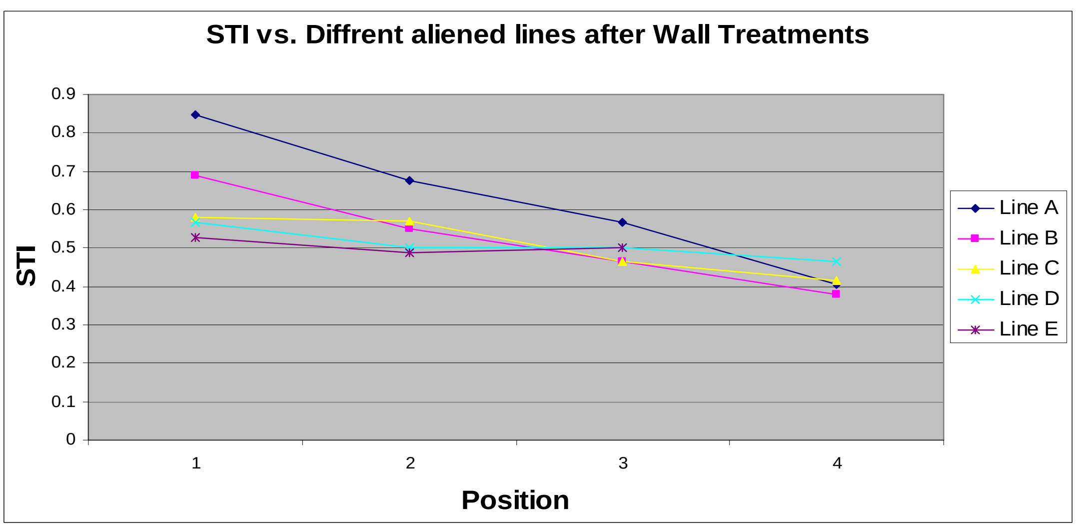



*Figure 57. STI at different measuring lines after wall treatments*

By comparing the STI curve of Figure 50 and Figure 57, it is clear that a significant improvement in the sound intelligibility has been achieved, but the same curve behavior is witnessed. These calculations have been done with an omni directional sound source. If we would equip the mosque with the right distributed sound system and more directed speakers toward the audience and not omni-directional speaker at one place, the STI distribution throughout the audience area would be more even. Also, the effect of the architectural influence on the sound quality will be decreased.

To conclude, as have been demonstrated in the previous part that a proper treatment of the floor carpet of a mosque will dramatically decrease the need for treating other wall part. In King Abdullah Mosque, placing a carpet that has absorption characteristics especially at low frequencies decreased dramatically the need to treat another 60% of the total surface area of the mosque. Only another 22% surface area was treated to decrease the RT further to match the same results obtained in the first approach. This means that 38% (60-22) of the total surface area was not needed in the second treatment approach what implies lower treatment cost and less manipulation of the interior design of the mosque. Furthermore, increasing the thickness of the carpet by increasing its padding material to manipulate its absorption implies making it more convenient for the worshippers walking, sitting or kneeing on the floor. There is no doubt that increasing the thickness of the carpet or the padding material will be a little bit more expensive than using a normal carpet, but it is still cheaper than the  treating another 38% of the mosque's surface area.

## 3.2b: Wall Structure:

Generally, wall structure in mosques is simple compared to other structures like in Churches, Theatres and Conference Rooms. The absences of more complicated wall structures like waved and concaved surfaces makes it more easy to investigate mosques acoustic in this respect. The majority of the art work in mosques is been done along the Qibla Wall compared to other walls. Wall Ornament, primarily, covers most of the space in the Qibla wall. Mainly, they are verses from the Quran. Such kinds of ornaments have an acoustical effect on the radiated sound.

Wall ornaments have the same influences on sound waves as rough or corrugated surfaces. Depending on their wavelength in correspondence to the dimension of the ornaments, the sound waves will be scattered or reflected, see the following figure for better illustration.

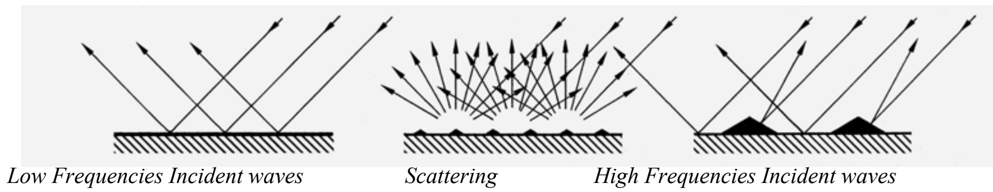



*Figure 58. Reflection of sound wave at the ornament plate at different incident wave frequencies*

When wavelength of the incident wave is comparable to the dimension of the ornament, the sound wave scatters as it hits the ornament plate. When wavelength of the incident sound wave is bigger compared to the dimension of the ornament (at low frequencies), the sound wave will be reflected with respect to the ornament plate regardless the irregularities presented in the ornament plate. Finally, when the wavelength of the incident sound wave is less than the dimension of the ornament (at high frequencies), the sound wave will be reflected with respect the irregularities presented in the ornament plate.

In the hypothetical mosque build in EASE, such an Ornament has been included. A closer look at this Ornament is presented in the Figure 59.

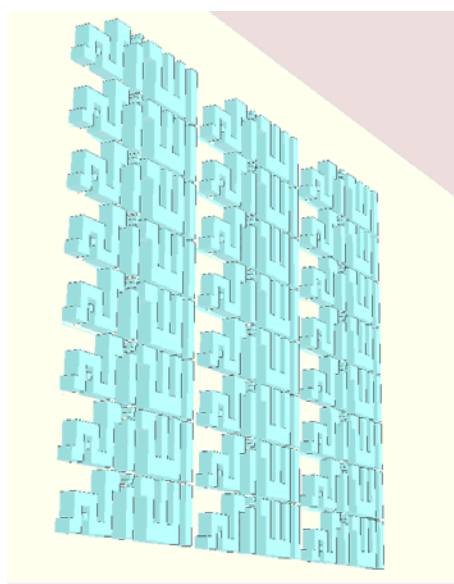


*Figure 59. The Ornament as viewed from inside the mosque*

A new scattering tool called "EASE Scatterer" newly developed by SDA was used to investigate the scattering behaviour of such an ornament plate. The Ornament plate presented in Figure 59 was modelled in this program and then arrayed to form wide enough plate to be recognized by the low frequencies Octave-Band, see Figure 60.

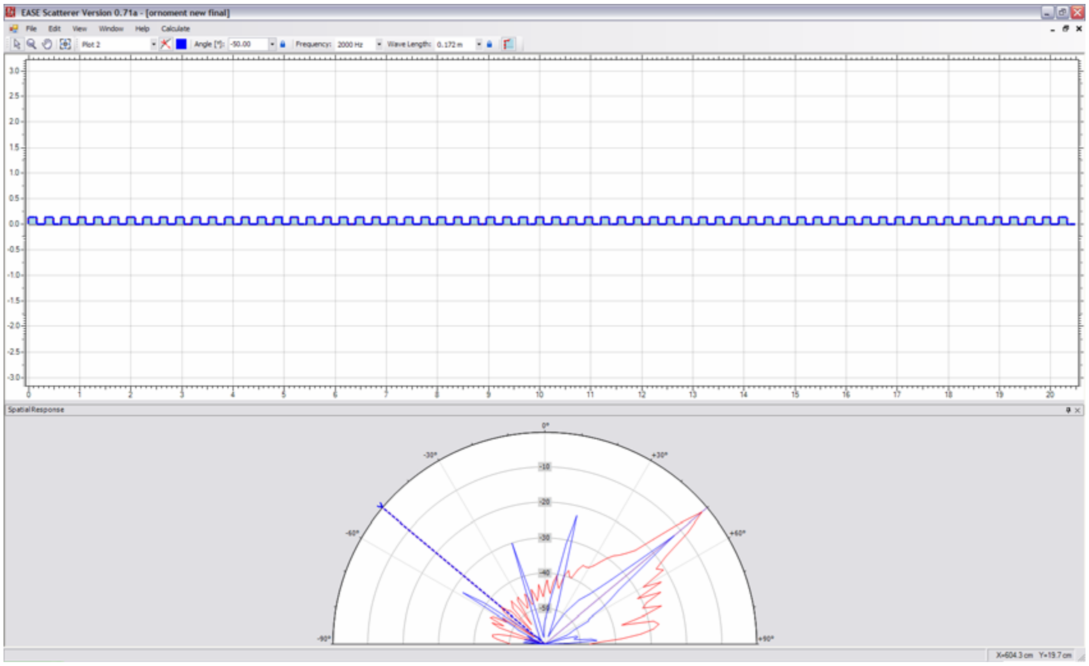


*Figure 60. The Ornament modelled in EASE Scatterer as along with their scattering behaviour at 500Hz(Red) and 2000Hz(Blue)*

The scattering behaviour was clear at 2000Hz (represented by the Blue line), sine the irregularities dimensions is comparable to the wavelength at this frequency. One the other hand, at 500Hz (represented by the Red line) the incident sound tends to reflect with regard to the ornament plat surface ignoring the irregularities on the Ornament plate.

Decorating mosque's walls with Ornaments and other Amazonite structures will scatter the radiated sound depending on their width and depth. Thus, it will give the sound an extended sense of warmness and prolongation. Also, it will drop the sound pressure to a certain level according to their scattering effect.

# Chapter 4

## 4.1: Electro-Acoustic Survey of Mosque's Sound Reinforcement systems:

Sound Reinforcement systems main objective is to assist listeners understand a talker whose vocal effort cannot cover them all. Intelligibility is measured by figures that reflect how easy a listener, at a given location, can understand what a talker says. This is basically a function of two factors, signal-to-noise ratio and early-to-late energy ratio. There are a number of methods to evaluate the intelligibility of a Sound Reinforcement System; $AL_{Cons}$% and STI are the most popular ones.

In an acoustical survey dedicated for the analysis and optimisations of mosques sound systems using DSP controlled equipment, impulse responses measurements at different places were executed for eight different mosques to recognize crude acoustic errors and to find out the sources for such errors as a result of different interior designs. With portable measurement set-up and using EASERA software some basic parameters like Intelligibility numbers, Clarity of Speech and others have been measured. Nevertheless, primary inspection of the installed sound reinforcement systems and the arrangement in each mosque was conducted. Getting an overview of what the administration of each mosque including the Imam expect from the installed sound system was part of this survey.

### 4.1a:Used Sound Systems:

Generally speaking, not only in mosques, there are two basic sound system configurations; centralized and distributed systems, with each configuration having advantages and disadvantages.

Centralized system consists typically of a number of loudspeaker components stacked together in an array at one location and used to cover the entire, or most of, audience. It has the advantages of being economical with fewer loudspeakers, less cabling, less installation efforts, cheaper and easier maintenance.

Its disadvantage, however, centre cluster speakers in mosques might not be result in appropriate quality of sound. For aesthetic reasons Central cluster sound systems need to be insulted in high ceiling structures while it might block important architectural element in mosques like the Minbar or a big portion of the decorated Qibla wall. Also, it has a higher sensitivity to weather changes since it has bigger speakers located in a central point with a bigger internal coil. Furthermore, according to the existence of roof supporting columns and lowered surfaces in mosques central clusters sound system will produce shadowed areas were intelligibility of sound will be degraded as was mentioned in section 3.1b. Centralized speakers can be considered in big mosques were no columns or lowered levels are available. Its location might be chosen carefully so it does not block significant elements in the mosque and not too close to a microphone to prevent any feedback loop.

Unlike Centralized sound systems, decentralized or distributed sound systems are more flexible to design. The distributed system is based on a larger number of loudspeakers arranged in the venue, so that each loudspeaker covers a given part of the audience. It brings the loudspeakers closer to listeners, the perceived frequency response is wider and delay times are much shorter with better control over individual parts of the audience area. The disadvantages of a distributed system are often higher costs and more amplification and cabling as well as more maintenance burden. All the evaluated mosques had their sound systems arranged in distributed circular venue. Every wall has its own installed speakers. Also, roof supporting columns had an installed sound system to cover the central area of the mosque. None of the evaluated or the visited mosques has a centralized sound system. Shown below are two different mosques with an installed distributed sound system. The speakers used almost in all the surveyed and the visited mosques were small in size, week in their maximum output Sound Pressure Level ($SPL_{max}$) and installed as high as 5m from the nearest worshippers (sometimes more). Such speakers have almost omni-directional characteristics what implies lower intelligibility levels compared to more directed speakers toward the worshippers.

*Figure 61.Two different mosques with an installed distributed sound system*

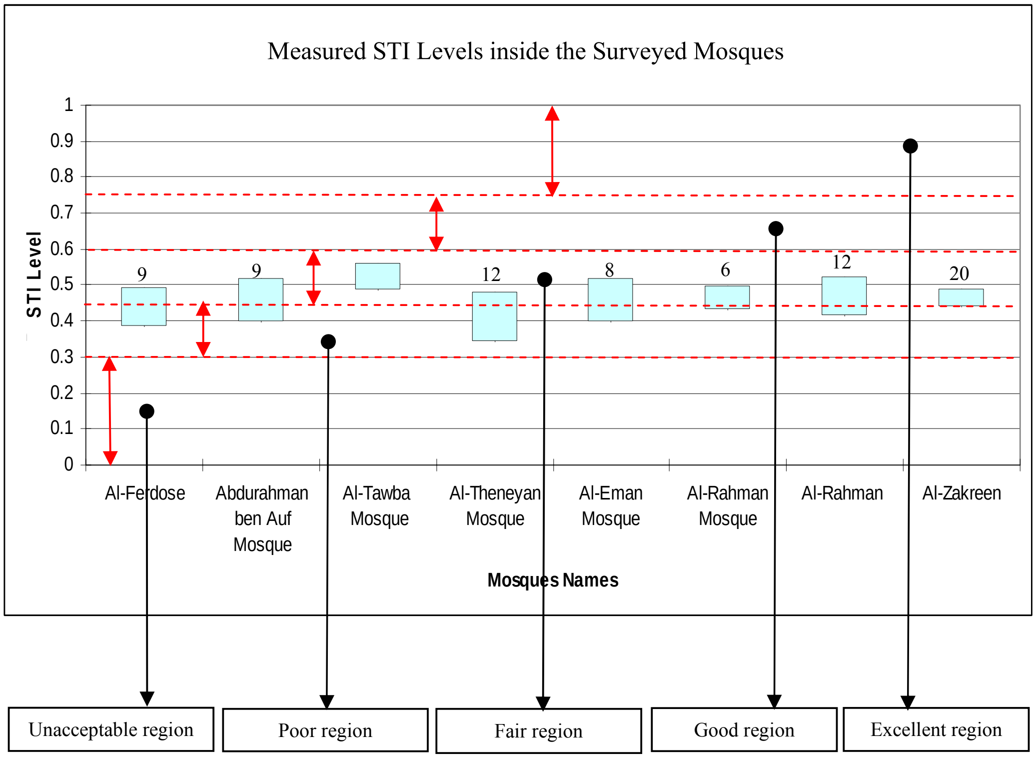
Evaluation of the used sound systems in the surveyed mosques and their influence on sound parameters is the scope of the next part. Extensive measurements have been taken in selected mosques of different sizes in order to characterize their acoustical quality and to identify the impact of the sound Reinforcement System on their acoustic quality. The impulse responses at different places are a good acoustic representative of each mosque. These impulse responses were recorded and in post-processing some other objective room acoustic parameters like Speech Transmission Index (STI), Clarity of Speech ($C_{50}$) and others have been driven from it.

## 4.1b: Evaluation of the Used Sound Systems and Their Effect on Sound Parameters:

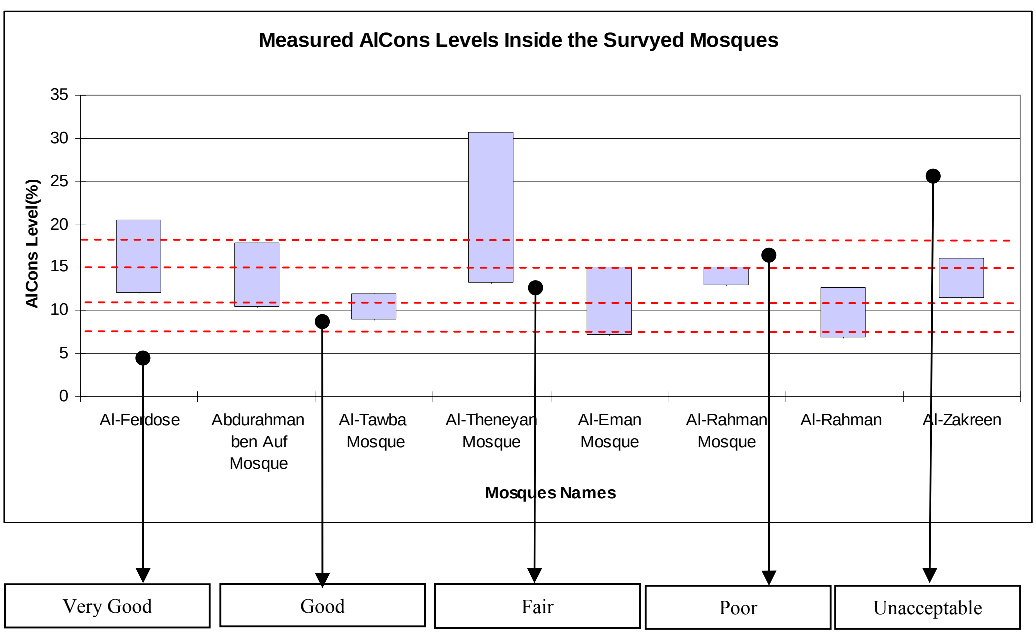
STI values are influenced by the amount of Reverberation Time inside a structure. Intelligibility expressed in STI values suffers in very reverberant spaces. Audience absorption is the largest absorption contributor not only in a mosque, but in all structures. In fact in hard surfaces structures, nearly 75% of the total "absorption material" is the audience. So, the "Occupancy absorption" factor must be kept in mind when designing a mosque. In the following, we evaluate intelligibility in the surveyed mosques in its worst case scenarios when mosques are empty (higher Reverberation Time).

### 4.1b.1: Intelligibility:

In the survey carried out in different mosques in Saudi Arabia to evaluate the installed sound systems, different acoustical Parameters were measured in unoccupied mosques according to the ISO-3382 standard. Measurements were taken at two different worshipping modes while standing at 1.75m and in preaching mode (seated worshippers) at height of 0.85m. The averaged STI and AlCons% levels for the two modes as an indicator of the intelligibility range throughout each mosque are shown in the figure below. The numbers of measuring points at each mosque are, also, shown. Measured STI Levels inside the Surveyed Mosques




(a)



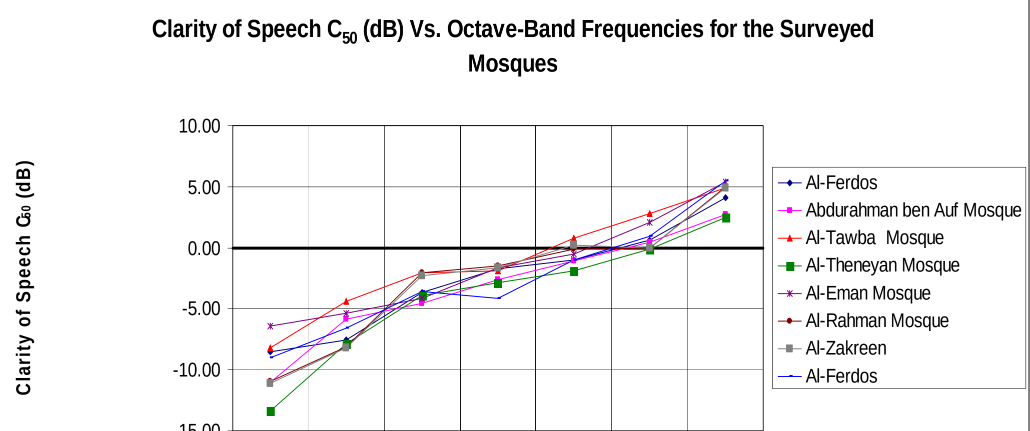

(b)

*Figure 62. averaged STI(a) and AlCons% (b)levels for the two modes*

According to the STI measures, most of the mosques had their intelligibility between Poor and Fair scale. The fluctuation of the AlCons% measures in some mosques is evidence and it goes as high as 15% as a difference between the maximum and the minimum values, see the recorded AlCons% in Al-Theneyan mosque.

### 4.1b.2: Clarity of Speech ($C_{50}$):

The clarity of speech reinforcement systems are measured in terms of the clarity index $C_{50}$, which is defined as the ratio of the energy arriving at a given seat within the first 50ms after the direct arrival to the energy arriving at the same seat afterwards. Accordingly, in mosques it is important to know the amount of energy arriving at certain location within the first 50ms which enhances the intelligibility and clarity of sound compared to the energy that follows afterwards. The target value of $C_{50}$ in dB is frequency dependent. A general guideline is to keep this value **above** 0dB especially for sound systems designed for speech purposes what implies that the amount of direct sound arriving at certain point should more than the reflected sound. The following figure depicts the measured Clarity of Speech $C_{50}$ for all the surveyed mosques.




| | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| Al-Ferdos | -8.52 | -7.53 | -3.71 | -1.76 | -1.01 | 0.62 | 4.11 |
| Abdurahman ben Auf Mosque | -11.01 | -5.83 | -4.53 | -2.63 | -1.11 | 0.47 | 2.71 |
| Al-Tawba Mosque | -8.17 | -4.38 | -2.06 | -1.86 | 0.74 | 2.79 | 4.91 |
| Al-Theneyan Mosque | -13.38 | -7.88 | -3.93 | -2.83 | -1.93 | -0.13 | 2.46 |
| Al-Eman Mosque | -6.45 | -5.39 | -4.13 | -1.68 | -0.49 | 2.08 | 5.39 |
| Al-Rahman Mosque | -10.95 | -8.15 | -2.05 | -1.52 | -0.08 | 0.00 | 4.95 |
| Al-Zakreen | -11.12 | -8.20 | -2.33 | -1.65 | 0.25 | -0.03 | 4.93 |

Octave-Band Frequencies (Hz)

*Figure 63. The measured Clarity of Speech C50 for all the surveyed mosques.*

It is evident from the previous figure that all mosques are experiencing low level of clarity especially between 125-2000 Hz Octave-Band frequencies. The frequency bands which are important for speech (250 to 2000Hz), almost all mosques showed negative numbers as an indication of bad speech intelligibility. Above these frequencies the amount of energy arriving before 50ms is a bit more than the energy arriving afterward.

No big fluctuations were found between the recorded results of $C_{50}$ for the different mosques despite their differences in volume. For example, Al-Eman Mosque and Al-Zakreen Mosque both have a $C_{50}$ of -1.6 dB at 1 KHz despite the big difference in volume; Al-Eman Mosque has a volume of 555$m^3$ and Al-Zakreen Mosque as big as 10034 $m^3$ and both uses the same speaker type. This implies that much more effort was done in the Al-Zakreen Mosque to bring its speech clarity to an acceptable level, since it has a bigger volume and difficult to be handled acoustically compared to smaller mosques. Al-Zakreen Mosque still suffers from the lack of clarity and intelligibility of speech.

### 4.1b.3: Background Noise Level (BN) Inside Mosques:

As a part of this Survey, Background Noise inside each mosque was assessed. All Air Conditioners and Roof Fans were switched ON. Using a portable Set-up and EASERA software the A-Weighted Noise Level at different points throughout each mosque was measured. Sometimes, it was as high as 70dB (A). Most of the mosques if not all, had the relatively comparable noise level what makes the resulting curve from averaging there values some how a descriptive curve of all the mosques. The following figure depicts the averaged Background Noise of the surveyed mosques plotted along with the RC curves.

RC curves are used to evaluate and diagnose the continuous noise from HVAC systems (Heating, Ventilation and Air Conditioning systems) according to the measured sound pressure level, Shape of frequency spectrum, tonal content and low frequency forced vibration. Any value located in the shaded area A indicates high probability of audible noise-induced vibrations in lightweight walls and ceiling constructions see the following figure. A sound level in shaded area B indicates low possibility of moderately “feelable” vibration. The bolded curve at the bottom of the graph indicates the threshold of hearing for continues noise. It is worth mentioning that the threshold of hearing for pure tons such as the ones existing in HVAC systems is much lower due to grater human sensitivity to theses tones.

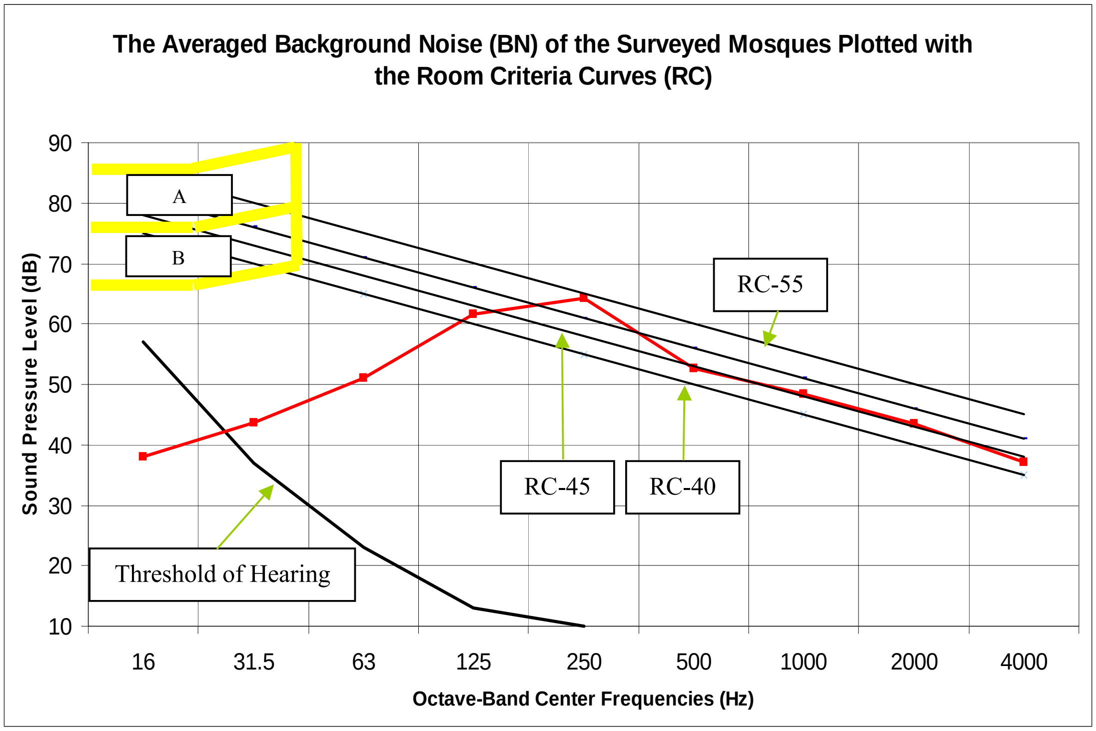



*Figure 64. The averaged Background Noise of the surveyed mosques plotted along with the RC curves*

Unlike the NC rating, where different spectra can have identical rating, the RC rating can be determined by taking the arithmetic average of the sound pressure level at 500 Hz, 1000Hz and 2000 Hz and draw a line with a slop of 5dB per octave passing through that particular average at 1 kHz. Secondly, a subjective "quality" evaluation or classification of the Background Noise as "hissy" (H), "Rumbly" (R), "neutral" (N) and "vibrate surfaces" (V) can be done using the same curves. Because of that the RC curves are described as more comprehensive and descriptive than the NC curves.

Let us go through these procedures of determining which RC curve represents the averaged background noise curve BN shown in the last figure and how a subjective evaluation can be conducted. Now, a subjective evaluation of the averaged curved might not be meaningful, since it does not describe a physically existing mosque. But, still it has the descriptive measures of all the surveyed mosques. So, the maximum in this averaged curve shown in the following figure at 250Hz of approximately 65dB is a result of the fact that most of the measured mosques having a maximum BN sound pressure level at that particular frequency. To evaluate the averaged BN curve presented in the last figure, the following two steps can be followed.

First, the average of sound pressure level has to be taken at 500 Hz, 1000 Hz and 2000Hz. It is 48.2dB ((52.7+48.5+43.5)/3). Hence, the averaged BN in the surveyed mosques are **RC-48**. Now we must classify this environment as N, H, R or

V. Therefore, we begin with drawing a line, which passes through 48dB at 1Kz with a slop of 5dB per octave, see the following figure. Next, we draw two lines parallel to the RC-48, one to the left of 500Hz and 3dB above the RC-48 line, and the other is to the right of 1000Hz and 5dB above RC-48 line. These lines are called R and H respectively [17].

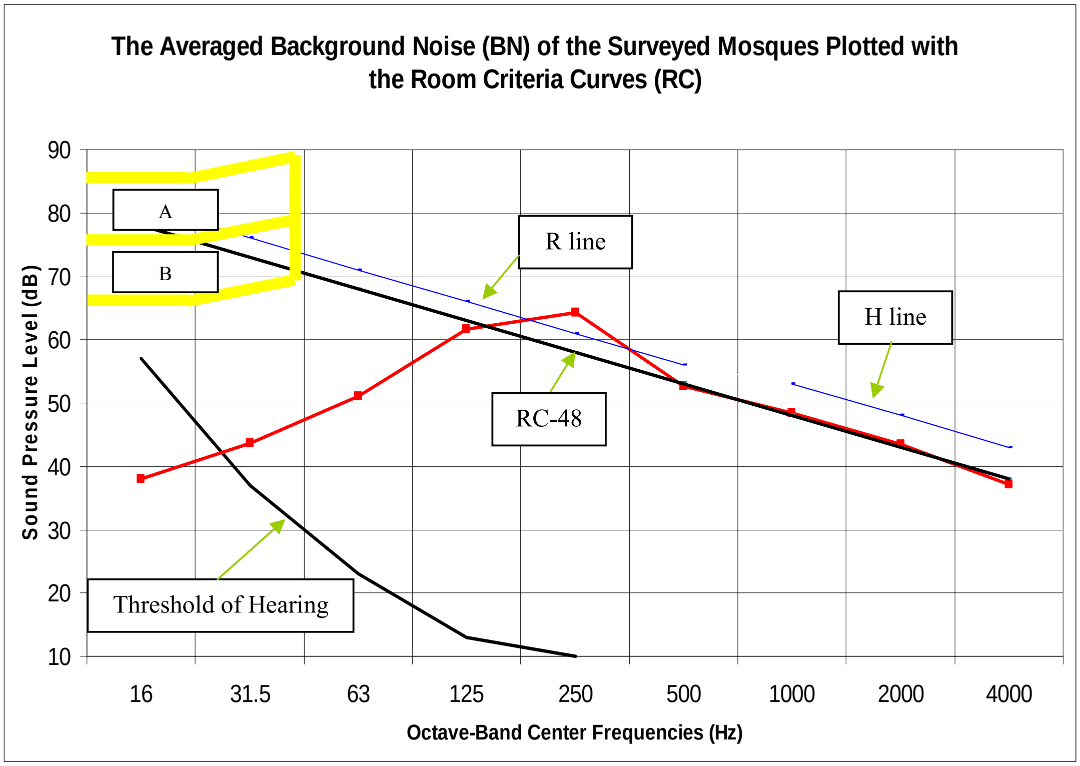



*Figure 65. The averaged Background Noise of the surveyed mosques*

It is observed that one value is above the R line. Therefore, the Background Noise represented by this curve sounds “rumbly” and it is rated as RC-48(R).

## 4.1c: Relationship between Quality of Sound and Reverberation Time by Means of Sound System:

The relationship between quality of sound and Reverberation Time is highly proportional. High Values of Reverberation Time will lead to unacceptable level of intelligibility especially in places were clarity of speech is essential. In some other places where speech is not the central focus of the sound design (like for symphony music) and a more reverberant structure is recommended higher values for Reverberation Time should be maintained.

The optimisation of the quality of sound by reducing the Reverberation Time was introduced in chapter 3. It was shown that carpet treatment by means of "Passive Treatment" plays a significant rule in reducing the Reverberation Time of any mosques, since it covers a large surface area of the total area. Consequently, sound quality influenced by lowering the high Reverberation Time will be improved.

In the previous section, the influences of sound systems implemented in the surveyed mosques on different parameters were presented. The quality of sound is influenced by the Reverberation Time and Background Noise level. The influence of the second item on the quality of sound was addressed, also, in the previous section. In this part the relationship between quality of sound and Reverberation Time influenced by the used sound System will be addressed. The following figure depicts the averaged measured Reverberation Time in the different surveyed mosques. As discussed earlier in chapter 3, the Reverberation Time is not only defined by the volume of the mosques, but the constructional features of mosques and the thickness of the carpet both have a significant influence.

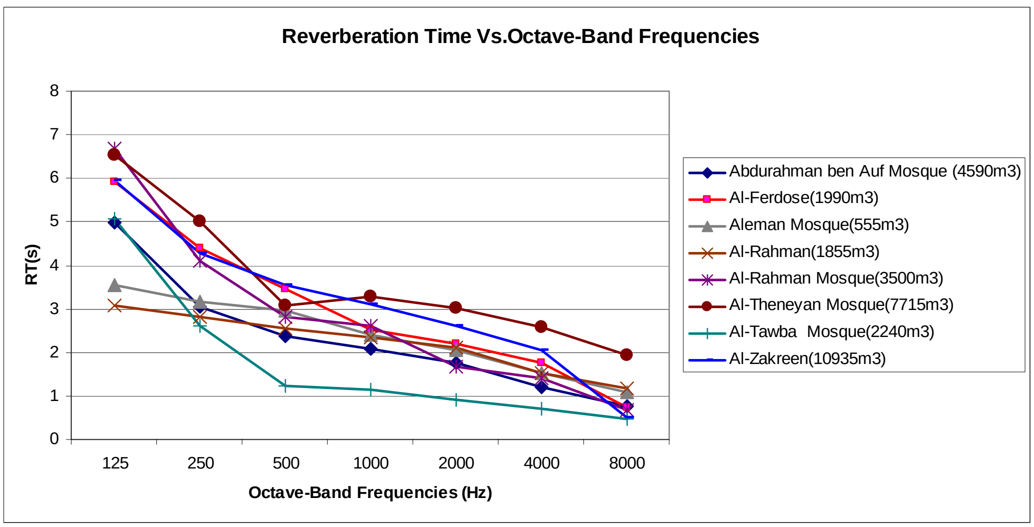



*Figure 66. Averaged measured Reverberation Time in the different surveyed mosques*

Comparing these values to the recommended Reverberation Time for different acoustical application at different volumes presented in Figure 17(b), all mosques seem to be very reverberant. For example, the recommended RT for 10,000m$^3$ structure used for speech is 1.5s while the RT of Al-Zakreen mosque, using the fact it has the same volume, is 3.1s. The intelligibility and clarity of sound in such a reverberant structures are not prevailed, see Figures 62and 63.

The influence of Reverberation Time on quality of sound can be minimized using more directed speakers toward the audience or what is so called loudspeaker columns. None of the visited or the surveyed mosques had a sound system designed using such loudspeaker. Only small conventional loudspeakers, like TANNOY CPA5, installed at heights of 5m from the audience with a low front-to-random factor and almost omni-directional directivity balloon were adopted for designing the different mosques. See Figure 67 to look at the directivity balloons of such a speaker at 400Hz and 1000Hz frequencies. This implies that a great deal of the energy transmitted from the speakers is not focused toward the worshippers but toward different surfaces of the mosque like the roof and sidewalls. Also, hanging small loudspeakers at high elevation means that worshippers at far distances are located in the diffuse sound field.

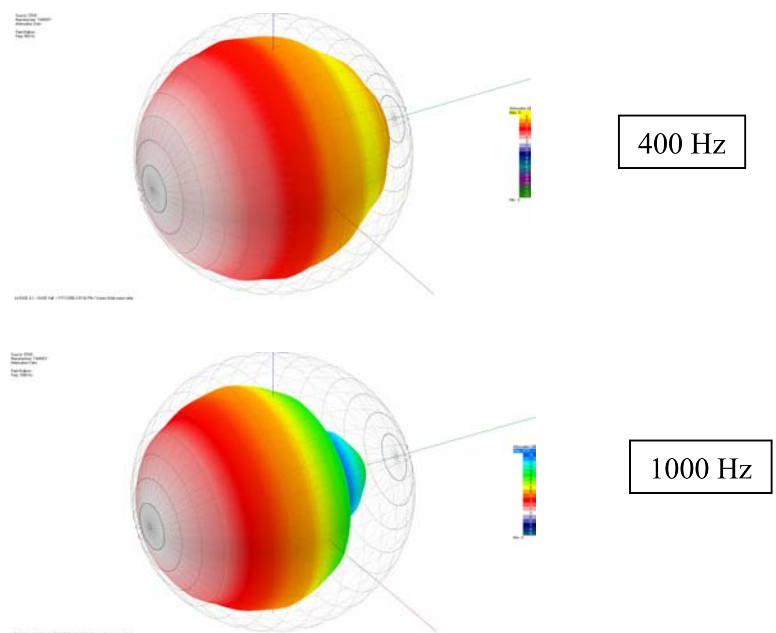



*Figure 67. Different directivity balloons for TANNOY CPA speaker at 400, 1000 Hz*

The occurrence of new digitally controlled sound columns did revolutionize the optimisation of sound quality in reverberant structures. Such a sound column offers a highly directive vertical plane, which strongly reduce the ceiling and the ground reflection. See the following figure. More about sound columns and the new methods to control them and to optimise their behaviour will be covered in a later chapter.

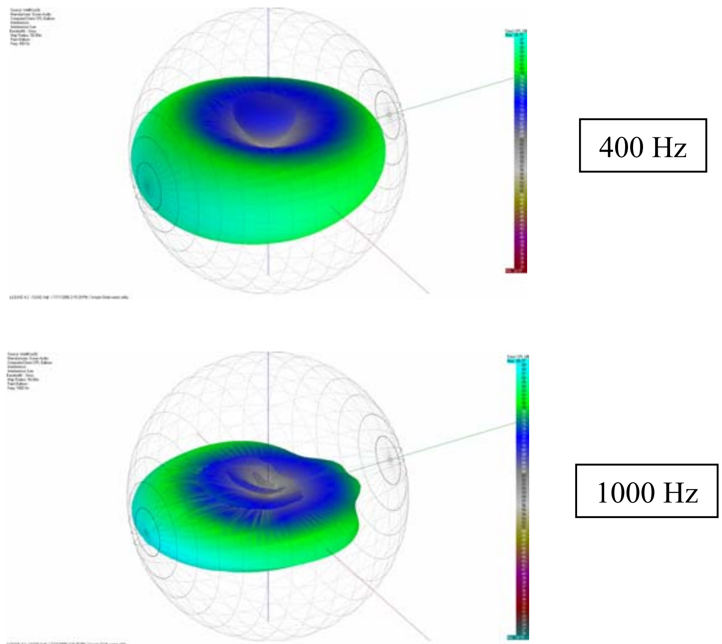



*Figure 68.Different directivity balloons for Intellivox2b Loudspeaker Line at 400, 1000 Hz*

Now let us take an example of one of the Surveyed mosques and implement a digitally controlled loudspeaker column. Afterward, the simulated intelligibility levels will be compared with the measured ones to estimate the efficiency of such a loudspeaker column in contrast to normal distributed system.

Al-Eman Mosque has a small worshipping volume of 555m$^3$. It is located in the downtown of Jeddah, Saudi Arabia. It can accommodate up to 300 worshippers. It is an unsymmetrical structure mounted with 5m diameter dome. The zigzag design of the walls and the existence of the dome have suppressed the need for roof supporting columns.

The current installed sound system consists of 6 TANNOY CPA loudspeakers distributed throughout its structure. This mosque is equipped with an Air Conditioning system to restore pleasant climate conditions. Accordingly, a noticeable increase in the Background Noise (BN) was measured. The following figure shows an internal view of the Mosque and a measured BN spectrum at one of the measuring point. As we can notice, two peaks are measured at 125Hz and 250Hz both of which represents the noise produced by the Air Conditioning system and the Fans respectively.

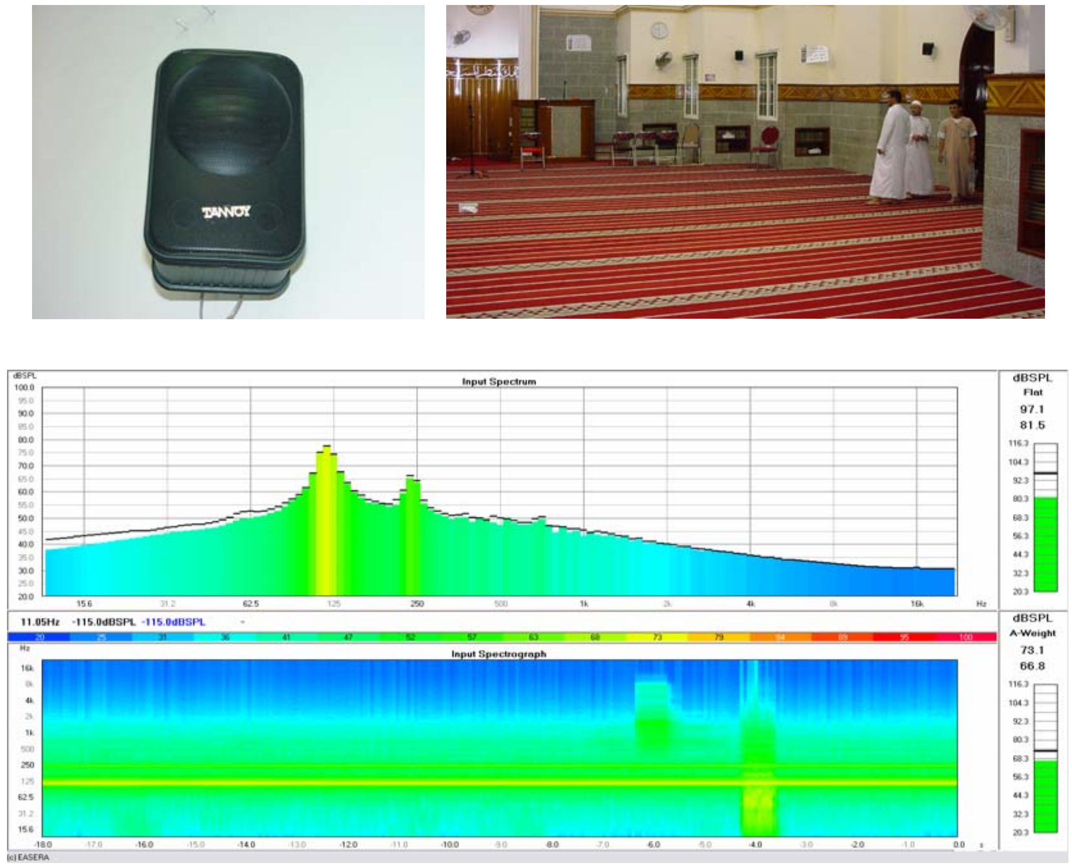



*Figure 69. Internal view of Al-Eman Mosque and the measured BN spectrum at one of the measuring point*

Eight different Measuring point were chosen as good representatives of the whole mosque. During the BN assessments all Air Conditioning Unit and ceiling Fans were switched on. The measurement procedures were conducted in an empty mosque. Different sound parameters like STI, Alcons%, Clarity of speech $C_{50}$ and the Reverberation Time were presented in Figures 62a, 62b, 63, 66 respectively.

Even though the mosque was small in size and it was expected to obtain acoustically better values than in bigger mosques, the measured results did not show the anticipated intelligibility values in this structure. For this mosque STI, AlCons%, Clarity of speech $C_{50}$ all indicated a poor quality of sound. The Reverberation Time in this mosque should be around 1s where the measured RT at 1 kHz was 2.4s. Now let us see how the acoustical environment inside the mosque can be optimised using one sound column. We will start with evaluating the current acoustical situation inside the mosque and compare with the optimised design.

An EASE model of the Al-Eman Mosque was created; Figure 70 to get an overview of the general outlook of the mosque.

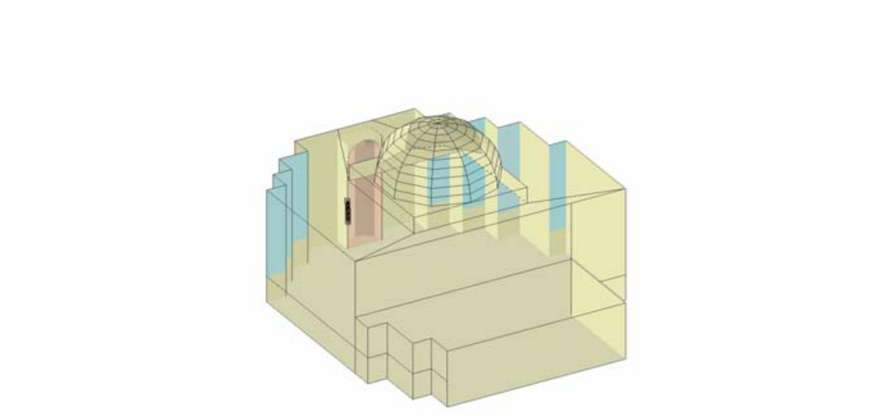
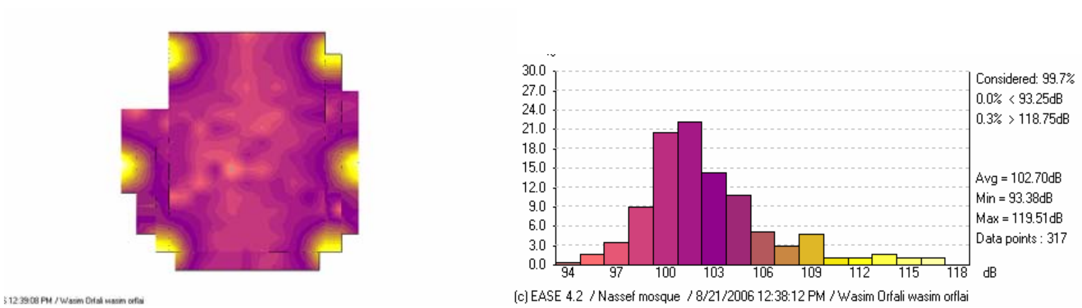
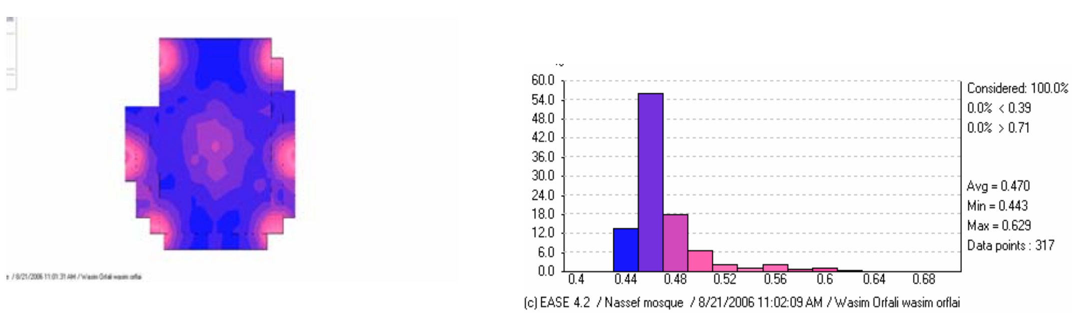


*Figure 70 EASE model of Al-Eman Mosque*

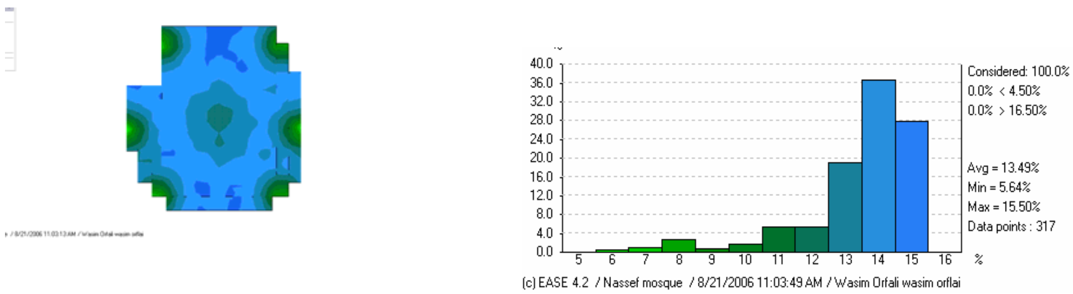
After simulating the current situation inside the mosque using 6 TANNOY CPA, the resulted STI, Alcons% and Clarity of speech $C_{50}$ were comparable to the measure data presented in Figure 62a,62b and 63 respectively. This means that the acoustical environment inside the designed EASE model along with its sound system within a good agreement with the acoustical environment in the real mosque and can be compared to the optimised sound EASE model. The simulated SPL, STI, AlCons% and $C_{50}$ before optimisations are shown below.



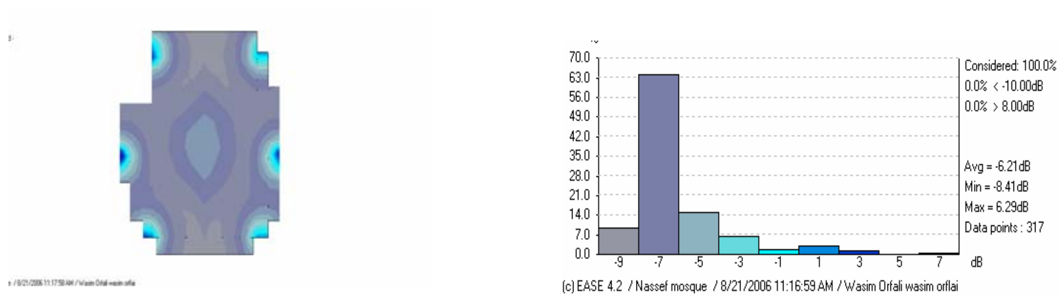

(a)




(b)




(c)




(d)

*Figure 71 (a) SPL (b) STI (c) AlCons% levels (d) C50 (at 1KHz)*

Figure 71a shows the SPL inside Al-Eman Mosque using 6 TANNOY CPA. Even though, the mosque has a modest volume, the designed sound system did not maintain an acceptable homogeneity of SPL, intelligibility and clarity levels. The SPL ranges between 97dB and 109dB (12 dB difference throughout).The intelligibility levels inside the mosque by means of STI and AlCons% ranging between poor and fair. Sometimes, it has a good level in the areas near the loudspeakers. Therefore the acoustical parameters should be optimised using controlled sound columns.

Only one digitally controlled sound column was used at height of 1.8m in the centre of the Qibla wall. Sound Pressure Level and different sound parameters were simulated. Afterward, the simulated results generated while using 6 TANNOY CPA were compared to the simulated results generated using one sound column to show the benefit of using such loudspeaker columns. Figure 72 depicts the Sound Pressure Level in the audience area along with its distribution range

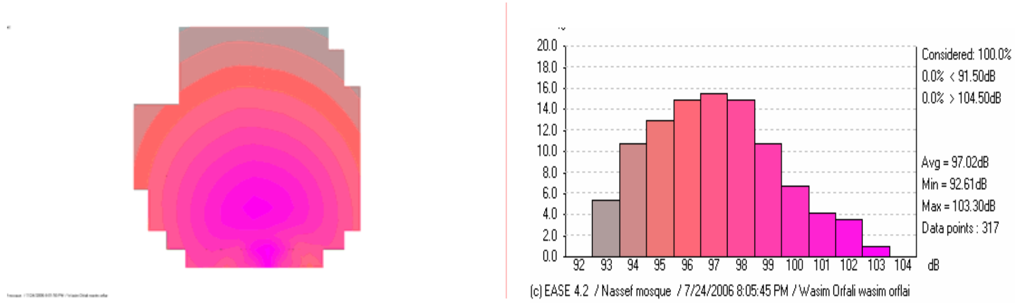
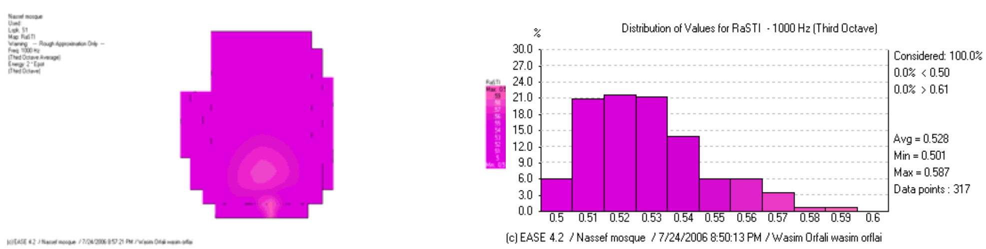


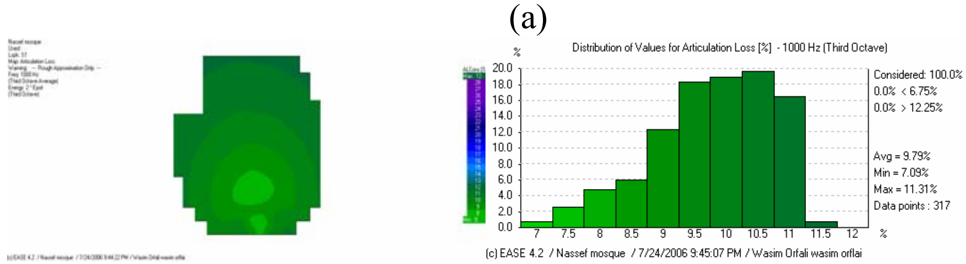

*Figure 72 Sound Pressure Level in the audience area along and its distribution range using one sound column*

The above figure shows a range of only 6 dB difference between places within the main coverage area of the loudspeaker column and remote places are evident. A direct sound level of 94dB was notice at farer distances from the source, which is still 30dB more than the Background Noise level (in its worst case scenario). This different assure good signal to noise ratio, consequently, higher intelligibility levels especially in mosques where BN levels were very high.

See the following figure to observe the homogeneity in the intelligibility levels inside the mosque by illustrating the STI (a) and AlCons% (b) values and using one loudspeaker column.




(a)




(b)

*Figure 73. (a)STI and (b) AlCons%)levels in Al-Eman Mosque*

As we may observe, the intelligibility measures between good and very good figures on the two scales. On the STI scale the values ranging between 0.5 and 0.59 compared to a range between 0.4-0.5 using the distributed system as in Figure 71b. Also, the simulated AlCons% values show a range of 7 to 11.5, which is a good indicator of good intelligibility. On the other hand, the measured values with the installed distributed system showed that a big part of the audience area had poor ineligibility, see Figure 71c.

This chapter have started with addressing the current electro-acoustical situation in the surveyed mosques. All the surveyed and the visited mosques were equipped with distributed sound system. It turned out that the designer of the sound system only made a simple approach, namely "*Every 25m$^2$ should be covered by one speaker*", but they didn't give a proper attention to the quality parameters. Also, no proper attention was given to the kind of speaker used, the speaker height and its directivity patterns. Small size speakers with modest maximum SPL(90dB) installed as high as 5m with almost omni-directional characteristics were noticed to dominate the choice of the sound system designers. Such speakers have no enough energy to generate sufficient SPL at farer distances to overcome the Backgound Noise levels.

After conducting an evaluation of the sound system installed in each one of the surveyed mosques according to the ISO-3382, it was noticed that intelligibility is very low in such structures were speech intelligibility is necessary. Sound intelligibility were ranging between unacceptable, poor and sometimes fair on the STI and AlCons% scales. Clarity of speech $C_{50}$ was below -2 for the Octave-Band between 250 to 2000 Hz which is important for speech. Although some of the surveyed mosques had small structures still intelligibility parameters and other acoustical parameters in big and small mosques were in bad figures. Independent from the mosque's volume all the surveyed mosques showed very similar bad clarity measures.

Background Noise BN was evaluated since it is an important factor, which degrades intelligibility. The BN was assessed using Room criteria curves RC. Using these curves, it was found that the BN has a level of RC-48(R) where R stands for "rumbly" sound. A proper solution has to developed to decrease the noise level inside mosques and, consequently, increasing S/N ratio which will improve the intelligibility in such structures. Isolating the A/C unites in a speared technical room could be the best solution to eliminate such a noise.

To improve the S/N ratio further, the Background noise level has to be reduced. Also, a special column or loudspeaker line which has more directed directivity pattern toward the audience and less energy to be reflected from the ceiling or other remote surfaces has to be considered. These loudspeakers lines have the capability to cover larger spaces with only 3dB decrement of SPL in the near field and behave as a spherical source (6dB decrement) in the far field if compared to a conventional loudspeaker with a constant 6dB decrement in the near and far field. Consequently, less number of sound sources is needed to cover the whole audience area as was demonstrated in Al-Eman Mosque. This implies less cabling, less installation, easier maintenance effort and lower cost.

# Chapter 5

## 5: Acoustical Rules for Designing and Reconstructing Mosques

Unlike auditoriums, there are no defined recommendations or rules for the acoustical parameters inside mosques. Most of the presented recommendations are with regards to halls with multipurpose use, opera theatre and structures built for organ music. Forming general Sound Parameters for mosques requires a good understanding of the acoustical and the spiritual environment expected in such structures.

## 5.1: Mosque's Type and Volume Dependent Rules:

Newly defined values of the acoustical parameters with regard to the Mosque's volumes and type will be addressed in this part. New designing rules for Mosque's major two types like Closed or Courtyard structures will be presented below. Also, mosque's volume dependent parameters like Reverberation Time will be introduced as new recommended values especially designed for mosques.

### 5.1a: General Rules of Acoustical Quality Parameters:

The most primary parameter which has to be sorted out is the Reverberation Time. High Reverberation Time will lead to unacceptable intelligibility levels. On the other hand, low Reverberation Time will result in what so called "Dead" spaces where spiritual ceremonies looses the attention of the worshippers. So, let us start with the following equation to formulate the relation between the Reverberation Times and Volumes of mosques.

$$r_R^2 = r_H^2 \times \gamma_L \Gamma_L^2(\vartheta) \ldots\ldots(12)$$

Where,

$\gamma_L$ – the effective front-to-random factor of the sound source

$\Gamma_L$– the directivity factor of the source (in main radiation direction ≈ 1, i.e. negligible)

$r_H$ – the Reverberation Radius

$r_R$ – the critical distance

It is known that

$$r_H^2 = \left(\frac{A}{16\pi}\right), \quad A = 0.163\left(\frac{V}{RT}\right)$$

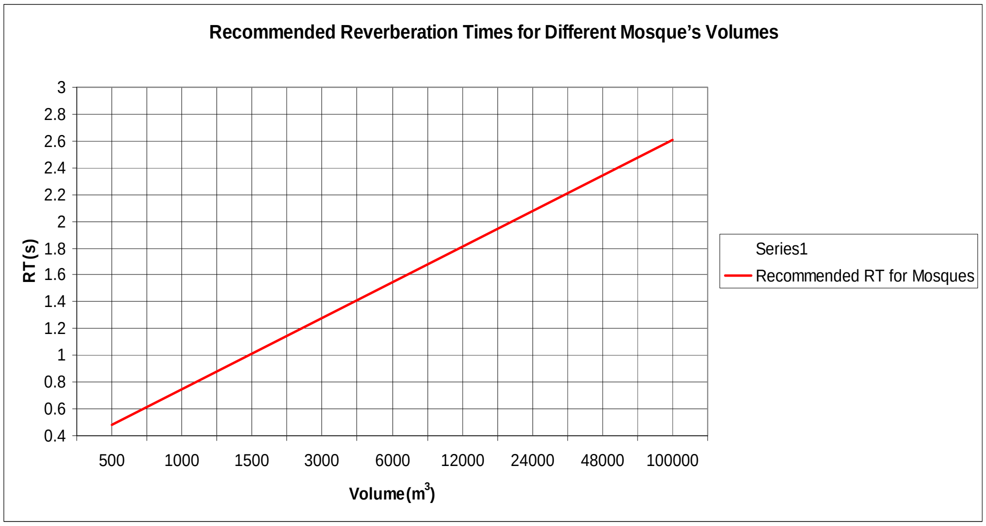
Thus by substituting in equation 12;

$$r_R^2 = \left(\frac{0.163V}{16\pi RT}\right)\gamma_L \text{......}(13)$$

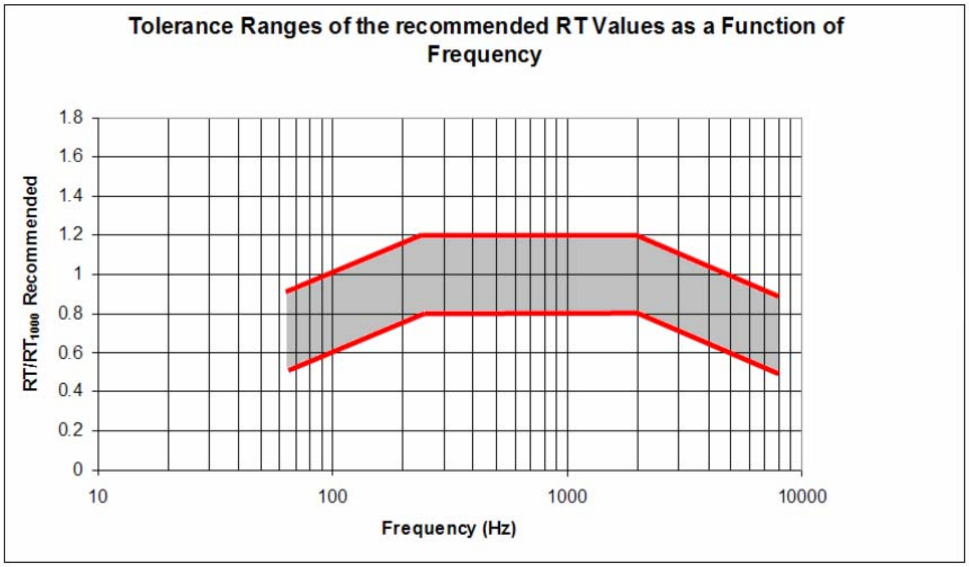
Therefore;

$$RT = \left(\frac{0.163\gamma_L}{16\pi r_R^2}\right)V\text{......}(14)$$

From equation 14, drawing a relation between Reverberation Time and Volume was possible as shown below along with its tolerance ranges as a function of frequency. As a starting point on this relation and as it was calculated and assumed in Figure 23 (assuming that at 1kHz C=10log $\gamma_L$ = 2, $r_R$=2.82m, $L_{diff}$=65dB in a mosque with 1440m$^3$ volume as was presented in chapter 3), equation 14 results in RT equal to 0.94s.




*(a)*




*(b)*

*Figure 74. (a)Recommended RT for different Mosque's Volumes (b)Tolerance Ranges of the recommended RT as a function of frequency*

It was assumed that the effective front-to-random factor $\gamma_L$ is 2 (at 1 KHz) for loud man voice and the natural increase of equivalent absorption area (*A*) coexists with increase of the mosque's volume. Increasing or decreasing the volume to draw the relationship presented above was found by increasing and decreasing the critical distance as it is influenced by the volume change. In Figure 74(b) the Tolerance Ranges of the recommended RT as a function of frequency are demonstrated. The RT at frequencies less than 250 Hz degrade at a rate of 0.2 per Octave. In mosques where a speech performance dominates, the effective frequency spectrum is ranging between 250 and 2000 Hz. Therefore, the contribution of frequencies lower than 250Hz should be omitted. This will ensure the suppression of Flutter Echoes emerging at low frequencies. Also, the recommended Tolerance Ranges decrease at frequencies higher than 2000Hz. This behaviour is enforced according to the natural sound energy loss as it travels throughout a mosque. Also, this behaviour is valid according to higher absorbing characteristic of surface materials (especially carpet) at high frequencies.

The Recommended Reverberation Time presented in the last figure was used to calculate the Articulation loss of Consonants as a measure of intelligibility using the following equation.

$$AlCons\% = 0.652\left(\frac{r_{LH}}{r_R}\right)^2 RT ......(15)$$

The relationship between the distance ratio $r_{LH}/r_R$ and the Articulation loss level at different Reverberation Times is shown below.

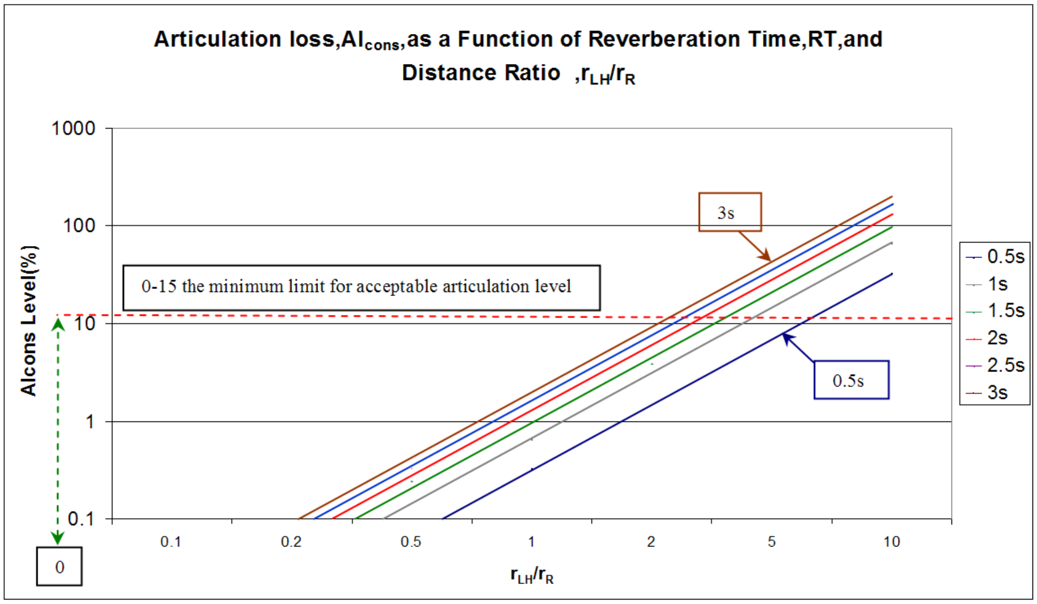



*Figure 75. Articulation loss as a function of RT and rLH/rR*

To maintain an acceptable level of intelligibility by means of AlCons% (a minimum of 15%) for structures with Reverberation Time between 0.5-3s, the ratio $r_{LH}/r_R$ ranges between 2 and 7 respectively.

Another measuring tool of intelligibility is $C_{50}$. Here the ratio of energy before and after 50 milliseconds in decibels is measured. Statistical Clarity of Speech $C_{50stat}$ formula as a function of Reverberation Time is shown below using a statistical approach [18].

$$C_{50stat} = 10\log \frac{(r_R / r_{LH})^2 + 1 - e^{\left(\frac{-0.69}{T}\right)}}{e^{\left(\frac{-0.69}{T}\right)}} \text{......(16)}$$

The relationship between $C_{50\ stat}$ and Reverberation Time for different $r_{LH}/r_R$ ratio is shown below.

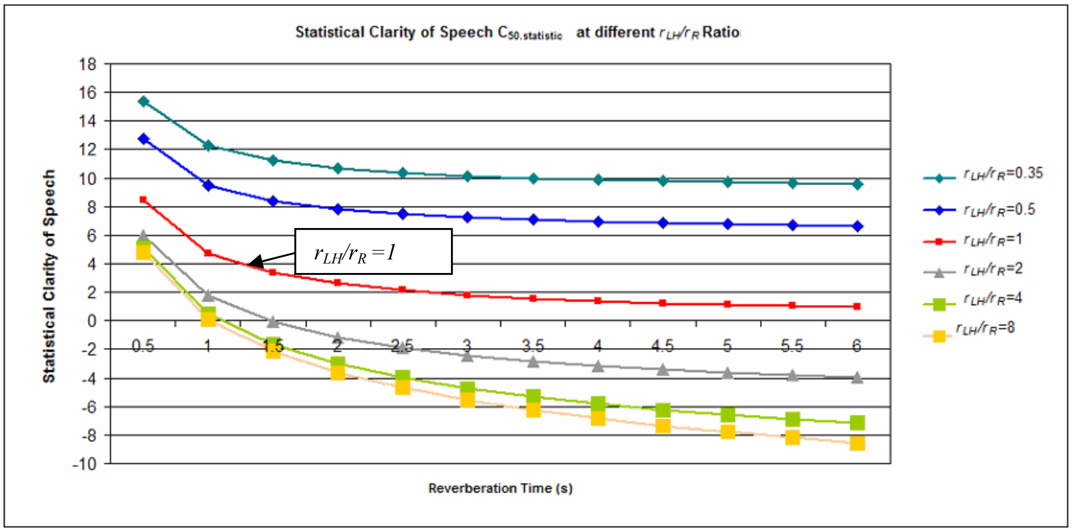



*Figure 76. Statistical Clarity of speech for different $r_{LH}/r_R$ ratios*

Values above the zero line depict more energy arrivals before the 50msec than after it what enhances the direct sound and increases clarity. The integration of sound arrivals within 50msec with direct sound is due to human nature of our ears. Values under the zero line depict more energy is arriving after the 50msec. This should not be the case in a sound system built for speech purposes. All arrival of sound energy between 50-80msec will be effectively integrated to reverberant sound and considered useful for musical performances.

Speech Transmission Index, STI must also be investigated, since it is one of the most popular parameter to evaluate the intelligibility. An equation that takes into consideration the contribution of the direct sound in the calculated STI was provided by Houtgast and Steeneken in 1980 [19]. It represents the squared impulse response as a component of direct sound and reverberant field.

$$r(t) = r_d(t) + r_r(t)......(17)$$

Where

$$r_d(t) = \frac{3}{r_{LH}^2}\lambda(t)....(18) \quad \text{at} \quad t$$

$$r_r(t) = \frac{1}{r_C^2}\frac{13.8}{T}e^{\left(\frac{-13.8t}{T}\right)}....(19) \quad \text{for} \quad t > 0$$

Equation 18 represents only the direct sound component *r(t)* obtained as the product of Delta function (*λ(t)*) by the relative weight of the direct field $q_{t,1}/r^2_{LH}$ *(*$q_{t,1}$ representing the enhancement of the direct field by the directivity index of the talker sound field and as a result of listener's directional hearing capacity). Here $q_{t,1}$=3 as estimated by Plomp and Mimpen [19].

Equation 19 illustrates that the reverberant field is a combination of its relative weight $1/r_c^2$ multiplied by the loss factor 13.8/T and decaying exponentially ($r_c$ is the room's critical radius and it is influenced by the loss factor). This means that the initial value of the reverberant field is subject of the Reverberation Time (T) and the room's critical radius.

By substituting (17), (18) and (19) in the basic equation founded by Schroeder in 1981 [20] for the Modulation Transfer Function MTF give

$$m(F) = \frac{\left| \int_0^\infty r(t) e^{-j2\pi Ft} dt \right|}{\int_0^\infty r(t) dt} \text{....(20)}$$

And after including the noise factor the final equation of MTF yields to:

$$m(F) = \frac{\sqrt{(A^2 + B^2)}}{C} \frac{1}{1 + 10^{((-S/N)/10)}} \text{....(21)}$$

Where

$$A = \frac{3}{r_{LH}^2} + \frac{1}{r_R^2} \frac{1}{\left[ 1 + \left( \frac{2\pi FT}{13.8} \right)^2 \right]}$$

$$B = \frac{2\pi FT}{13.8} \frac{1}{r_R^2} \frac{1}{\left[ 1 + \left( \frac{2\pi FT}{13.8} \right)^2 \right]}$$

$$C = \frac{3}{r_{LH}^2} + \frac{1}{r_R^2}$$

Here
T The Recommended Reverberation Time in (sec)
$r_{LH}$ Talker-to- listener distance
$r_C$ The room's critical distance
$F$ Modulation Frequency from 0.63-12.5Hz
$S/N$ Signal to Noise ration in dB at the listener position

To derive the STI values from the calculated MTF the following set of equations can be considered for each Octave-Band:

$$X_i = 10\log\left(\frac{m_i}{1-m_i}\right)dB \longrightarrow X = \frac{1}{14}\sum_{i=0.63}^{12.5} X_i \longrightarrow STI_{Oct} = \frac{X+15}{30}$$

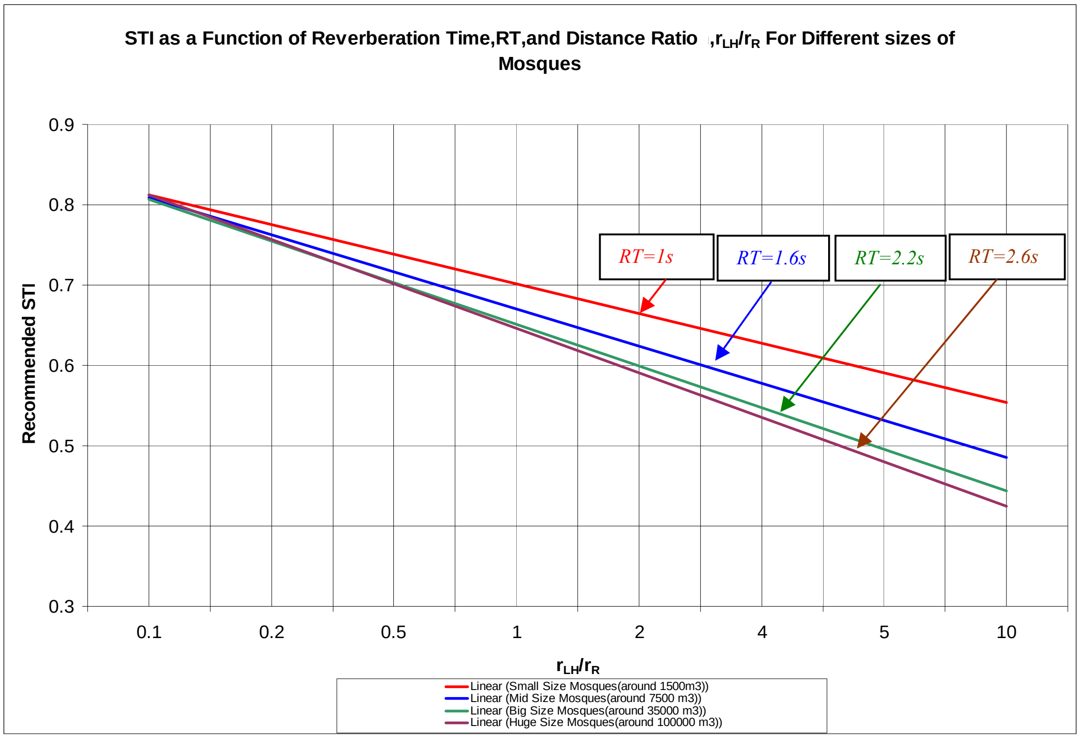
To calculate the total STI for the seven different Octave-Bands, the Weighted Mean of all $STI_{oct}$ Should be considered to balance the influence of all Octave-Bands on the final STI value. The equation associated with this is as follows:

$$STI_{total} = \frac{w_{125}STI_{125} \times w_{250}STI_{250} \times w_{500}STI_{500} \times w_{1000}STI_{1000} \times w_{2000}STI_{2000} \times w_{4000}STI_{4000} \times w_{8000}STI_{8000}}{w_{125} + w_{250} + w_{500} + w_{1000} + w_{2000} + w_{4000} + w_{8000}}$$

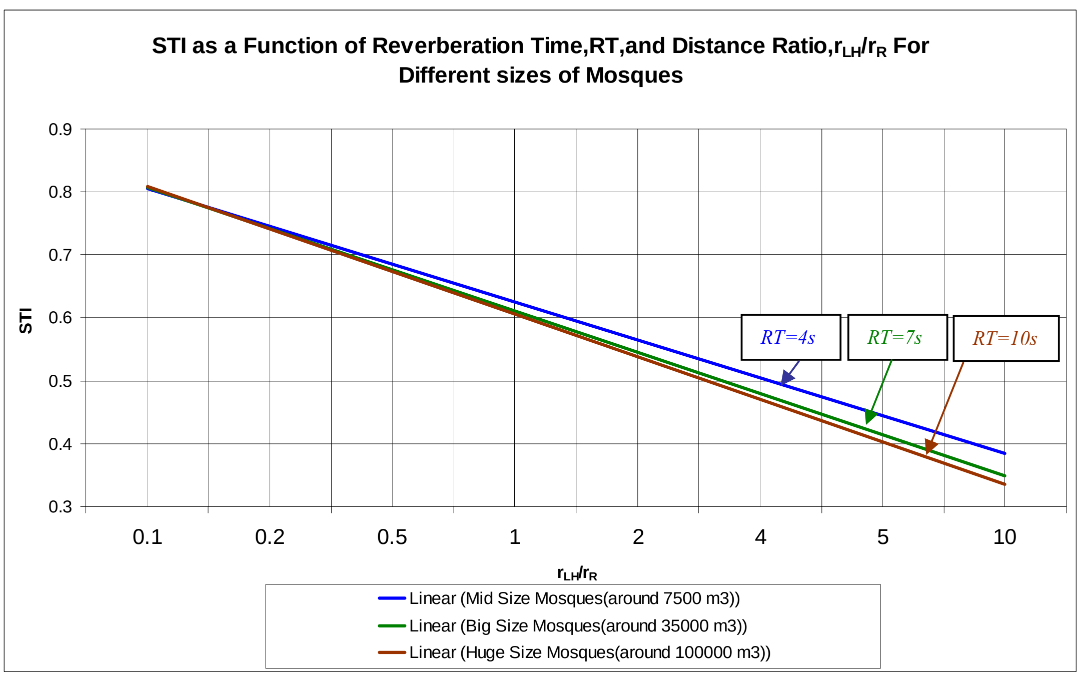
Where the weighting factors for each Octave-Band are :

$W_{125}$=0.13, $W_{250}$=0.14, $W_{500}$=0.11, $W_{1000}$=0.12 $W_{2000}$=0.19, $W_{4000}$=0.17 and $W_{8000}$=0.14

The following figure presents the relation between the recommended STI as a function of RT and the distance ratio $r_{LH}/r_c$. It is concluded from equation 21. Here the recommended RT presented in Figure 74 was used to calculate the Recommended STI values.




(a)




(b)

*Figure 77. (a)Recommended STI for different rLH/rR ratios for different mosques sizes(b) STI values for different $r_{LH}/r_R$ ratios for different mosques sizes using high RT Values.*

Let us assume that the recommended RT's for the different mosque's volumes have not been considered. What would be the resulting STI figures for the same Mid-size, Big-size and Huge-size mosque used to generate Figure 77a? Giving that the associated not preferable RT's are 4,7 and 10s for Mid-size, Big-size and Huge size mosque respectively (here, the small-size mosque has been excluded while in such mosques high RT time values are not most likely to happen). By using the same formulas used to calculate STI figures presented in Figure 77a, the STI were acquired for the same mosques with the new RT's, see 77b.

In general, the intelligibility of the different mosques volumes decreases compared to the same volume mosques where the recommended RT values were used. The decrements of intelligibility in term of STI were evident especially as $r_{LH}/r_R$ ratio increases. In other words, when the distance between a worshipper and loudspeakers increases compared to the associated critical distances of the used loudspeakers, STI are detected to drop more compared to STI values calculated using the recommended RT. Maintaining closer distance between worshipper and sound source will improve the intelligibility figures and makes them less dependent on mosque's volume.

In this section, general rules and recommendations for some sound parameters which matters in mosques were introduced. RT, STI, Alcons% level and $C_{50stat}$ were calculated upon good understanding and experience of the acoustical environment needed in mosques. Some of these parameters were a function of the distance ratio $r_{LH}/r_c$ at different Reverberation Time values to address wide range of conditions in constructed and newly constructed mosques.

## 5.1b: Newly Constructed Mosques Rules:

Early cooperation between the architects and the acousticians should take place to avoid any acoustical complications in later phases. Moreover, cooperation in early stages will save a considerable amount of cost which might be spend to relocate walls or changing of wall materials.

The first question to answer when starting to design a mosque is: Are we dealing with a large state mosque, a community mosque or a small mosque? As the mosque volume increases the Reverberation Time increases accordingly. Coincide with increase of Reverberation Time, the Intelligibility and Clarity of sound decreases. These dependent relationships have to be clear to the designers of the mosques. This is, also, does not mean that no big mosques have to constructed, but, if necessary, especial treatment of walls and under the carpet should take place to make this relation disproportional again. Also, it was found that all worshipping ceremonies in mosques with volumes less than approximately 1500 $m^3$ can be done without the need for Sound Reinforcement Systems (SRS) giving the fact that S/N ratio has to be at least 10 dB.

Regarding the internal design of mosques, as acousticians we have a few more words to say. Constructional features like Roof Supporting Columns, Domes and walls must be designed the right way; so it behaves in favour of sound quality in such structures. There is no doubt that eliminating the roof columns will improve the intelligibility especially in the areas shadowed by them. Increasing thickness of the roof and walls might be the solution of eliminating such columns and decreasing noise intrusion and consequently increasing intelligibility. It is more recommendable to use 4 in 1 columns, since sound wave can penetrate through them and decrease the shadowed areas. Also, as was mentioned in chapter 3, circular columns help reducing the shadowed area behind them compared to squared shape columns.

Constructing domes in mosques eliminate the need for using roof supporting columns. When the architect decides to design a mosque with a Dome, the relationship between the focusing height and the speaker's height must be watched. The ratio s/r should be more than 1.1 to prevent focusing at the height of listening plane of the worshippers. Such a relation is addressed in Figure 39 to provide guidelines for architects.

While concaved surfaces must be avoided especially at the back wall to prevent focusing, conveyed surfaces can be attached to parallel walls to degrade the possibility of flutter echoes. Also, ornaments can be added to parallel walls to scatter the sound waves and preventing it from forming fluttered sound echoes. Furthermore, lowered surfaces which are usually included within the main praying hall and represents woman worshipping area requires extended number of carrying columns which causes shadow ,accordingly, it must be brought outside the main hall as a separate structures. This will decrease the number of roof supporting columns inside the main hall and will improve the sound parameters in areas under the lowered surface.

Background Noise (BN) is a major contributor in degrading the overall intelligibility levels in mosques. It is mainly resulted from Air Conditioning operation noise. It is highly recommended to isolate the Air Conditioning unit in a separate Technical Room. This will reduce dramatically the Background Noise level and consequently improving the overall intelligibility level.

Open courtyards mosques are more exposed to Environmental Noise surrounding them. In case of constructing a mosque with an open courtyard, caution must be exercised to reduce the late arrivals of sound radiated from the Minaret sound system.. Also, a proper aiming and orientation of the Minarets sound systems should take place to decrease the possibilities of sound reflections from the neighbouring building and high landscape into the courtyard. Furthermore, constructing a moveable dome or glass roof to prevent the noise and late reflected sound from penetrating into the courtyard should be considered. Such a solution has drawbacks which we must deal with. A noticeable increase of reverberation in the courtyard will be evident when the dome covers the courtyard or when the glass roof is constructed over it. This will form different acoustical environmental conditions which have to be treated to maintain acceptable quality of sound. Such a treatment will be introduced in the following part as treatments recommendations for constructed mosques.

## 5.1c: Recommendations for Constructed Mosques to Optimise Acoustical Parameters:

Fortunately, once the internal design of a mosque is completed and can not be further modified, secondary structures can be treated to optimise the sound quality. Different recommendations of carpet treatments as a prime solution and walls materials will be presented here. Furthermore, recommendation of digitally controlled loudspeakers which enforce better intelligibility levels in such structures will be within the scope of this part.

Architecturally, mosques come in two major architectural forms. These forms are mosques with an open courtyard and others as closed structures. Both of which have different acoustical recommendations according to their architectural form. The recommendations for the two architectural forms are according to the study presented in chapter 3. Let us start with the open courtyard mosque.

### 5.1c.1: Open Courtyard Mosque:

An open courtyard was designed in the early days to accommodate high numbers of worshippers in communal praying. It is open to the open air to expose the worshippers visually more to the sight surrounding them. From the designer's perspective, it opens an extended view of the sky to consolidate the relation between God and the worshippers during the praying ceremonies. On the other hand, such a design exposes the worshippers more to the environmental noise surrounding the mosque compared to closed structures mosque. A solution has to be developed to decrease noise intrusion to the courtyard and in the same time to maintain a good view of the sky and the geographical sights surrounding the mosque.

Electrically sliding light weight structured Domes or Transparent Roof can be considered as prime solution, but has to be treated acoustically right to prevent high Reverberation Time and consequently low intelligibility while they are closed. Both of them are shown below.

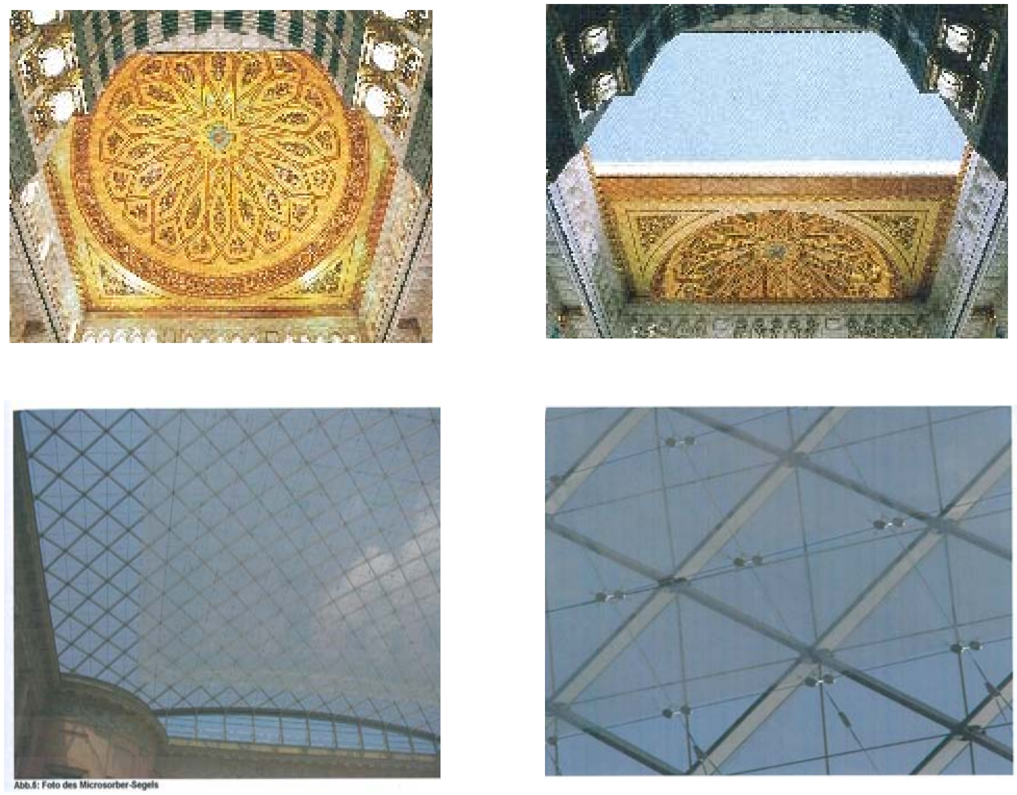



*Figure 78. Sliding light weight structured Domes and transparent roof*

Also, the concept of Convertible Umbrellas has been introduced as a prime solution to maintain the purposes of courtyard mentioned above. Such umbrellas were developed and implemented by SL-Rasch Sttutgart, Germany in the courtyard of the Prophet Mohammed Mosque in Mahdina, Saudi Arabia as shown below.


*Figure 79.Umbrellas implemented in the Courtyard of the Prophet's Mosque in Madinah*

The absorption coefficients of the material used in this project were measured in two different set-ups in the Reverberation Chamber of the TU in Berlin. The results are shown below.

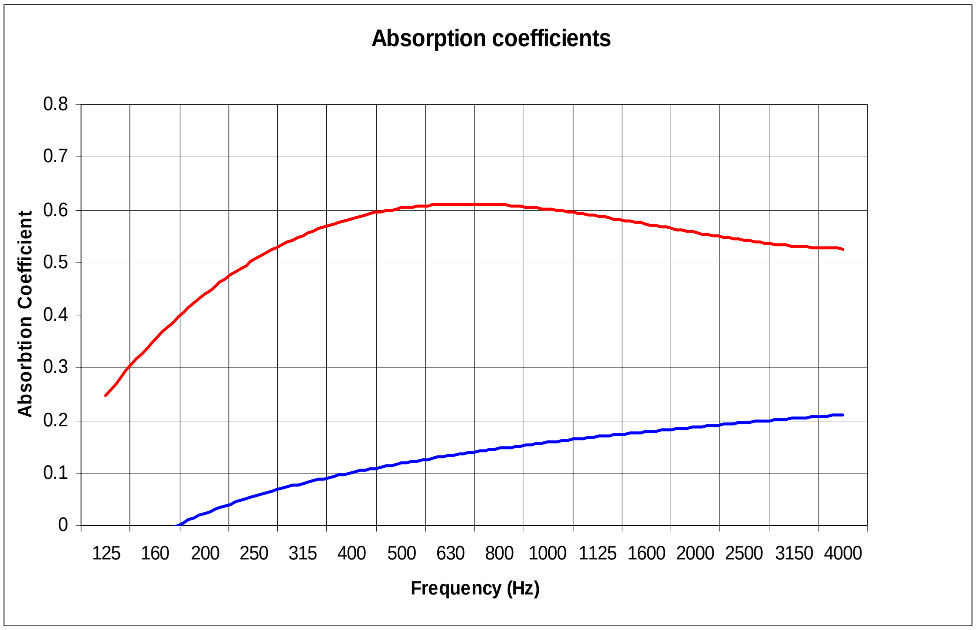



*Figure 80.Absorbtion Coefficients of the material used in the Umbrellas on the ground (blue Curve)and with a air gap from the wall (red curve)*

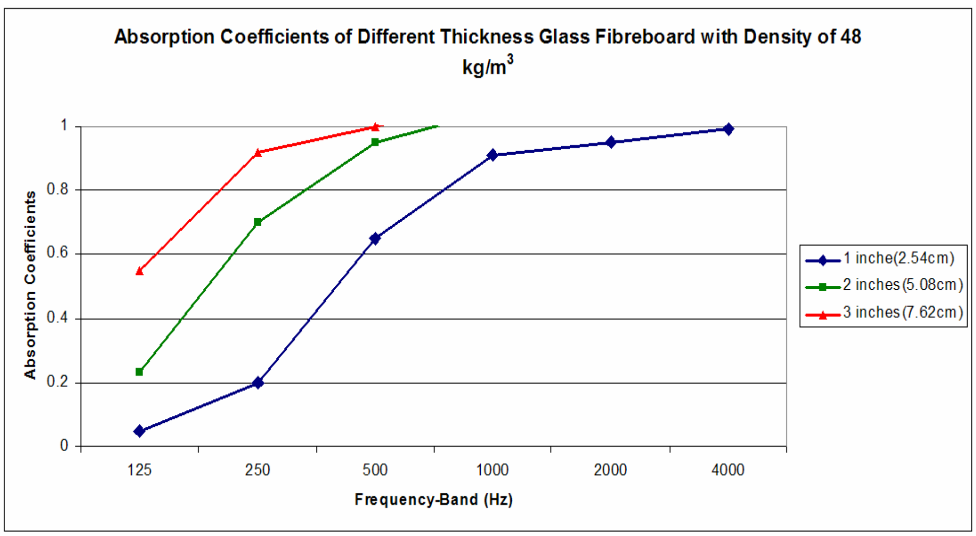
First set-up(blue curve) was to place the material on the ground. It will result in a more classical semi-linear relation between the frequency and the absorption of the material with higher absorption at higher frequencies. Hanging the material 20 cm away from the side wall will result in the second relation shown in red in figure 10. Spacing the material from the wall will boost up the absorption which will have a maximum value at the lower frequencies. Also, increasing the gap further will introduce another maximum at a lower frequency compared to the first curve and so on. The second set-up involves placing the material with a defined distance from the wall (red curve).

Material thickness, density and weight manipulate the absorption of the material. It is logic that increasing the thickness of the used material will increase its absorption, but this logic holds primarily at low frequencies. As if we were to place air cavity between the absorbing surface and the substrate, increasing the thickness of the material will result in placing its surfaces at a higher practical velocity, consequently, increasing its absorption.

Material density affects sound penetration; therefore, it affects the amount of the absorbed sound energy. The measurement results were conducted for one material with its associated density. Generally speaking, less dense materials with wide spaced fibres will give the chance for the emitted sound to penetrate back and forth through it (bigger flow of resistance); thus, increasing the sound absorption and vice versa. Also, increasing the weight of the absorbing material will acquire more energy of the incident sound to shake it (more absorption).

The construction of such umbrellas using the same measured material at a height of 8m or higher will not contribute significantly in changing the courtyard acoustic. Once the height of the umbrella from the ground floor exceeds the wavelength of the lowest frequency of interest in the speech spectrum (60Hz), the umbrella construction will not contribute significantly in manipulating the courtyard acoustic. They might only boost-up the Sound Pressure Level in the courtyard. One of its advantages is that it can be considered as acoustically transparent. So, putting or removing them will be harmless to the acoustical behaviour of structures (depending on their set-up).

Two different treatments can be applied for the sliding dome and transparent roof to improve their absorption. In case of the sliding domes highly absorptive glass-fibres with different thickness and with an appropriate air gap can be used to lead to the required absorption behaviour. The figure below shows the absorption coefficients for glass-fibres material with a different thickness and 1 inches (2.54cm) glass-fibre with different air gap from the solid surface.



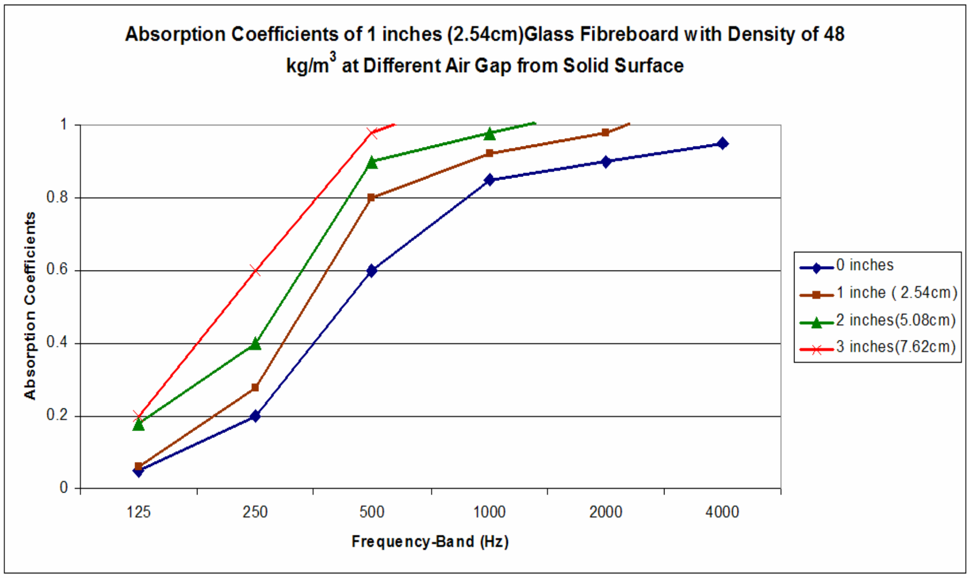



*Figure 81. Absorption Coefficients (a)with different thickness glass(b)with different air gap thickness*

The internals of, for example, a light weight structure dome can be stuffed with a fibre-glass material (with/without an air gap) with a certain thickness to obtain the required absorption behaviour and to seek the required results. It is clear from the figure above that increasing the thickness of the fibre-glass or the air gap will result in increasing the absorption especially at low frequencies.

Transparent roof like glass can be considered in the courtyard to decrease outside noise intrusion. They can be constructed as fixed or sliding roofs. Additionally, acoustical treatments have to be associated with this solution to decrease unacceptable Reverberation Time. Constructing such roofs on the top of a courtyard gives the possibility to make a further treatment to the floor, since by having a roof the floor is protected from weather conditions like rain, snow, etc. Also, Air Conditioning can be added to the courtyard in the existence of the roof to improve its temperatures in countries where hot weather prevails.

Especial transparent micro-perforated foil can be attached to the glass with a certain air gap from the glass surface. The transparent micro-perforated foil with two different distances from the glass surface along with its absorption coefficients are shown below. The implementation of the transparent micro-perforated foil with 100mm to the reflecting surface and 30mm distance between the foils is more adequate for mosque applications, since it is broad band absorber. In some other application where less absorbing are needed at lower frequencies a distance of 50mm to the reflecting surface and 30mm distance between the foils can be considered.

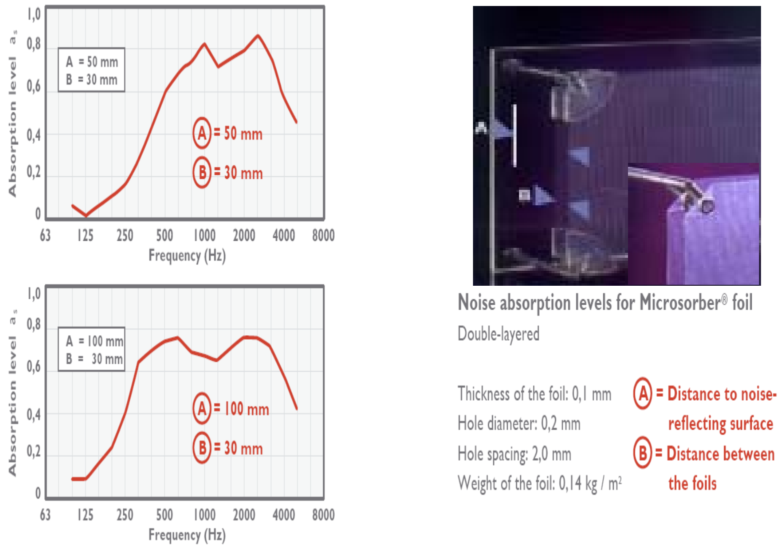



*Figure 82.Micro-perforated foil with two different distances from the glass surface along with its absorption coefficients*

Not only treatments of the glass roof and the floor can be implemented to improve acoustical parameters inside mosques. The merge of transparent absorbing surfaces makes it possible to "passively" treat and manipulate the internal design without changing the mosque's general overview. This can be very effective treatment solution especially in old especially in old and historical mosques and sensitive parts in modern mosques like the Qibla wall. Such a treatment would be a prime solution which satisfy the architect and will result in acoustically successful treatment. Transparent Micro-perforated Acrylic Glass can be implemented in these kinds of "passive" treatment applications. Here below is shown a suggested configuration of the two layers Acrylic Glass with defined distances from each other and from the reflecting wall.

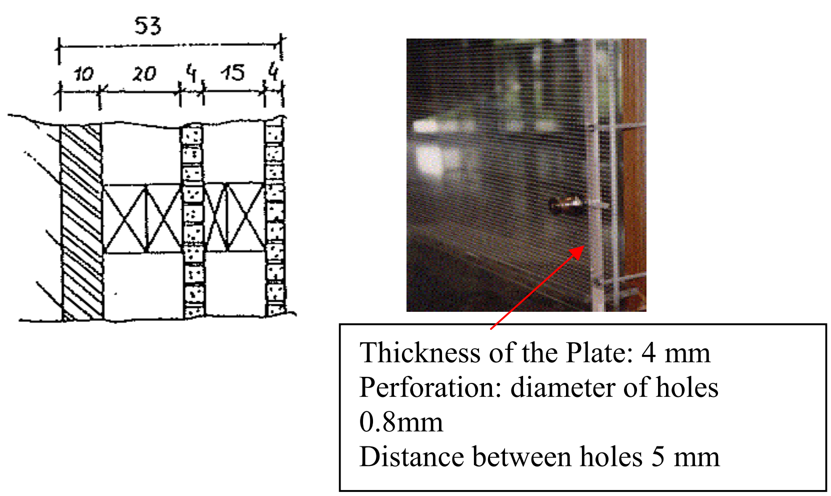



*Figure 83.The two layer glass along with its specifications.*

The absorption coefficients of the above shown configuration are shown in the following figure.

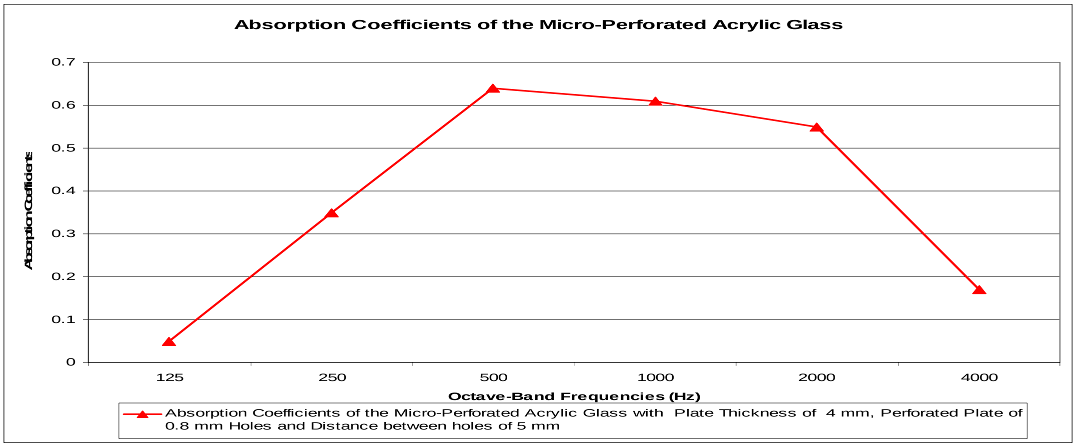



*Figure 84. Absorption Coefficients of the two layer Micro-perforated Acrylic Glass.*

Let us assume that the primordial Prophet Muhammad Mosque in Madinah shown in Chapter1 (Figure 7) is still standing until nowadays. A "Transparent Architectural" approach is suggested to take place in the renovation of the mosque. It was decided to adopt this approach in the renovation process to maintain the same ancient materials and architectural design of the mosque.

Now, the architect decides to implement glass surface above the court yard of the mosque. This decision was taken to give the chance of implementing an Air Condition system in the courtyard. Unintentionally, the overall sound intelligibility in the courtyard benefited from such a decision by reducing noise intrusion into the mosque. Also, late sound energy arrivals which cause reduction of overall intelligibility were prevented from penetrating to the courtyard.

The influence of transforming mosques from an open courtyard to a closed structure mosques on acoustical parameters must be taken into consideration. The increase in the Reverberation Time after implementing such a roof has to be treated acoustically. The Reverberation Time of the virtual mosque after constructing the roof is shown below.

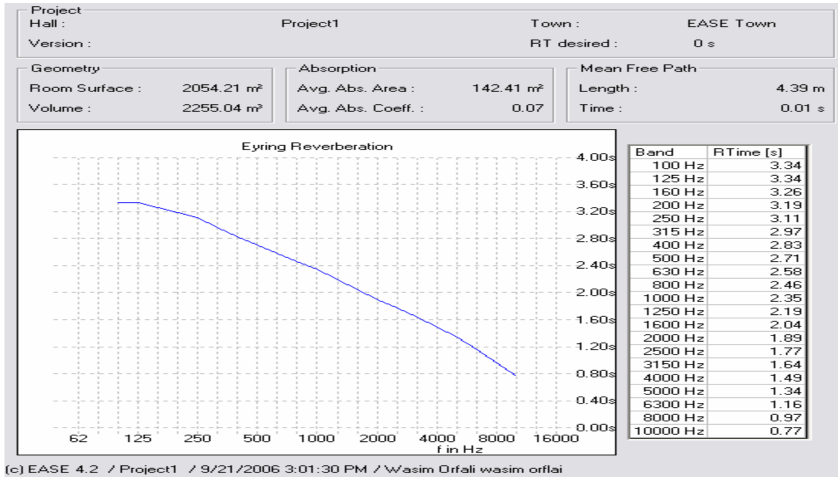



*Figure 85.RT of the Prophet Mosque before treatment of the glass roof*

The mosque volume is around 2200 m$^3$. The Recommended RT represented in Figure 74 for the same size mosque is around 1.2 s. It is quite clear from Figure 85 that the mosque need treatment to decrease its Reverberation Time to the recommended value. Different treatment approaches with one and double layer micro-perforated foil as a transparent treatment of the glass roof were implemented to the Glass roof to decrease the overall Reverberation Time. Below the Reverberation Time after treatment is shown.

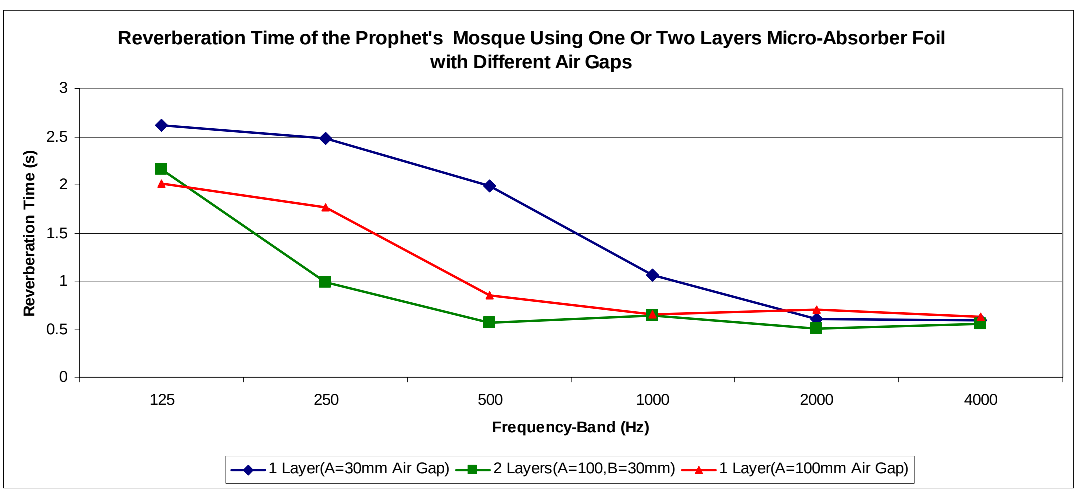



*Figure 86. Reverberation Time of the Prophet's Mosque using one or two layers of the Micro-Absorber Foil with different Air Gaps after treatments*

All of the three suggested treatments are within the acceptable RT values. As mentioned earlier the recommended RT for the same size mosque is around 1.2s. To stay within acceptable treatment cost a 1 layer with 30mm air gap will result in Reverberation Time of 1.1s at 1 kHz .

The implementation of the Sliding Domes or Glass Roof to decrease the intrusion of outside noise must be associated with a proper acoustical treatment to decrease the Reverberation Time. Fibre-Glass stuffed in the sliding domes with an air gap or micro perforated foil attached to a Glass Roof with a proper air gap are recommended to decrease Reverberation Time and to improve the overall intelligibility levels. If further acoustical improvements are needed, the carpet could be manipulated as suggested in chapter 3. Constructing Glass roofs on the top of a courtyard makes it possible to treat the floor, since by having a roof the floor is protected from weather impacts like rain, snow, etc.

### 5.1c.2: Closed Structures Mosques:

In mosques, treatments which involve manipulating the main internal design after it is finalized might be costly and require a lot of effort.It was shown in section 3.2a; how efficient is the carpet treatment compared to other surfaces treatments. Usually, carpet covers large portion of the total surface area of a mosque. Consequently, a small change in its absorption behavior will make a considerable difference in term of reducing the total Reverberation Time. Additionally, increasing the thickness of the carpet or adding an additional absorbing pad under the carpet to increase its absorbing behavior at low frequencies will make it more convenient for the worshippers setting and kneeing on the ground.

Two different kinds of carpet have shown an acceptable absorption results. Heavy Carpet on a thick pad (1.5cm rubber pad) and Carpet Pad on 1134 kg/m$^3$ FOAM RUBBER are the names of the two recommended carpets for their absorption behavior. The absorption coefficient of the two materials is shown below. The Heavy Carpet on thick pad has more absorption at the low end frequencies than the Carpet Pad and vice versa. The decision to select between the two carpet types depends on the required acoustical effect.

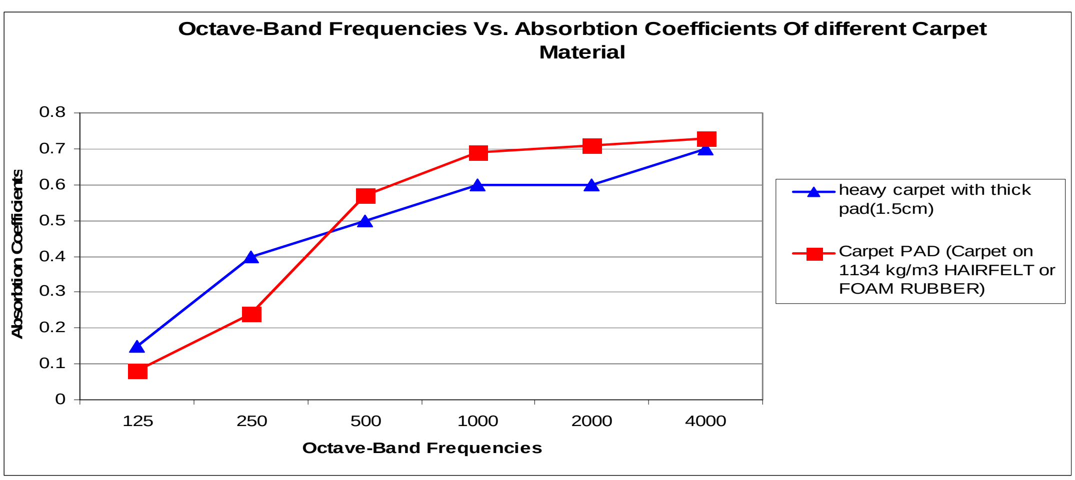



*Figure 87. Absorption Coefficients of two recommended carpet material*

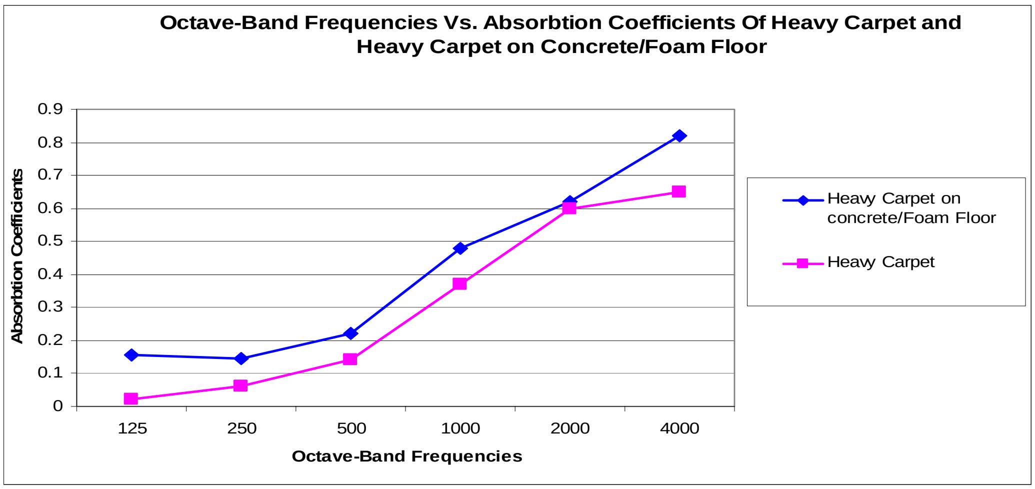
The benefit of concentrating the acoustical treatment on the floor surface by adopting an appropriate carpet or padding material under the carpet was investigated in section 3.2. In this section a recommended carpet and padding material were pointed out. In some occasions the architect rejects even treatments under the carpet surface. Although, this treatment is very efficient and dramatically decreases the need for further treatments of other visible walls, sometimes it fails to satisfy the architect. The reasons behind this decision are different. Some of them think that such a material is beyond the acoustical treatment budget and some others find it inappropriate and do not fit the general outlook of the mosque's interior. In this case some sort of other solution should be developed.

Usually, the surface under the carpet in any mosque is a hard reflective concrete. This concrete surface is formed from cement powder, sand and water. Sometimes, it is mixed with fine particles of stones to increase its stiffness. For acoustical purposes, a high percentage of white foam bubbles to concrete ratio can be adopted as a new concrete mixture. This light-weight structure is demonstrated in the following figures during production. Also, a cross-section view of the final concrete/foam bubbles surface is shown.

*Figure 88. cross-section view of the final concrete/foam bubbles surfaceand the light-weight structure during production*

The resulting mixture of concrete and foam bubbles is more absorptive compared to the concrete mixture only. The absorption behaviour of this concrete/foam bubbles surface was measured using an impedance tube in the TU Berlin lab. The following figure shows the absorption coefficients of such material at different Frequency-Bands and material placed inside an impedance tube.

(a)




(b)

*Figure 89.(a) Concrete/foam bubbles with and without the carpet inside the impedance tube(b)absorption coefficients of the heavy Carpet and heavy carpet on a concrete/Foam floor*

The addition of the white bubbles foam to the concrete under the carpet adds to the total absorption of the mosque's floor. It will allow a certain amount of air to be located underneath the carpet; accordingly, more absorption will be added to the low end frequencies. Even though the increment is small it will make a different since the total surface area of the floor in any mosque is large. If bigger size bubbles are used more air will be placed underneath the carpet what makes it more absorptive at the lower frequencies.

In this chapter we have started by introducing new acoustical quality parameters quantities in mosques. Reverberation Time, ALcons%, STI and C50stat figures were established for the first time to govern the acoustical environment in such structures.

Also, newly constructed mosques acoustical rules were recommended to avoid complexity in mosques acoustical behaviour. The elimination of roof supporting columns by constructing central dome with an appropriate relationship between the focusing height and the speaker's height to prevent focusing or by adopting other architectural techniques was stressed. If the existence of columns is a necessity, 4 in 1 columns design must be adopted as was discussed in chapter 3. All kinds of concaved surfaces and conveyed faces must be avoided as well as wall Ornaments must me adopted in the existence of parallel walls to decrease the risk of Flutter Echoes occurrence. The existence of only one well defied praying hall without lowered surfaces proved to be in favoured of establishing a good acoustical environment inside a mosque, since eliminating lower surfaces will be associated with removing the columns supporting them.

Big units of Air conditioning systems placed in main praying halls have increased the Background Noise level. It was suggested to locate all the air conditioning units in a separate eliminated and acoustically isolated Technical Room. There are a lot of acoustical isolation standards for such rooms which can be adopted.

Designing a mosque with an open courtyard is usually accompanied with complexity inside the courtyard. Contemporary covering methods like Transparent Sliding Glass Domes and Light Weight Structured Sliding Domes have been introduced along with proper effective acoustical solutions. The pros and cons of electrically controlled umbrellas which do not have a considerable influence on the acoustical environment when placed in the courtyard were presented. Treatment of the courtyard walls can be associated with the implementation of the controlled umbrellas with Transparent Micro-perforated Acrylic Glass; this was shown to be effective and suitable in mosques applications.

In closed structure mosques, treatment of the carpet floor compared to other surfaces was proven to be more efficient while the carpet covers large portion of the total surface area of a mosque. Also, it is more practical in a sense that it does not required deformation of important wall figures and characteristics. Manipulating the absorption of the carpet by increasing its thickness or adding an additional layer underneath it will make it more convenient for the worshippers sitting or kneeing on the floor. Two different materials have been recommended for the treatment of the carpet. A Heavy Carpet on thick pad (1.5cm rubber pad) and Carpet Pad on 1134 g/m3 FOAM RUBBER did show considerable beneficial results especially at low frequencies.

Another floor surface treatments alternative was discussed. When the floor treatment using thick carpet or padding material under the carpet are rejected such a treatment can be considered. A mixture of concrete and foam bubbles was introduced to be used as sound absorber. This mixture is very light in weight and has a considerable positive acoustical behaviour.

# Chapter 6

## 6.1: Modern Sound Systems:

### 6.1a: Introduction:

A **S**ound **R**einforcement **S**ystem **(SRS)** is an Electro-Acoustic system which can be used to reproduce an amplified version of the original sound produced by a human speaker. As a result, distant individuals from the original source may hear an audible and understandable sound.

Configurations of most of sound systems implemented today in mosques are similar. Three microphones, a modestly-powered mixer-amplifier (which incorporates a mixer and an amplifier in a single unit) and several loudspeakers are the main parts. As in the most basic sound reinforcement system, the Imam sound is picked up by a microphone, the sound signal is boosted using an amplifier and then reproduced by a loudspeaker enclosure.

Larger sound Systems can have dozens of distributed speakers throughout the entire worshipping area in a mosque to reinforce and propagate the Imam voice. In such a situation, it is necessary to choose the right place of the used speakers to avoid problems like feedback and phase cancellations and to ensure good sound quality with minimum number of speakers. Sound Reinforcement Systems need to be designed and installed by an experienced audio engineer, who will be able reduce the risks inherited in the use of such a big system.

Modern sound systems can decrease (but not completely eliminate) the interaction between the architectural design of a mosque and the sound quality radiated from the installed speakers. Acoustical problems like focusing and low intelligibility levels can be improved by using an appropriate sound system, but some sort of "Passive Treatment" is also needed to improve the overall acoustical environment. "Active treatment" solution includes installing good sound systems and it can minimize the need of "passive treatment". Hence, a good sound system can reduce the cost of the expensive passive treatment involving manipulation of a mosque interior design.

Chapter 4 has discussed the used sound systems in mosques today. In this chapter we will talk about how a mosque's sound system should be? Also, different loudspeakers columns manufactures along with different programming algorithms like*"Beam Controlled Sound Radiation"* and "*Predefined listener area Method"* will be introduced.

## 6.1b: Conclusion from Existing Sound System (Current Condition):

All the surveyed mosques presented in chapter 4 and the visited mosques used distributed sound system in their design. Even though, some of these mosques were small and built without roof supporting columns, a distributed sound system approach were adopted. Such small mosques with no columns can be handled electro-acoustically with one or two loudspeaker columns as was demonstrated in chapter 4. Furthermore, the choice of the used speakers in the distributed system was not successful. In particular, small size loudspeakers, which have a weak maximum output Sound Pressure Level (SPLmax), were widely used. Such speakers have almost omni-directional characteristics which imply lower intelligibility levels in contrast to more directed speakers toward the worshippers. In other visited mosques, a number of omni-directional loudspeakers were installed. These speakers have almost unity directivity ratio which means wasting energy by radiating it into the roof and unwanted wall part instead of focusing it toward the worshippers. This unwanted radiation might, also, enable other problems like focusing from the domed roof and Flutter-Echoes from side walls.

In the next sections, more appropriate sound system solutions will be discussed. The use of advanced loudspeaker columns in mosque applications will be introduced. Loudspeaker columns controlled with programming software should be implemented to optimise their behaviour in mosques with a more sophisticated worshipping area plan. A combination of centralized and decentralized sound systems in a mosque could, also, be used to cover areas under the dome and areas under the balconies respectively.

## 6.1c: Appropriate Sound System Solutions:

### 6.1c.1: Introduction:

It is important to introduce the available solution before choosing the most acceptable one. Prior to introduce the most appreciated sound system solution in mosques, we will introduce all types of sound sources starting from an ordinary Directed Point Source to the most advanced programmable Digital Loudspeaker Columns.

First, most of the speaker designs used in mosques is made in horn-like shape. From here such a radiator became to be known as horn radiator. Because of its high sensitivity and directional characteristics, this radiators design are very suitable for sound systems in big auditoriums where desirable frequency range and different coverage areas requires the use of different types of such horns. For some technical reasons such horns could not be build in one broadband item. A better solution is to use several horns for mid and high frequencies range and a woofer for low frequency in order to have a complete broadband solution in form of multi-way system. In Mosques such an arrangement is not in favour of the internal design, since it involves a lot of cabling effort. Also, its fixed directional features do not make it possible to address the different worshipping modes in mosques.

Another possible arrangements are the Conventional Classical columns, the "passive Columns" or Loudspeaker Array In-line Arrangement of Radiators. Just like in mosques, many tasks of sound reinforcement systems requires radiators that are capable of producing a high sound level at large distances from their point of installation, while minimally affecting microphones located closer to them. Consequently, they must produce a determined directional characteristic and directivity. The right type of sound sources fulfilling these requirements would be stacked arrangement of in-phase identical loudspeakers or Sound Columns. The elements of this column are only attached physically but not electronically, as we will see later in a more advanced type. Such an arrangement is shown in the following figure.

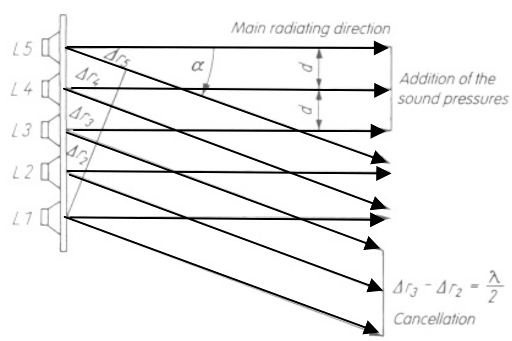



*Figure 90. Arrangement of classical columns*

As we can see in the plane perpendicular to the loudspeakers arrangements, there occurs a pressure addition above and pressure cancellation below due to different run time phase summation from different loudspeakers. Each of the individual loudspeakers radiates the sound spherically and the sound waves get favorably superimposed in the far field, whereas the effect of the individual loudspeaker prevails in the near field. For the far field the following equation was given by Stenzel and Olson already in 1927 for the angular directivity ratio Γ [21,22,23],

where
$$\Gamma = \frac{\sin\left[\frac{n\pi d}{\lambda}\sin\alpha\right]}{n\sin\left[\frac{\pi d}{\lambda}\sin\alpha\right]} \quad ....(22)$$

$n$ = number of individual loudspeakers
$d$ = spacing of the individual loudspeakers
$\alpha$ = radiation angle
$\lambda$ = wave length of sound
$l = (n\text{-}1)\ d$ = length of the loudspeaker line

Each column has a critical frequency (wavelength equals the spacing of the loudspeakers) where above this frequency, secondary maximum occurs (side lobs). The disadvantages of this arrangement are:

- Only below the critical frequency the desired directional behavior is obtained, whereas above that frequency some side lobs occur.
- The directivity is frequency-dependent (front-to-random factor $\gamma$ of the main maximum ≈ **5,8 l f** [24])
- The directivity increase does not only occur in the "directivity domain", but also, owing to the distances of the individual loudspeakers, in the "scattering domain", so the column is loosing directivity at high frequencies

Even though, these columns had these drawbacks, they are still been used in important mosques like the Holy Haram in Makkah. Mosques where such “Passive columns" are used should be acoustically revaluated and more new advanced Sound columns must be considered.

All these frequency-dependant properties of the loudspeaker lines involve the possibility for timbre changes to occur over the width and depth of the covered Structure. In order to eliminate or limit this drawback, the lines are often subdivided in the upper frequency range. This is done either by "buckling" the line "banana-like" or by making the alignment of elements of the line deviate by maximally 10° to the right and the left.

A more advanced and modern concept called “Modern Line Arrays” is introduced here. They are consisting of linear arrangement of wave-guides instead of individual horn loudspeakers. Compared to the traditional columns introduced before, they radiate sound in cylindrical manner in the near field (3dB reduction of sound level per doubling the distance). This near field behaviour is frequency dependant and governed by the following relation

$$r = \frac{l^2}{2\lambda} \quad ....(23)$$

$r$= limit of the near field region in meter
$\lambda$ = wave length of sound
$l$ = length of the line array in meter

Beyond this range the sound source is seen as a spherical source (6dB reduction of sound level per doubling the distance). This way it is possible to cover large distances with high sound levels and without having to use delay towers. The following figure shows an example of such arrays.

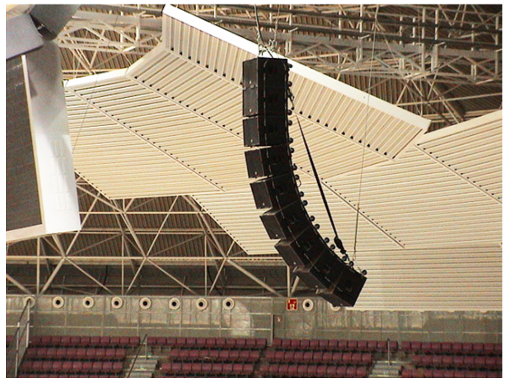


*Figure 91 An example of an VerTec Line array from JBL professional Inc.*

These modern arrays might not be a practical solution in Closed Structures Mosques, since it is big and heavy in size. They might block important figures like the Mihrab or the Minbar. So, their integration into the internal design of mosques may not be possible and remains difficult even in courtyard mosques. Such big arrays might be useful for outdoor applications like being installed on the Minarets to cover remote areas. Also, it can be installed around a particular state mosque as delayed towers at lower height compare to the Minarets height to cover the worshippers gathering around the mosque in big and important congregational prayers. An example of similar gathering is the annual gathering for praying of more than 1 million worshippers in pilgrimage ceremonies near "Rahma Mountain" in "Niamirah Mosque" Makkah, Saudi Arabia, See the following figure.

*Figure 92 Namirah Mosque in Makkah*

For Indoor applications and taking into consideration the sound system integration to the internal design of a mosque "Digitally Controlled Line Arrays" should be used. These lines arrays have been used in sound system optimisation examples in previous chapters as the most appreciated solution. It uses a "Beam controlled sound radiation Method" to control digitally the radiation behaviour of a loudspeaker. [25,26] This way the dependency of the sound quality inside a mosque on the architectural design can be decreased. Adopting such an approach will make it possible to avoid many acoustical problems related to the architectural design. This is achieved by concentrating the sound energy directly toward the audience and decreasing roof and side wall reflections. Different loudspeakers arrays in form of stacked small woofers (Intellivox[27], Iconyx[28], Messenger[29], EWA[30]) have been developed by different manufactures to demonstrate this approach. These manufactures use different programming algorithms to fully control the directivity behaviour of each loudspeaker.

Using "*Beam Controlled Sound Radiation*" approach, loudspeaker arrays show a strong, almost frequency independent, directional behaviour. This results in uniform audience coverage, even over very long distances. Depending on the needed coverage, the beam is adjusted to fulfil certain coverage requirements. The far field directivity pattern can be controlled by a number of beam parameters: "opening angle", "elevation angle" and "focus distance". So, the "throw" and the aiming of the beam can be changed electronically, i.e., without any mechanical adjustment of the array. Also, strong second maximal" side loops" at higher frequencies will be prevented. Here the length of the loudspeaker lines is reduced with increasing frequency by electronic means (by switching on/off the filters associated with each individual cone speakers in the column. Also, a constant Sound Pressure Level Distribution will be evident, while the interference effects in the listening plane are strongly eliminated. The outcome of this Beam control method will be a remarkable directivity in the vertical domain and constant sound pressure level in the horizontal domain.

In a more complicated layout of the worshipper area, the previously mentioned method may not be the most favourable. Moreover, using the previous method certain sound level distributions can be obtained only after several corrections. A solution which requires less designing effort could be provided by using the " Predefined listener area Method" which produces an adaptable directivity pattern to the audience area. Also, it produces a uniform SPL distribution in complex shaped audience areas. It is worth mentioning that the sound pressure level of both methods decreases in the near range by only 3dB with distance doubling as a cylindrical radiator, and begins to decrease like those of spherical radiators only beyond the near range.

It is an advanced, versatile array control optimisation concept. Using the "Predefined listener area Method", any desired 3D radiation pattern could be synthesized within the physical constraints of a pre-defined array (e.g. transducer distance, array length etc.). Starting from a desired direct SPL distribution in a mosque, the optimum output filter for each array channel is calculated. In other words, the desired coverage of the hall or space is 'mapped' back' to the array, instead of mapping the array response to the hall. Note that the physical array configuration itself is not optimised using this method [26]. Using proper software the output filters can be uploaded to the on-board DSP hardware, which takes care of the real-time signal processing. A part from the DSP, each array unit is equipped with a micro controller that takes care of all the surveillance routines, DSP management, storage and logging and network functionality.

In contrast to churches, the hearing plane height in mosques is not fixed. For a worshipper seated on the floor the hearing plane height is 0.85m while it is 1.75m for standing worshippers. This is considered as an issue especially when using loudspeaker columns. The height of the acoustical centre of a loudspeaker column is considered one of the key design issues. Vertical Elevation of the acoustical centre should be between 0.5 to 1m above the worshippers hearing plane. Since the worshipping modes change, the hearing plane height changes accordingly. Consequently, the acoustical centre of loudspeaker columns must change to keep the distance between the acoustical centre and the worshippers hearing plane fixed.

Designing one mosque with different sound systems to address the different praying modes in mosques may not be very practical and at the same time expensive. So, programming the loudspeaker columns with a simple switching key is important in order to change their acoustical centre as the worshipping modes change between preaching and praying.

In term of size, mosques are ranging between small size, mid-size and big mosques. Sound systems for small size mosques (< 3000 $m^3$) can be done using one loudspeaker array at the centre of the Qibla wall as was proposed in Al-Eman mosque in Chapter 4 Figure 70. The approach in bigger Mosques should be different. Here, the size and design of bigger mosques requires more loudspeaker array with a proper delay time to cover the extended audience area evenly. The designing task is easier in the absence of roof supporting columns especially in the main hall. In such a case, one loudspeakers array (but not in wide rectangular mosque) with appropriate size installed in the Qibla wall can be used to cover the main hall depending on their horizontal coverage.

In rectangular mosques where the horizontal coverage of one loudspeaker column is not sufficient to cover worshipper in the far left/right corner, more loudspeaker arrays installed in the Qibla wall should be considered. Under the lowered surface where a number of columns exist, distributed sound system can be used to cover shadowed areas behind the columns. Let us consider different general layouts of mosques. Here below are shown typical designs of mosques.

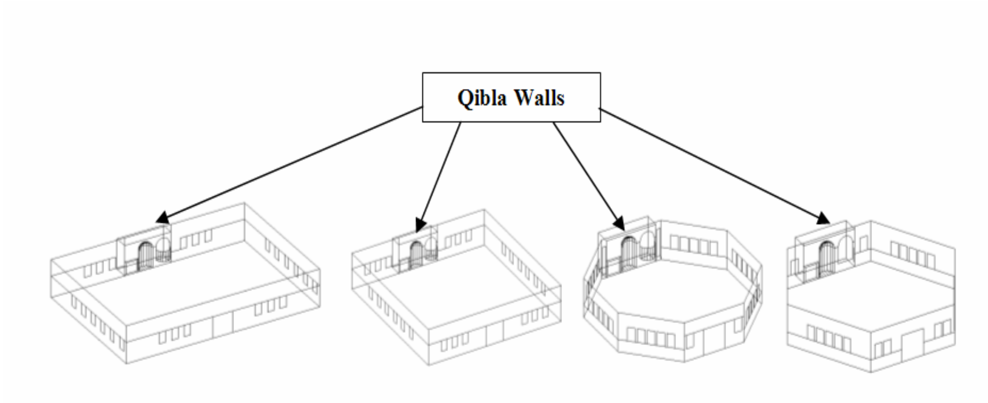



*Figure 93. Different General layouts of Mosques*

All the four different layouts were designed to have the same volume. It was found that the Qibla wall of the rectangular and the square mosques need more installed loudspeaker arrays at the far right/left sides of the Qibla wall to cover the worshipper located in the far left/right locations. Below, mosques are divided upon their volumes to Small, Middle and Big (prestigious) size Mosques. In Small Mosques, different basic and advanced design approaches will be introduced in a chosen mosque's layout. Afterwards, the most successful and advanced design approach will be used in the Middle and Big size mosques to show its potentials.

### 6.1c.2: Small mosques:

Small mosques (< 3000 $m^3$) designs have rectangle, square, hexagon and octagon shapes. The existences of roof supporting columns are seldom according to their modest dimensions and the existence of domes. Accordingly, the design of their sound systems should not be difficult. One loudspeaker column with proper length should be enough to cover the whole worshipper area evenly. Let us consider a basic rectangular mosque layout for the purpose of our investigation for the most appropriate sound system since it is the widely chosen layout. Here, a single loudspeaker, distributed loudspeaker, Classical Columns and Digitally Controlled Columns (which uses *Beam Controlled Sound Radiation* and *Predefined listener area Method)* will be implemented once at the time for the same rectangular mosque to justify the different pro and Cons presented before. In chapter 4 a brief comparison between omni-directional source and Digitally Controlled Columns has been performed. Here, more intensive investigation for all possible solution is considered.

The following figure shows the mapped audience area of a small rectangular shoebox model generated using one single loudspeaker (94a) and distributed loudspeaker (94b) as first basic approaches. The direct SPL and STI of each system were simulated at 1 KHz where the RT is 1.75s. The direct SPL and STI of each sound system will be compared afterwards with the more advanced solution results (using Classical Columns and Digitally Controlled Columns) for the same area.

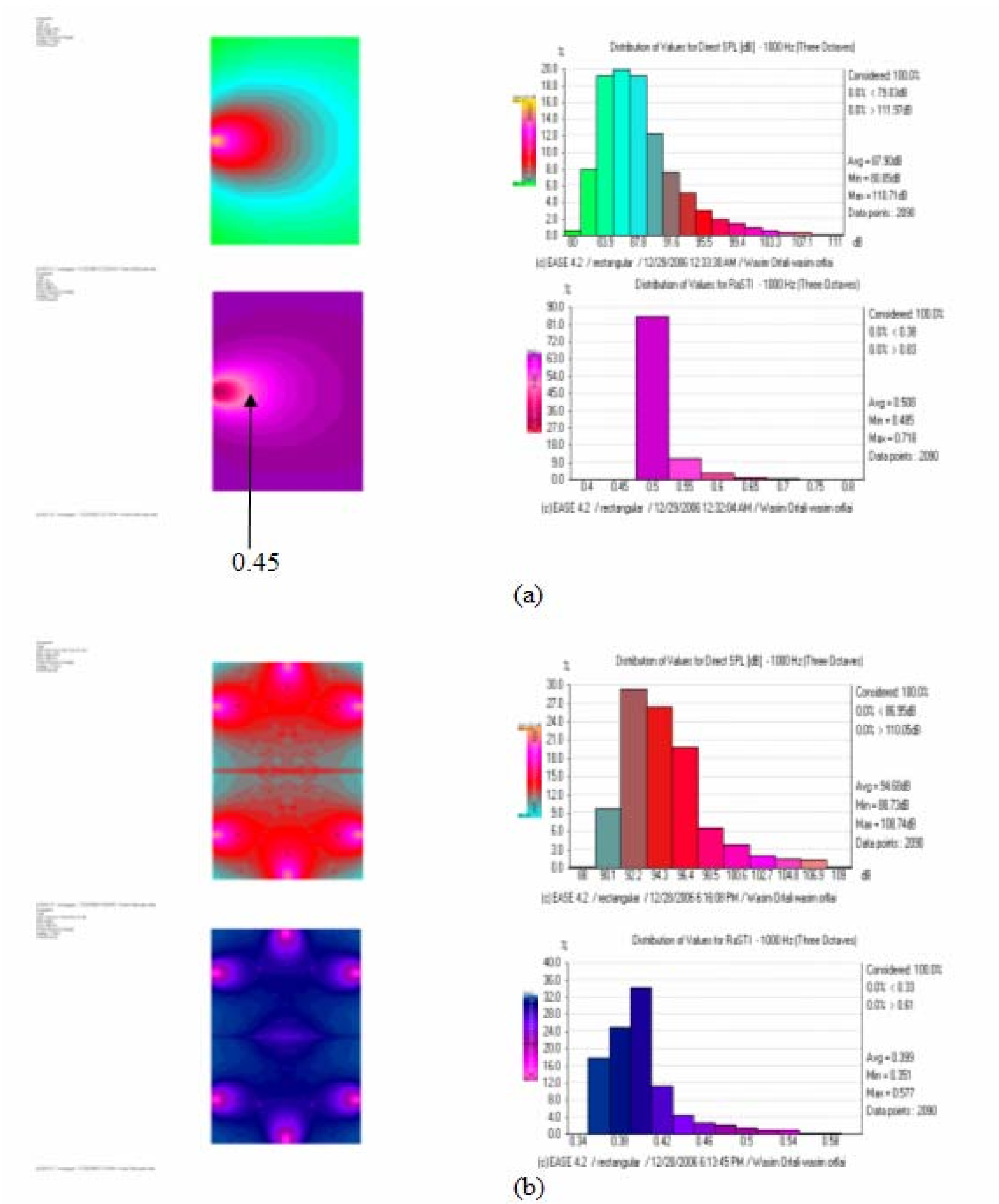
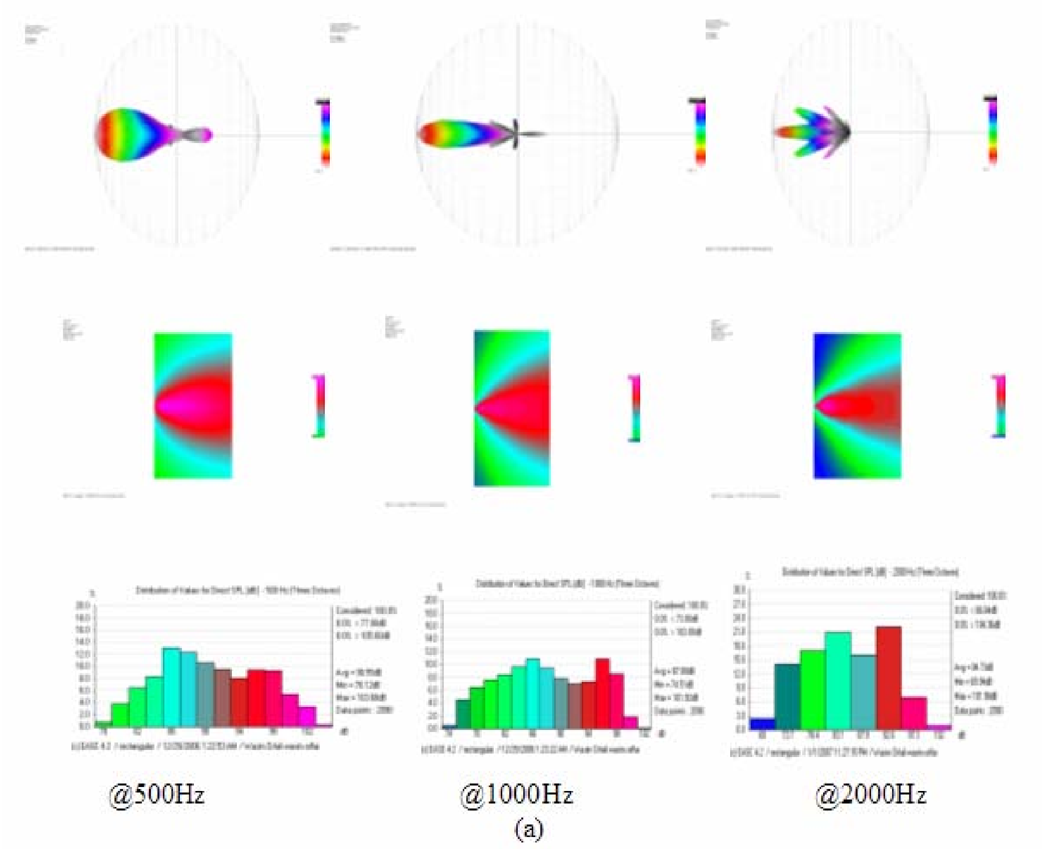



*Figure 94. The direct SPL and STI using (a) 1 signal loudspeaker (b) distributed Sound system*

By comparing Figures 94a and 94b, it is clear that by adding extra loudspeakers, higher level of Direct SPL covering the worshippers at almost all locations can be noticed compared to the simulated mapping results using only one loudspeaker. On the other hand, the STI was decreased to lower numbers according to late sound energy arriving from all the different loudspeakers at a given location in front of a single loudspeaker. The loudspeaker used in this simulation has almost omni-directional behaviour over all frequencies of interest which implies less directivity and intelligibility values, see chapter 4. Figure 67 shows the directivity balloons of the used speaker at different frequencies.

To produce more direct sound toward the worshippers and to become independent from the architectural design, ordinary woofers stacked above each other known as “classical columns” were introduced, see Figure 90. The column behaves as a cylindrical source in the near field and as spherical source in the far field. The behaviour transition from cylindrical source to spherical source is marked by the critical distance, see equation 23.

Below, we will use such a classical column in the same mosque to study its behaviour and compare it to the previous and subsequent systems set-ups. The mapping results of four different loudspeakers used to form a classical column and placed in the centre of the Qibla wall are shown below. Such column might not be ideal to be used as a sound system design in this mosque. This design was used here to investigate its behaviour only.



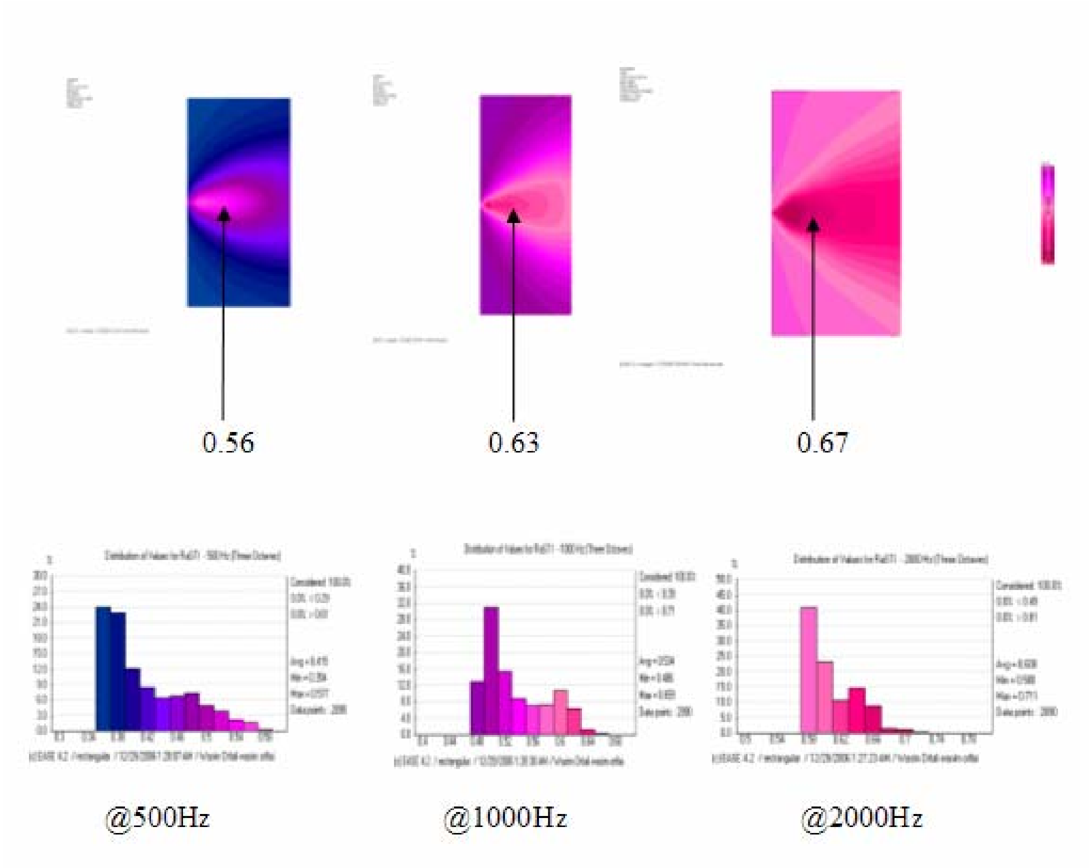



*Figure 95. The direct SPL and Directivity Balloon (a) and STI(b) using Classical Columns consist of 4 Community Horns PC164-280 at 500,1000,4000 Hz*

By looking at Direct SPL mapping presented in the previous figure, one can note that as the frequency increases, the classical column is more directed and more energy is transmitted in front of the column as compared to other directions, refer to equation 22. At lower frequencies, the column has more omni-directional behaviour but it is still more directed than a single source. If we compare the STI values at a distance of 6m (less than critical distance of 8m) from the main axis of the single loudspeaker and the classical column at 1 KHz, we find it to be 0.45 and 0.63 respectively.

Making sound columns directivity less dependent on the frequency became an important issue in the last 10 years. Couple of speaker manufactures have introduced new digital loudspeakers columns. These columns have comparable directivity radiation at different frequencies of interest. They maintain the same radiation pattern by changing electronically the physical length of the loudspeaker depending on the frequency. Below, the directivity balloons of such loudspeakers columns at different frequencies are shown

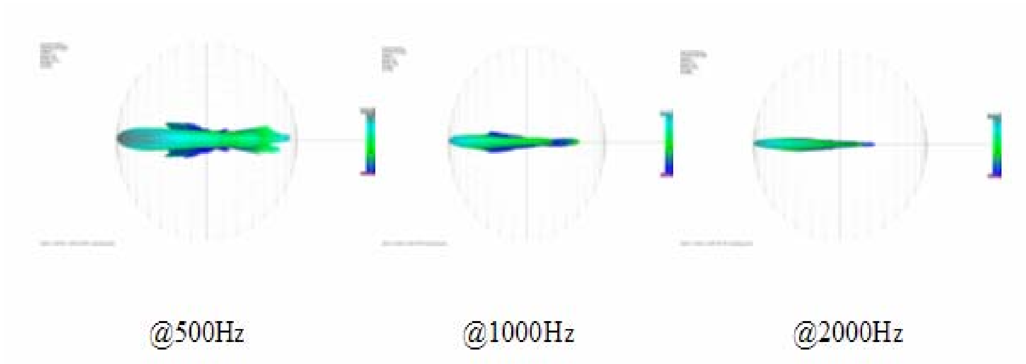
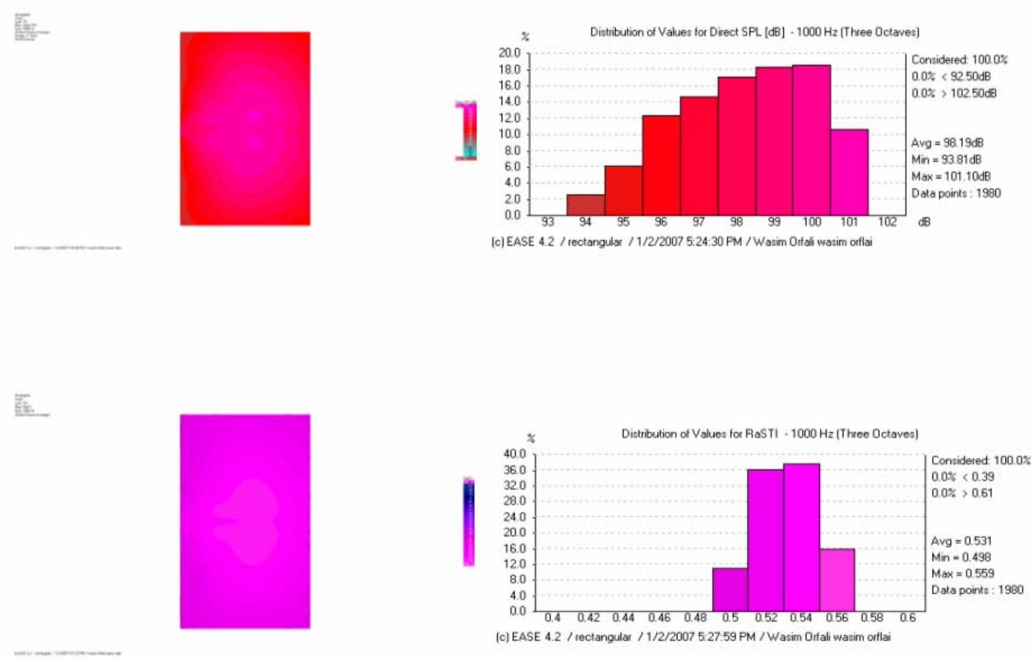



*Figure 96.The directivity Balloon of a loudspeaker column at different frequencies*

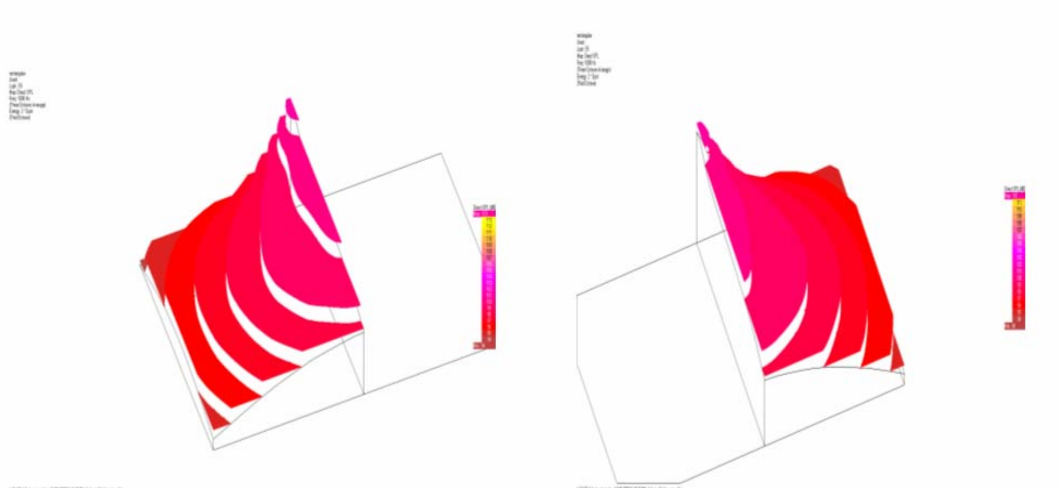
By comparing the directivity balloons of the above figure to the directivity balloon of classical columns, Figure 95a, the advantage of the digital columns will be clear. Suppressing side loops and having a constant directivity balloon at different frequencies are accomplished with the new loudspeakers columns.

A computer simulation was run for the same audience area presented before using the Digital controlled sound columns using "*Beam Controlled Sound Radiation"* and "*Predefined listener area Method"* as different design approaches or techniques.

Below is a rectangular small size mosque designed with one loudspeaker column using "*Beam Controlled Sound Radiation*" are shown. First, the mapping results for this mosque were simulated in order to compare it with the previous results presented in Figure 94, 95. In Figure 97b, the mapping results were conducted for two different praying modes, which imply two different listening plane heights. Praying Mode at height of 1.75m and Preaching at 1.4m. At both levels the results were comparable, since the acoustical centre was adjusted.




**(a)**



*Mapping at 0.85m (seated worshippers)*      *Mapping at 1.75m (standing worshippers)*

**(b)**

*Figure 97.(a) Direct sound mapping and STI for rectangular small size mosque(b) Direct sound mapping at 0.85m (seated worshippers) and source acoustical centre at 1.4m and listening plane at 1.75m (standing worshippers) and source acoustical centre at 2.3m for different layouts having the same surface area 500 m2*

In small mosques (<3000m$^3$ and >1500m$^2$), one mid-size loudspeaker column (IntelliVox2c or IC24 from Renkus-Heinz or Hacousta IIL loudspeaker column) can be installed in the middle of the Qibla wall with a opening angle of 8°, Elevation angle -1.5° and Focused distance of 22m to cover the worshipping area evenly. Since the listening plane height inside a mosque changes as the worshipping modes changes, the acoustical centre height of the loudspeaker column has to be changed accordingly. In praying modes (standing worshippers) the listening plane is at 1.75m and the acoustical centre of the loudspeaker must be at 2.3m from the ground. This is represented by the mapping results in the right hand side of Figure 97(b).

In the preaching mode (Ground seated worshippers) the parameters of the loudspeaker column should be changed consequently. The acoustical centre has to be lowered to **1.4m.** The Opening angle of 8° can be held the same since the geometry is kept unchanged. Also, the Elevation angle of -1.5° ((-) means it is steered downward) must not be changed while the listening plane height to the acoustical centre is kept constant (0.55m). The equation which calculates the Elevation angle **(α)** with respect to the Focus point at the height of the **li**stening plane (**$Z_{li}$**), the height of the Acoustical **C**entre (**$Z_c$**) and the **Foc**us Distance (**$D_{FOC}$**) is presented below.(the bolded letters refer to the abbreviation meaning)

$$\alpha = \arctan\left(\frac{Z_{li} - Z_c}{D_{FOC}}\right) \quad ....(24)$$

The following figure demonstrates the quantities presented above.

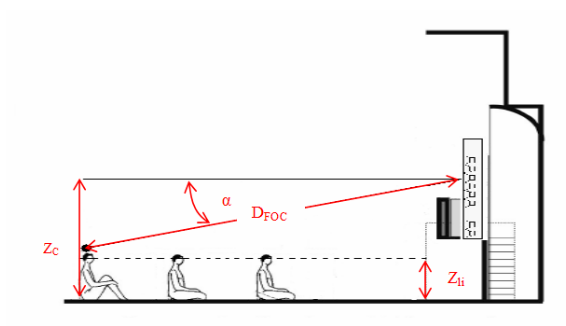



*Figure 98 .Demonstrations of α, Zli, Zc, DFOC*

In a praying mode $Z_{li}$ =1.75m, $Z_c$=2.3m, $D_{FOC}$=21m, therefore the Elevation angle is -1.5°. Also, in the preaching mode $Z_{li}$ =0.85m, $Z_c$=1.4m, $D_{FOC}$=21m, the Elevation angle is, also, -1.5°.

Once the mode is been switched from Praying to Preaching Mode, the above mentioned characteristics of the loudspeaker column can be kept the same but the acoustical centre must be changed from 2.3m in the praying mode to 1.4m. Changing the acoustical centre height must be trouble-free and not complicated for people normally not operating sound systems and should be conducted with a simple switching system. The previous results were acquired after multiple adjustments for the column's parameters. This approach can be time consuming in a more complicated worshipping area. Therefore, *"Predefined listener area Method"* should be considered to simplify the designing procedure. Below, the desired mapping results will be uploaded to the Programmable loudspeaker column in order to get the desired optimised radiation

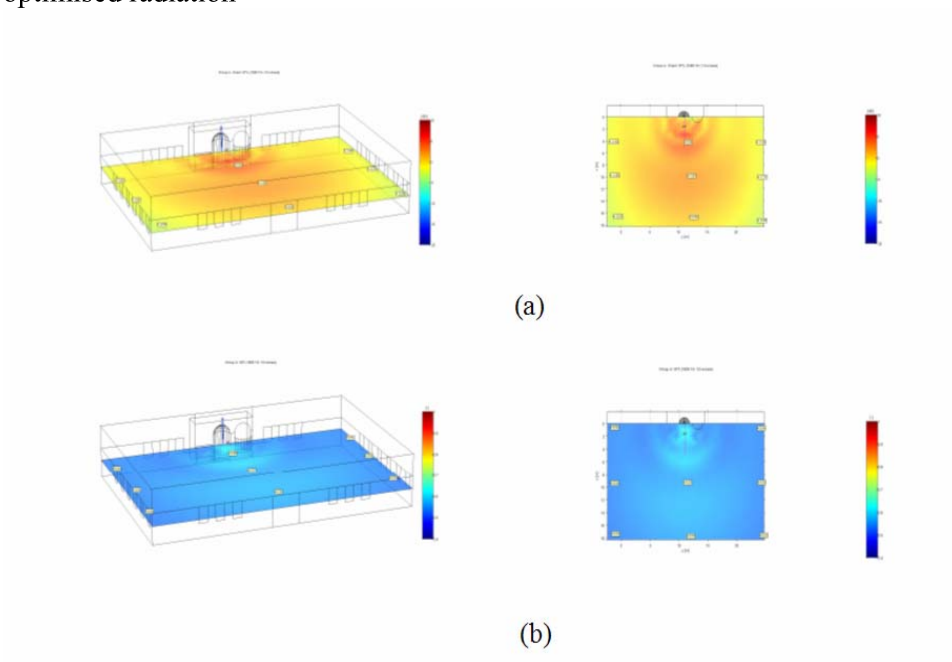


*Figure 99.Mapping Using "Predefined listener area Method" approach at 1 KHz using (a)The direct SPL (b) STI at 1 KHz using "Predefined listener area Method" approach.*

The optimum desired radiation of the loudspeakers was obtained with a simple approach. Compared to "*Beam Controlled Sound Radiation*", no adjustments for Elevation angle, Opening angle and Focus distance are required now. STI values between 0.55 and 0.65 were achieved and Direct SPL of 90dB with ±2dB variation was obtained. The desired radiation result depends on size of the audience area, mounting position and aiming of the array.

In the next parts only the optimum solution results concerning Digital Loudspeakers Columns will be provided. An experienced designer can use "*Beam Controlled Sound Radiation*" approach to design a mosque and still obtains very similar results as one obtains using "*Predefined listener area Method"* approach.

### 6.1c.3: Mid-Size mosques:

The rectangular shape dominates the major layout of Mid-Size mosques. They have a size between 3000m$^3$ and 6000m$^3$. The existence of lowered (Lowered surface are the area under the women praying area) surfaces and roof supporting columns in the main structure and under the lower surface are usually evident. In medium size rectangular mosque, the worshippers in the far left and right are difficult to be covered by one loudspeaker column. An adequate number of loudspeakers columns installed only in the Qibla wall should be sufficient. An example of rectangular mosque designed with columns in the main hall under the lowered ceiling is shown below. In this example, loudspeaker column designs from different manufacturers will be compared.

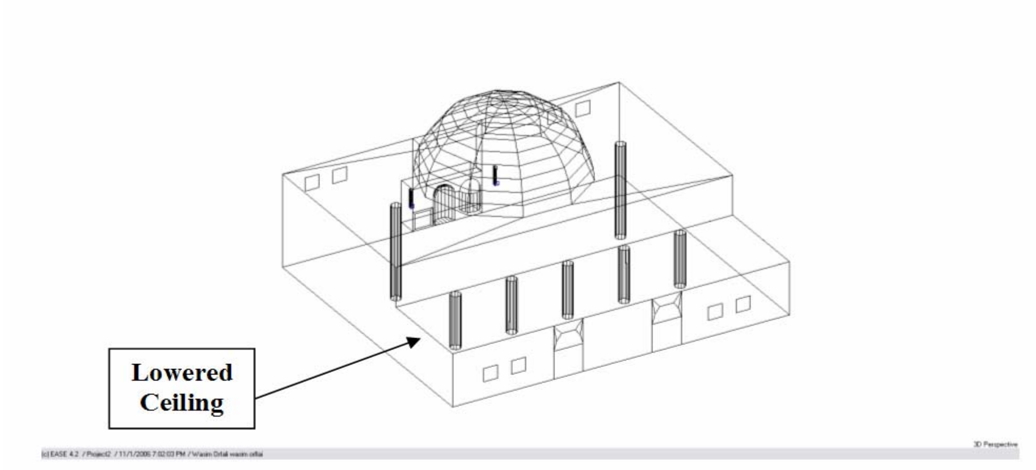
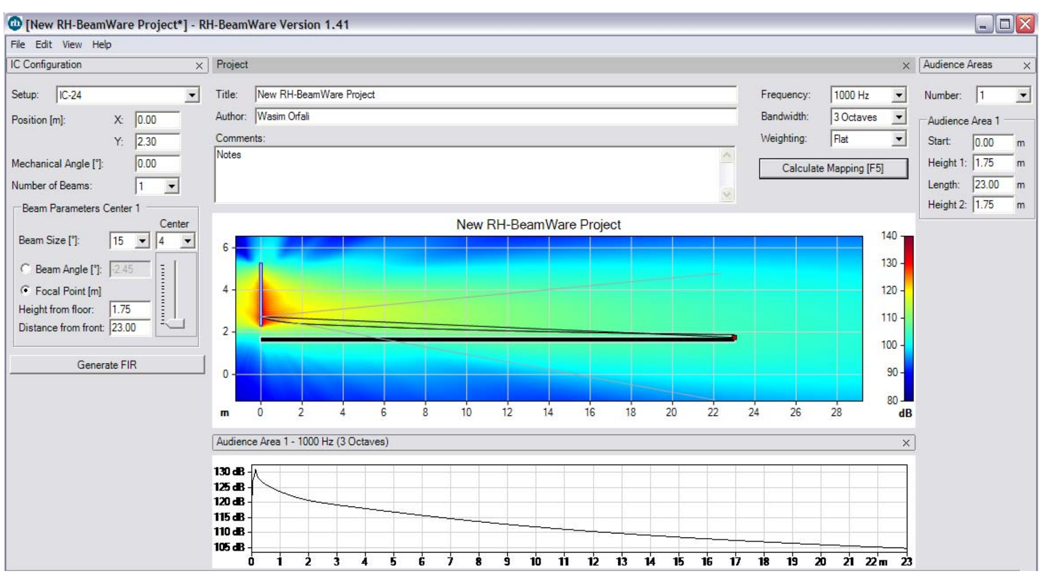



*Figure 100. Rectangular Mosque Modelled in EASE*

In our example the mosque's volume is approximately 5600m$^3$ with an audience surface area of 700m$^2$. Using four Mid-size loudspeaker columns, the desired STI at 1 KHz was obtained and the mapping result is shown below. Also, the result of adjusting the internal characteristics of the loudspeakers columns using the especial controlling programme is shown below.




(a)

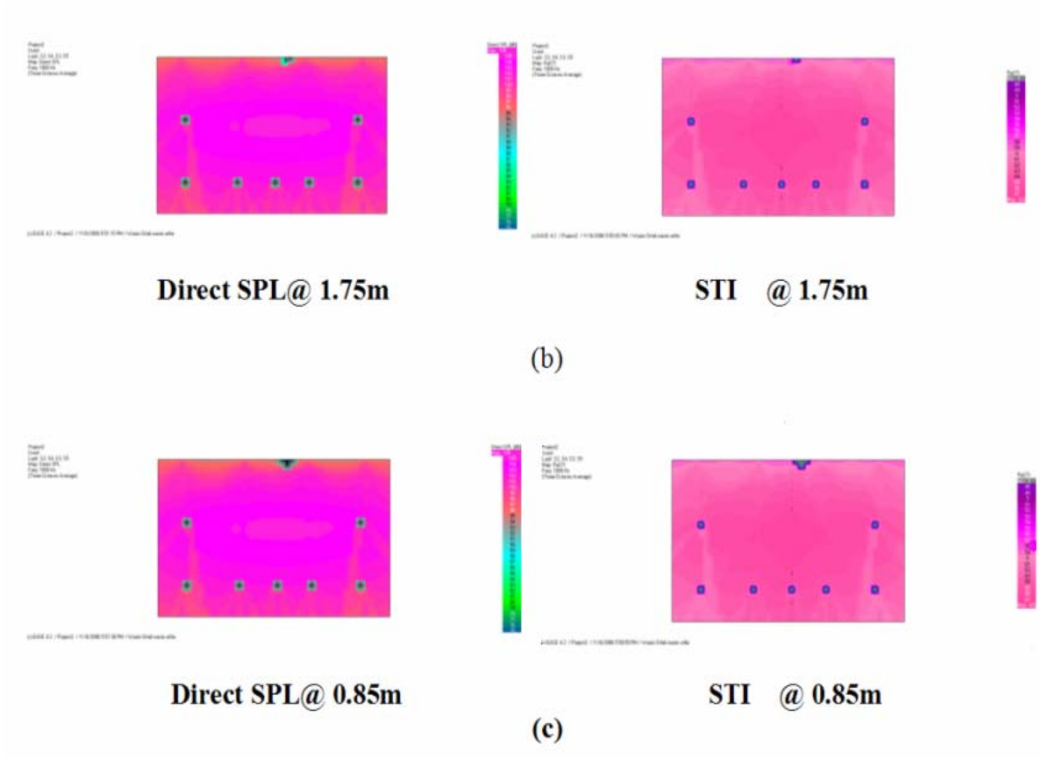
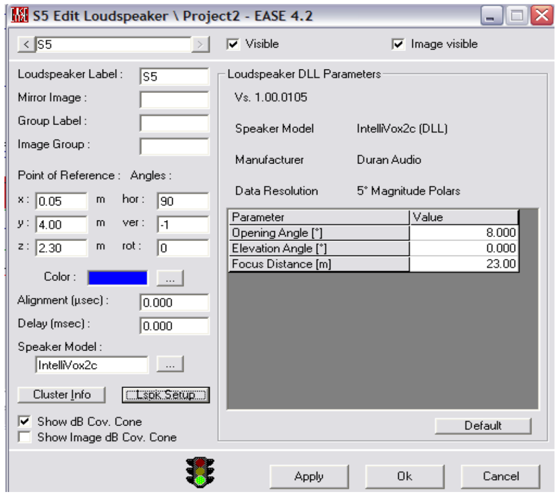
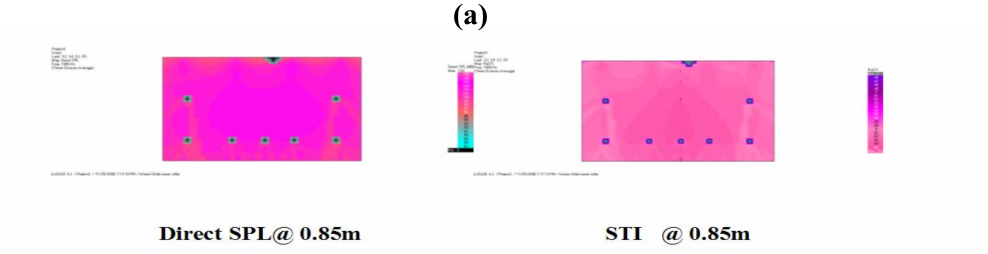



*Figure 101. (a)Using BeamWare Software to control the beam of RH-Iconyx Array IC24 manufactured by Renkus-Heinz(b)Mapping result of Direct sound and STI at 1.75m(c) Mapping result of Direct sound and STI at 0.85m*

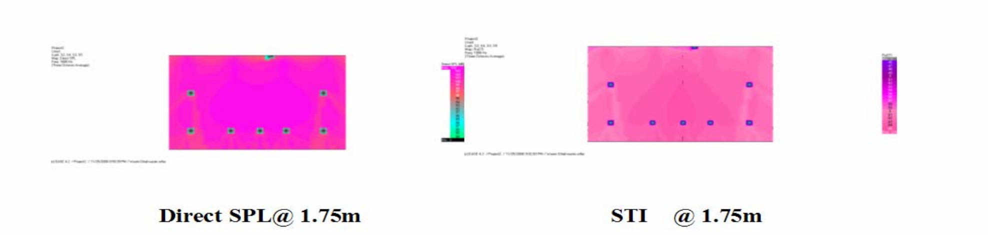
As we noticed in the previous figure, the mapping results of the direct SPL and the STI at the 1.75m (b) hearing plane and 0.85m (c) hearing plane are comparable. This similarity is a result of lowering the acoustical centre of the loudspeaker columns during the preaching mode (seated worshippers) from 1.75m to 1.4m in order to maintain a constant distance to the hearing plane of the worshippers of about 0.55m. All areas were covered with direct sound including area shadowed by the roof supporting columns. Compared to the conventional distributed sound system, no loudspeakers were installed behind the roof columns or under the lowered ceiling part. The same mosque was designed using another two different loudspeaker columns. The mapping results at 1.75m, 0.85m and the control beam parameters of the loudspeakers columns are shown below.




**(a)**




**(b)**




**(c)**

*Figure 102. (a)Internal Parameters which control the beam of IntelliVox2c Array IC24 manufactured by Duran-Audio (b)Mapping result of Direct sound and STI at 0.85m(c) Mapping result of Direct sound and STI at 1.75m*

Both types of loudspeaker columns maintained homogenous Direct SPL at the entire audience area even behind the columns. The mapping has been carried out for seated and standing worshippers at 1.75m and 0.85m hearing plane respectively. Moving the acoustical centre of the loudspeaker columns up and down by 0.55m as the worshipping mode changes maintained comparable results. So, acoustical centre at 1.4m and 2.3m for seated and standing worshippers respectively are adequate acoustical centre positions. Only four loudspeakers columns installed in a line on the Qibla wall have provided the shown results. For bigger mosques subsequent two lines of such speakers will be needed.

### 6.1c.3: Big and Prestigious mosques:

Most of the prestigious mosques, if not all, are considered big. They consist of main praying hall, courtyard and perimeter, which are sometimes used for praying. They can be considered as ***Major landmark structure*** or ***Large state Mosque.*** Both of which are considered as a major landmark area that shapes the town landscape and show a place of social identity. They are usually built by the state government or existed as an ancient or historical mosque.

Sound systems in such important structures are challenging according to their volume and architectural design. Big volume mosques require more distributed loudspeaker columns with appropriate delay times. Also, complicated architectural design needs more sophisticated loudspeaker arrangements. It is shown below, the holiest and the biggest mosque in the Islamic world created in EASE. The Model shows the MATTAF area and the surrounding arches.

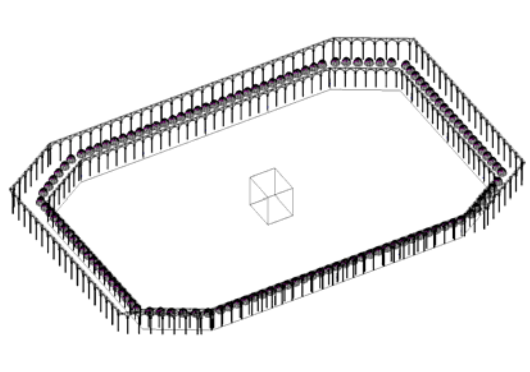


*Figure 103.Night view of the MATTAF and the associated EASE Model*

The MATTAF has a surface area of approximately 18000m$^2$. It can accommodate up to 15000 worshippers. The current designed sound system uses 36 Long throw Bose 4402LT and 96 short throw Bose 402 making a total of 132 loudspeakers. The directivity balloons of both types are shown below at low, mid and high frequencies.

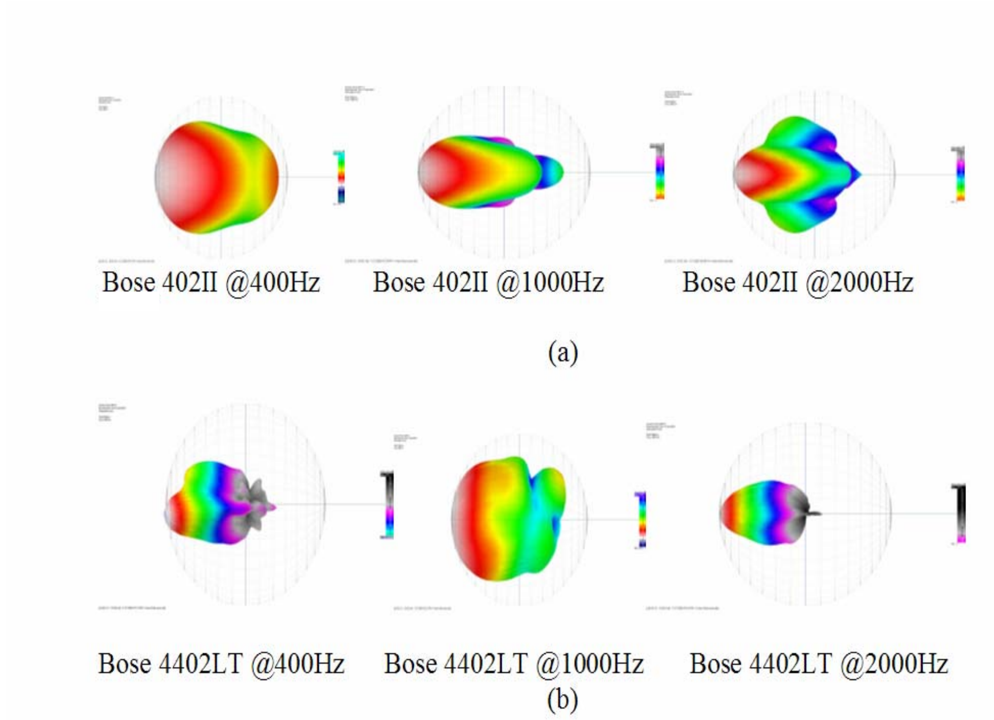


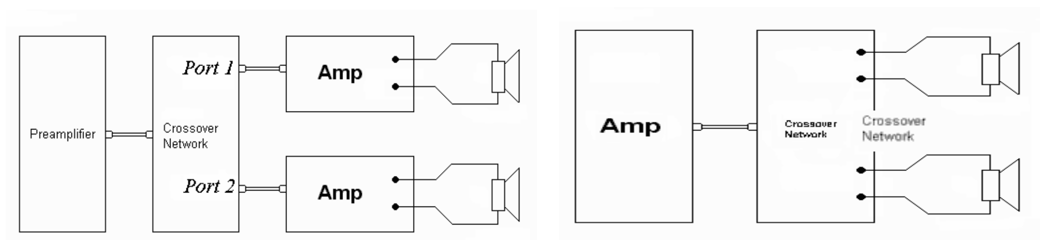

*Figure 104. (a) The directivity balloon of Bose 402II at Low, Mid and High Frequencies(b) The directivity balloon of Bose 4402LT at Low, Mid and High Frequencies*

Even using large numbers of loudspeakers as a short and long throw, given that the directivity balloons are not so much directed could not succeed in establishing a STI value of more than 0.4. The measured STI value at point 1 was 0.375 (see table2 in chapter 3). It was measured while conducting a series of measurement in order to evaluate the Holy Haram sound system. Not only late reflections from the environment surround the Haram, the late arrival of sound energy from the Minaret sound system and the high Background Noise (65dBA) have degraded the intelligibility of sound in the MATTAF area. Also, the non directional directivity of the used loudspeakers did not help to improve the intelligibility because the sound energy is not directed toward the audience.

The MATTAF EASE model was used as shown in Figure 103. We will now optimise the sound parameters in the MATTAF area using less numbers and more directed loudspeakers columns. All the used loudspeakers columns are active what implies better quality of sound compared to the currently used passive sound system.

In Active systems, each individual drive unit has its power amplifier, see Figure 105a. Also, each amplifier can be designed specifically for a limited frequency range of an individual drive unit (tweeters, woofers etc…). This will result in further benefits in efficiency, due to the fact that the smaller the amplifier bandwidth is, the more efficient it is. In such systems no frequency-dependent components are located between the amplifier and the driver unit except cables. This way the amplifier control is independent of other components located between the amplifier and the driving unit.

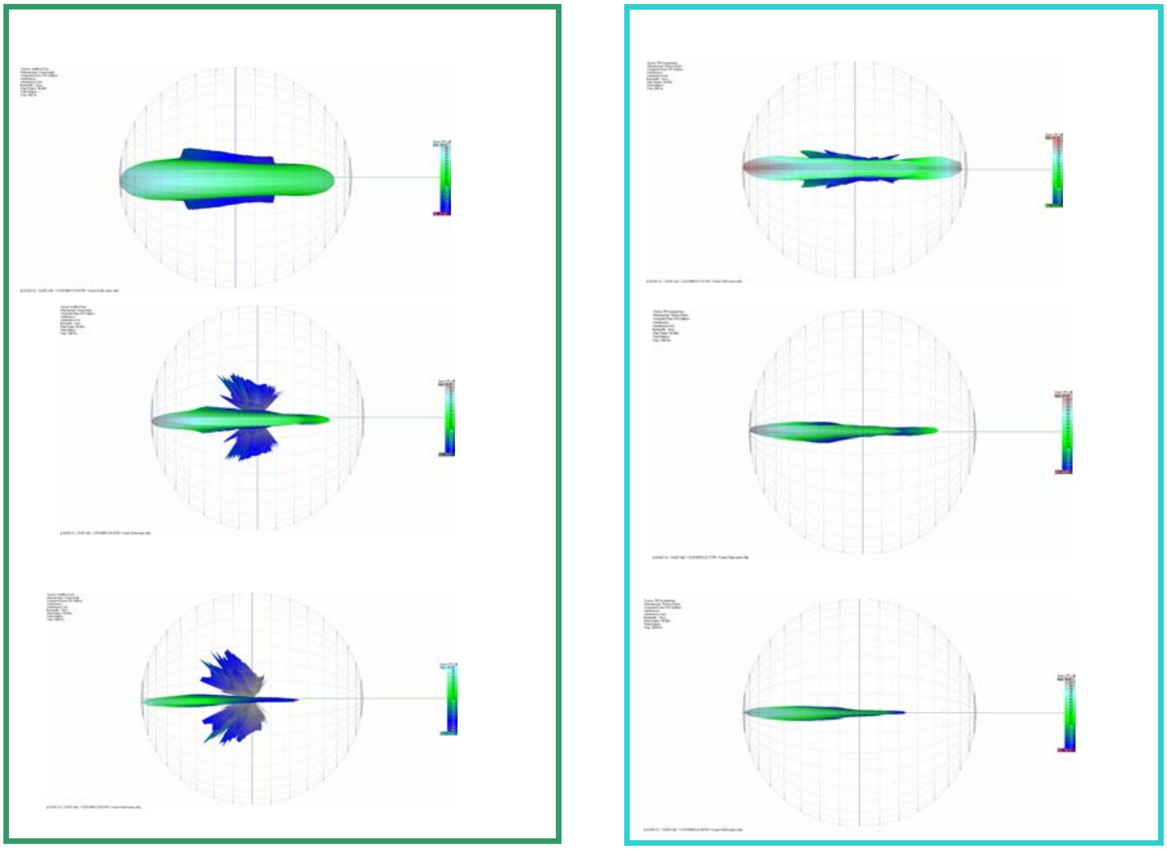
On the other hand, Passive Systems uses one amplifier for all driver units (tweeters and woofers), see Figure 105b. This will decrease the efficiency of the driver unit and the sound's quality, due to the fact that the wider the amplifier bandwidth is, the less efficient it is. Also, using a passive system will add undesirable loads additional to the driver impedance. Such impedances are presented by the components located between the drivers unit and the amplifiers. Accordingly, the quality of sound radiated from these drivers units will decrease, since the impedances are frequency dependent too.




(a) (b)

*Figure 105. (a)Active sound system network (b) Passive sound system network*

Loudspeakers columns have wide and almost constant coverage behaviour in the horizontal domain and at far distances. Their beams can be steered and controlled digitally. Furthermore, they have a fixed directed directivity balloon at the different frequencies. They manage to do that by changing the physical length of the loudspeaker column according to the change of the used frequencies by electronic means. The directivity balloons of the two different loudspeaker columns A and B proposed in this work are shown below.



*(a)* *(b)*

*Figure 106.(a) The directivity balloon of (A) at Low(top), Mid and High(bottom) Frequencies(b) The directivity balloon of (B) at Low(top), Mid and High(bottom) Frequencies*

Both the loudspeaker columns show very concentrated directivity balloon even at low frequencies as low as 400Hz. The directivity balloons presented in 100a shows some side loops at high frequencies, which is not the case in the other manufacture designed loudspeaker.

The mapping results using 16 loudspeakers columns (instead of 132 Bose speakers) are presented below. For the sake of diversity, the two suggested loudspeakers columns were used once at the time.

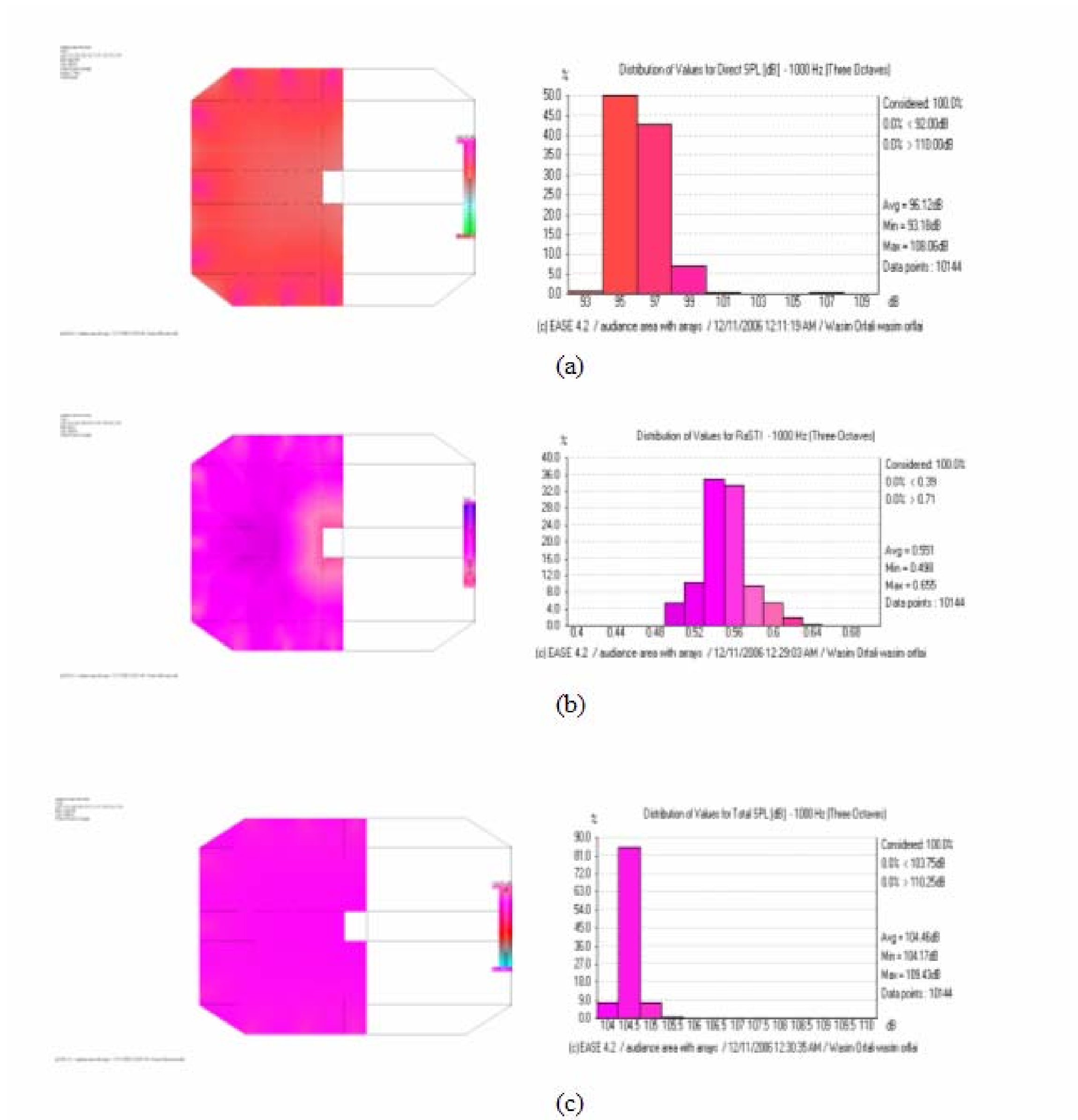



*Figure 107. Using IntelliVox7sym the (a) Mapping results of Direct Sound in MATTAF area (b) Mapping results of STI in MATTAF area(c) Mapping results of Total SPL in MATTAF area*

With another product of digitally controlled speaker columns [28] the calculations have been repeated and show similar good results, see figure 108.

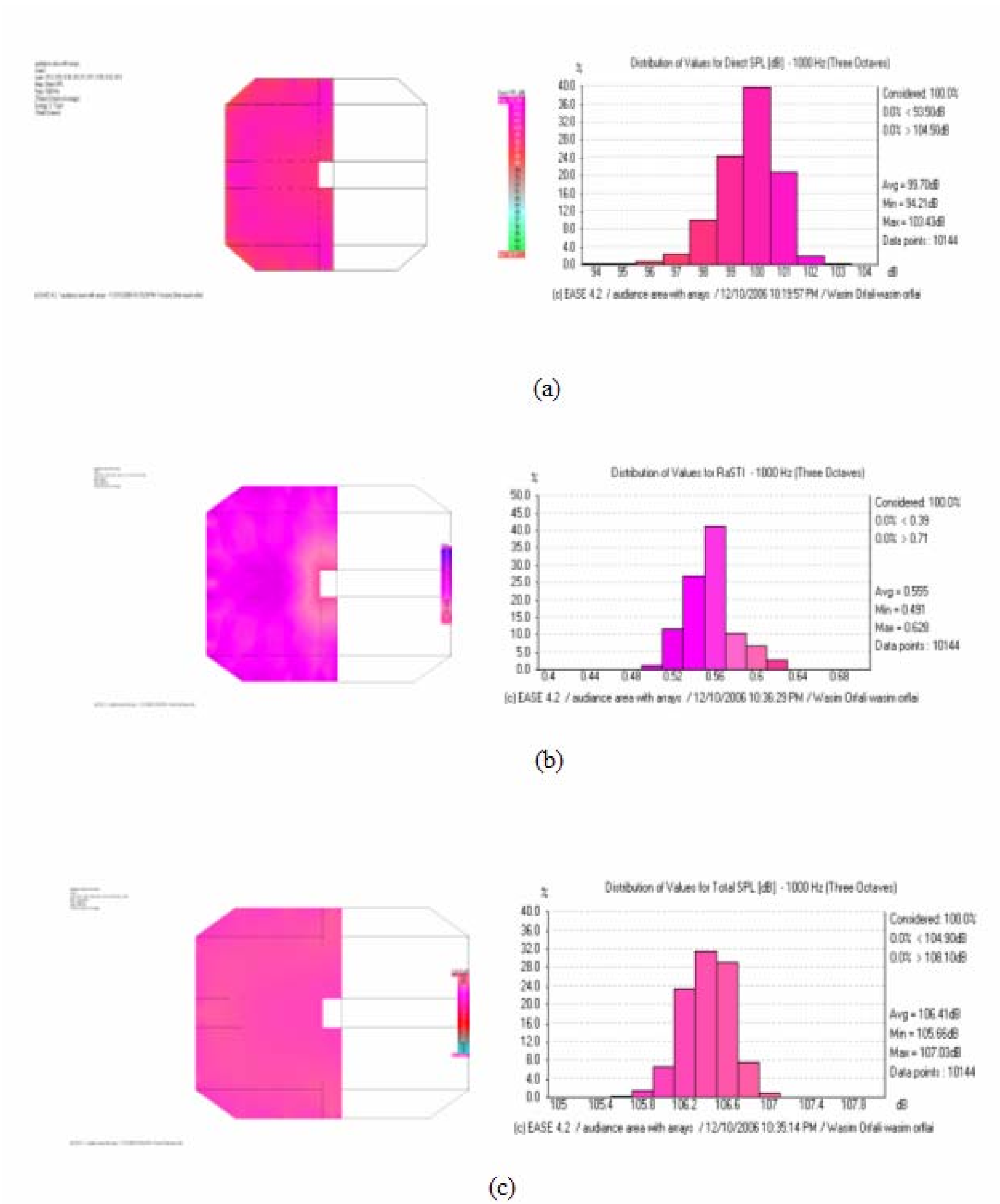



*Figure 108. Using RH-Iconyx Array IC32 (a) Mapping results of Direct Sound in MATTAF area (b) Mapping results of STI in MATTAF area(c) Mapping results of Total SPL in MATTAF area*

In big and prestigious mosques, by using digitally controlled and high-directed loudspeaker columns the numbers of speakers needed to cover the MATTAF area were substantially decreased. Consequently, less cabling, power and installation efforts will be needed as compared to the current conventional sound systems. STI values of more than 0.5 were achieved (all simulations were conducted with 60dB noise level) compared to the measured 0.375 presented in chapter 3. Since the directivity balloon of the loudspeaker columns has a pronounced sound pressure level in vertical domain and steady coverage in the horizontal domain, almost independent of frequency, compared to the conventional loudspeakers more sound energy is being radiated toward the worshippers. This way the signal to noise D/R ratio will increase. Using such columns, the two different hearing level of the worshippers can be addressed by switching the height of the acoustical centre up and down between 1.75m (worshipping mode) and 0.85 (preaching mode).

Not only big and prestigious mosques were discussed in this chapter. Also, different sizes of mosques have been considered to introduce new controlling methods after having investigated the pro and cons of conventional sound systems. A small size mosque was used as shoebox to compare the individual mapping results of 1 single source, distributed sound system and classical sound columns to a more modern loudspeaker column with different controlling methods. Afterwards, the optimum solution was implemented in representative mid-size and Big Prestigious Mosques. The Controlling method *“Beam controlled sound radiation Method”* makes it possible to control the Elevation Angle, Focus Distance and the Opening angle of the radiated beam. These parameters can help to address different needs in a mosque environment like different worshipping modes heights. In more complicated worshipping areas *“Predefined listener area Method”* can be used to make the design easier and more efficient. In this method, the layout of the worshipping area is mapped back to the loudspeaker column and loudspeaker adjusts its internal filter associated with each drive to produce the desired sound radiation coverage.

Also, different loudspeaker column set-ups which use different controlling algorithms have been established for different mosque’s volumes. Depending on the shape of the small mosque one or more loudspeaker column(s) of appropriate size was/were found to be sufficient. This means that rectangular small mosques may need more than one loudspeaker column to cover worshipper at the far left and right. On the other hand, for square or hexagonal mosques with the same volume as the rectangular mosques required only one loudspeaker column in the centre of the Qibla wall. In mid size mosques where more roof supporting columns are available in the main hall and under the lowered ceiling compared to small mosques, four mid size loudspeakers columns installed only on the Qibla wall resulted in satisfactory sound parameters. More than 100dB SPL through out the mosque and intelligibility STI values of more than 0.5 even under the lower ceiling parts and behind the columns were simulated. In Big mosques, more loudspeaker columns will be needed in parallel rows or in circular venue. In this case, proper delay time must be applied to selected number of loudspeaker columns to avoid late energy arrival (echoes) and to enhance the intelligibility.

# Chapter 7

## 7.1: Guidebook for Good Acoustics and Intelligibility in Mosques:

### 7.1a: Introduction:

Architects have significant knowledge of the way in which light, size, form, material and climate affect the perception of a room. The implication of sound, on the other hand, is rarely a subject for discussion. An architect should have an active role in designing the acoustics of structures such as mosques. They should establish a close cooperation with the acoustician from an early designing stage. There are many existing mosques where the sound environment is alarmingly bad, with the acoustics and the architecture taking up contradictory positions. If good cooperation between acousticians and architects is established at an early stage of the planning procedure, the architecture design can be given an extra feature through conscious acoustical design.

This chapter will show both professions how they ought to be better acquainted with each other's fields starting from very primary designing process.

### 7.1b: Architectural Issues:

To get the most of what an acoustician can recommend in a designed mosque, he has to be involved from the very early stages of a project planning. From the very beginning, the acoustician can help decide not only the space dimension and the geometry; they can address any structural limitations and restrictions that may exist. When the acousticians are involved even before the final blueprints are completed and the project site is selected, future necessary manipulation of implemented architectural designs could be avoided.

Architectural issues like location, mosque's significant, type and size of the designed mosque have to be discussed between the architect and the acoustician before the mosque is outlined on papers. First, the architectural type of the mosque has to be decided. A Closed Hypostyle Mosque or Courtyard Mosque both should be designed acoustically different. A Courtyard Mosque requires more attention, since it is more exposed to the environmental noise surrounding it.

When the mosque is decided to be a Courtyard Mosque, the next question to answer is where it is located? Normally, the acousticians should not support locating a Courtyard Mosque in a noisy environment. If necessary, especial acoustical treatment must be associated with this decision. In a Closed Structure Mosque the location can be discussed after the size and dimension issues are sorted out.

After chosen the proper location of the mosque, its size and dimension has to be addressed. These two factors determine the structure reverberation Time before treatment. When the mosque is to be built as a local mosque or a community mosque, it is irrelevant to enlarge it. It should be remembered that bigger mosques have high Reverberation Time values. Thus, they require more surface treatments to bring its Reverberation time and intelligibility numbers to the RT and intelligibility numbers recommended.

All mosques are considered important and valuable. In fact, architects who have the upper hand in any designed mosque are very sensitive to all issues and any recommended adjustments by the acousticians especially in a Prestigious or Large State Mosque. Therefore, Prestigious Mosques and Large State Mosque require more attention by the acousticians. Relatively, less effort is needed in smaller community and local mosques. So, exertion and time can be saved in smaller mosques.

## 7.1c: Room Acoustics:

### 7.1c.1: Primary structure:

Once all the Architectural issues have been agreed upon, all primary shape elements have to be discussed. The acoustician as a part of the decision making group should influence the mosque's size to ensure the optimal Reverberation Time for mosques as shown.

Also, if the selected site required especial acoustical treatment (like in the case of open courtyard mosque placed between elevated landscape surface and high raises buildings (as was presented in section 3.1b.3)), those should be addressed too. If the existence of roof supporting columns is a necessity, each column should be divided to 4 columns adjacent to each other forming one column. Such a column is possible to look throw it and accordingly the sound can travel through it must be emphasized by the acousticians. If they were to be eliminated by adopting central dome or distributed smaller domes, the height and the radius of each dome has to be chosen in a way to prevent sound focusing at the a worshipper listening plane. The relationship between Focusing Height and Sound Source Height is developed (Refer to Figure 39) as a designing tool to help the acousticians and architects achieve this objective.

The shape of the mosque should be established before discussing its Secondary structure elements. Once the mosque is decided to be a courtyard mosque, the outside noise intrusion issue has to be dealt with. In a Courtyard Mosque, the architect should realise that some sort of covering surface has to be placed on the courtyard to reduce the intrusion of noise. Hence, covering the courtyard with a transparent glass dome or sliding domes should be strongly stressed (Refer to chapter 5). Such a decision must coincide with especial acoustical treatment, which will bring the acoustics of the courtyard to the required optimal acoustical environment. In case of adopting a sliding dome as a solution, highly absorptive glass-fibres with different thickness and with an appropriate air gap can be stuffed in the light weight structure of the sliding dome to lead to the required absorption behaviour (see Figure 81). If the architect prefers a transparent glass dome, especial transparent micro-perforated foil can be attached to the glass with a certain air gap from the glass surface to result to a certain required absorption, as shown in Figure 82.

On the other hand, Hypostyle Mosque with Rounded back wall should not be approved by the acousticians. Such a layout causes concentration of sound energy in the centre of the mosque as was demonstrated in chapter 3. Also, Rounded and even octagonal shapes have a similar behaviour. Parallel walls in rectangular and square mosques will result in Flutter Echoes effect as was discussed in chapter 3 too. Here, some sort of appropriate diffusers or convex rounded surfaces have to be fixed to the surface the parallel walls by means of Secondary Structure design to prevent such an effect.

In general, the Volume, Domes, Columns issues have to be clarified, before the architect go ahead and decide the major layout of the designed mosque. Acoustically, the elimination of the roof supporting columns by adopting domed surfaces is beneficial. Also, the radius and height of these domes from the ground must be designed right to prevent focusing at the listing plane of the worshippers. Afterward, the architect and the acoustician should form some sort of agreement about the intended shape of the mosque keeping in mind its influence on the sound behaviour.

### 7.1c.2: Secondary Structure:

After the architect and the acousticians have agreed on final layout of the mosque, the acousticians should start to determine the acoustical materials needed to manipulate and improve the final acoustical identity of the mosque. As sound travels, it changes each time it hits a wall, floor or any other surface. It changes according to the nature of the materials it hits. By examining the shape and type of the material used at each surface, acousticians will suggest different kind of treatment materials to achieve the desired results. Sound-absorbing materials such as Thick Carpet, Mineral Fibreboard, Padding Materials and Transparent Micro-Perforated Material should be considered where sound absorption is needed.

The floor surface in mosques covers most of its total surface area. Accordingly, a small change in its absorption behaviour will result in a considerable change in the overall acoustical environment. Concentrating most of the treatment effort on the carpet and underneath it will be in favour of the architects since it will minimize the need for other surfaces treatments. It turns out that different carpet's materials which have considerable absorption behaviour should be used. Heavy Carpet on thick pad and Carpet on Foam Rubber Pad are solutions of the recommended carpets. Adding an extra material under the carpet will make it more convenient for the worshipper prostrating, sitting and kneeing on the ground. Discussing the carpet characteristics including its thickness and density with the acousticians before it is chosen is highly recommended. Choosing the right thickness and density might spare future necessary treatments for the other surfaces to bring the acoustical environment to its optimal status. Occasionally, if the right carpet is chosen, no padding material is essential. Accordingly, the overall treatment cost could be lowered. Sometimes, adding a padding material under the carpet will be rejected by the architect. In this case mixing the concrete under carpet with white foam bubbles can be suggested as an alternative solution. Such a combination has a considerable absorbing influence on the radiated sound energy (refer to chapter 5).

Most of the Ornamental Islamic Art is implemented on the Qibla Wall, Ceiling and the Copula. Therefore, no acoustical treatment will be possible in these walls. In fact, the architect will reject any recommended treatments, which will manipulate the decoration of such walls. In chapter 5, a Transparent Micro-perforated Acrylic Glass was suggested in such applications. Such a transparent material will maintain the original view of the wall behind it and will provide a reasonable absorption depending on its distance to the wall, thickness and the perforation percentage it has.

Fortunately, Secondary Structures treatments can resolve some of the acoustical deficiencies resulted from primary structures designs. Possible treatments of the Floor Area (the carpet and underneath it), Qibla Wall and the Ceiling were discussed in chapter 5. Conducting theses treatments will give the acoustical environment of the designed mosque its final intended identity.

## 7.1d: Building Acoustics:

### 7.1d.1: Noise control:

A layout design which contains an eliminated technical room for all air conditioning units should be enforced. Such units are a major source of the high level of ambient noise in mosques (see in chapter 4). Neon lamps and traditional Ceiling Fans both add to the total ambient noise measured. In all the surveyed and the visited mosques regardless of its size, type and importance, cheap and basic type of Neon lamps and Ceiling Fans were adopted. According to the discussion with the administration of each mosque, no proper attention was given to such issues. Finding a substitution for both of them will help decrease and limit the number on noise sources. The Neon lamps and the traditional ceiling fans can be substituted by halogen white pulps and modern quiet fans respectively. Eliminating the ceiling fans and relay on some of the existing big air conditioning units as air circulators (by putting them on the fan mode) is also an adequate solution and lowers the total cost .

### 7.1d.2: Noise Intrusion:

Because sound travels through structures of mosques, via columns and beams in the very skeleton of a building, it is important that proper materials are used throughout the designed structure. Accordingly, the construction of walls and windows has a great influence in determining the acoustical behaviour in such structures. Once a mosque is located in a noise neighbourhood, the acoustician should recommend walls with heavy mass, such as concrete or masonry and thick doors. The same works for windows and glass. Once the noise is more abundant, a combination of thicker glass and different layers with optimal performance should be used.

As an alternative solution, different sound isolators can be used to decrease the intrusion of outside noise into the mosque. Such isolator works as heat and cold isolators in the same time. They decrease the flow of heat/cold from and into the mosque. Thus, the needed number of Air Conditioning/Heater could be decreased. Outside noise intrusion reduction is not within the scope of this design work for a mosque. There are a lot of wall construction standards and noise isolators, which are recommended to minimize the intrusion of the outside noise.

### 7.1d.3: Summary:

All sources of HAVC noise should be eliminated or dealt with at an early design stage even before the mosque is built. Noise sources like Air conditioning units, Florissant lamps and Ceiling Fans should be eradicated or substituted with quieter alternatives respectively.

Intrusion of the outside noise should be decreased at its lowest rates. Thus, an appropriate type and thickness of the constructed walls should be considered. When additional isolation is needed at a later designing phase, efficient noise isolators can be attached and fixed on the walls.

Fortunately, Noise isolation and heat/cold isolation are interrelated subjects. Most of the noise isolators work like heat/cold isolators too. This can be considered an advantage, since one of them will work as noise and heat/cold isolator (lower cost). Isolating the mosque's walls, or even increasing its thickness and mass, will decrease the intrusion of noise and temperature into the mosque structure in the same time. Accordingly, less numbers of Air conditioning units will be needed what means less noise.

## 7.1e: Sound systems:

### 7.1e.1: Target of the Design:

One of the basic purposes of a professionally designed Sound Reinforcement System is to sustain an equal sound level distribution throughout the worshipper's area. In fact, a constant distribution of the Sound Pressure Level should be maintained with ± 3dB differences. A minimum Signal to Noise Ratio S/N of 20dB is recommended to achieve good intelligibility values. The ambient noise level in mosques is generally very high. In some cases, it is as high as 70dB (A) (see the measured survey presented in chapter 4). So, a signal level of 90 dB (A) (70+20) should be the minimum SPL design aim value, you may always go down in level in quite environments. An automatic level control is recommended anyway.

In any structure and especially in mosques, speech intelligibility is the main task and so the design of the sound system must assure recommended intelligibility parameters like STI and AlCons% (chapter 5,Figure 75,77a). In general, by considering different RT values and different source-listener to critical distance ratios ($r_{LH}/r_R$), STI values above 0.5 is recommended by standards. In very extreme situation when the mosque's volume is around 100.000m$^3$ and $r_{LH}/r_R$ is more than 5, the recommended STI may drop to 0.45. This value is still acceptable in such huge structure and at far distances from the source. Recommended intelligibility values by using the AlCons% measure was elaborated too. To obtain AlCons% values less than the minimum acceptable articulation limit (15%) for structures with RT between 0.5-3s, the $r_{LH}/r_R$ ratio should be between (or less) 7 and 2 respectively.

### 7.1e.2: Design Criteria:

Different design criteria influence the sound system for a mosque. The Size and Volume of the designed mosque, Distance form the Qibla wall (mosque's depth) and the existence of the roof supporting columns all influence the decision of the most appropriate Sound Reinforcement System of a particular mosque. As the mosque size increases, the needed Sound System demands more care. In contrast, small mosques (< 3000m$^3$) need (in most cases) a more modest and in the same time effective Sound System.

As the size of the mosque increases, the distance from the Qibla wall to the back row increases. By another words, the depth of the mosque increases. At some point, the need for roof supporting columns will become important. The implication of this need on the required Sound System have to be investigated. Here, extended numbers of loudspeaker are required to address all areas including areas behind columns. In better situations, the architect adopts another approach in his design for bigger mosques, which will eliminate the need for the roof supporting columns. In this case the only design criterion, which has to be addressed, is the mosque's depth; accordingly, the design task becomes easier. Here, especial loudspeakers can be used to cover the whole worshipping area uniformly (worshippers in the near and far rows).

### 7.1e.3: Insufficient Design:

Determining the adequate number of speakers needed in a designed sound system is important. Insufficient number of loudspeakers will lead to uneven sound level distribution and unsatisfactory intelligibility levels. In the same time, adding extra loudspeakers, higher level of SPL will be noticed. On the other hand, it may happen that the intelligibility will be decreased to lower values according to late sound energy arriving from all the different loudspeakers at a given location, see chapter 6.

The presence of shadowed area (as discussed in chapter3) and weak sound coverage under any lower ceiling areas is an indication of inadequately designed sound system. To avoid such problems the right type and numbers of loudspeakers, orientation and speaker aiming have to be used. In big mosques, insufficient design causes some sort of echoes because of the late energy arrival from the remote speakers. This problem is usually experienced under lowered surfaces. In this area the worshipper hear first the sound arriving from the speaker near to him and after some time (more than 80msec) another sound from speakers installed in the front of the mosque. Here, the speakers under the lowered surface were not adjusted to proper delay time.

### 7.1e.4: Recommended Design:

Influence of some architectural design deficiencies can be minimized by using directed loudspeakers. The ability of different types of these sound sources was examined at different mosques sizes (see chapter 6). Such sound sources concentrate sound energy toward the worshippers and minimize the influence of sidewalls and the roof on sound behaviour. Also, they increase the intelligibility values by increasing the D/R ratio. They radiate a constant Sound Pressure Level even for long distances. Accordingly, they decrease the needed number of loudspeakers in a designed mosque. Another advantage is that using such programmable loudspeakers makes it possible to change their acoustical centre according to the change in the praying mode. In mosques the hearing plane changes from 1.75m to 0.85m according to the change of the worshipping mode from Praying Mode to Preaching Mode respectively. Adjusting the acoustical centre of the loudspeakers as required will maintain the same listening experience regardless of the change in the worshipping mode. Using those loudspeakers arrays should be strongly emphasized by the acousticians to achieve the appreciated results in different mosque's sizes.

The needed type, size and number of such loudspeaker line arrays depend on the size of the designed mosque. Small mosques (< $3000m^3$) need (in most cases) one loudspeaker column with proper length fixed in the centre of the Qibla wall to get good results. In Bigger mosques, more loudspeaker columns will be needed in parallel rows or in circular arrangement. In this case, proper delay time must be applied to selected number of loudspeaker columns to avoid late energy arrival (echoes) and to enhance the intelligibility. Different sizes of mosques were investigated using different kinds of loudspeaker arrays (in chapter 6) to show the efficiency of such arrays. Acoustical simulation software could be used to select the proper number, size and type of the used loudspeaker array. This software will help the acousticians predict the acoustical environment inside a mosque and make the necessary adjustment and changes even before the mosque is built.

After the proper Electro-acoustical components has been installed, highly recommended onsite testing measurements with sound system in operation should take place to confirm that the desired outcomes were in fact achieved. The results of these measurements should be in agreement with the developed recommended sound parameters in mosques.

## 7.1f: Flow Chart of Acoustical and Electro-Acoustical Design for Mosques:

The flow chart shown below is a schematic representation of the designing process of a mosque. It ensures quality control, logical and systematic designing phases, which lowers the treatments cost, and designing effort. It helps the reader to visualize the content of this chapter better and to find flaws in the designing process.

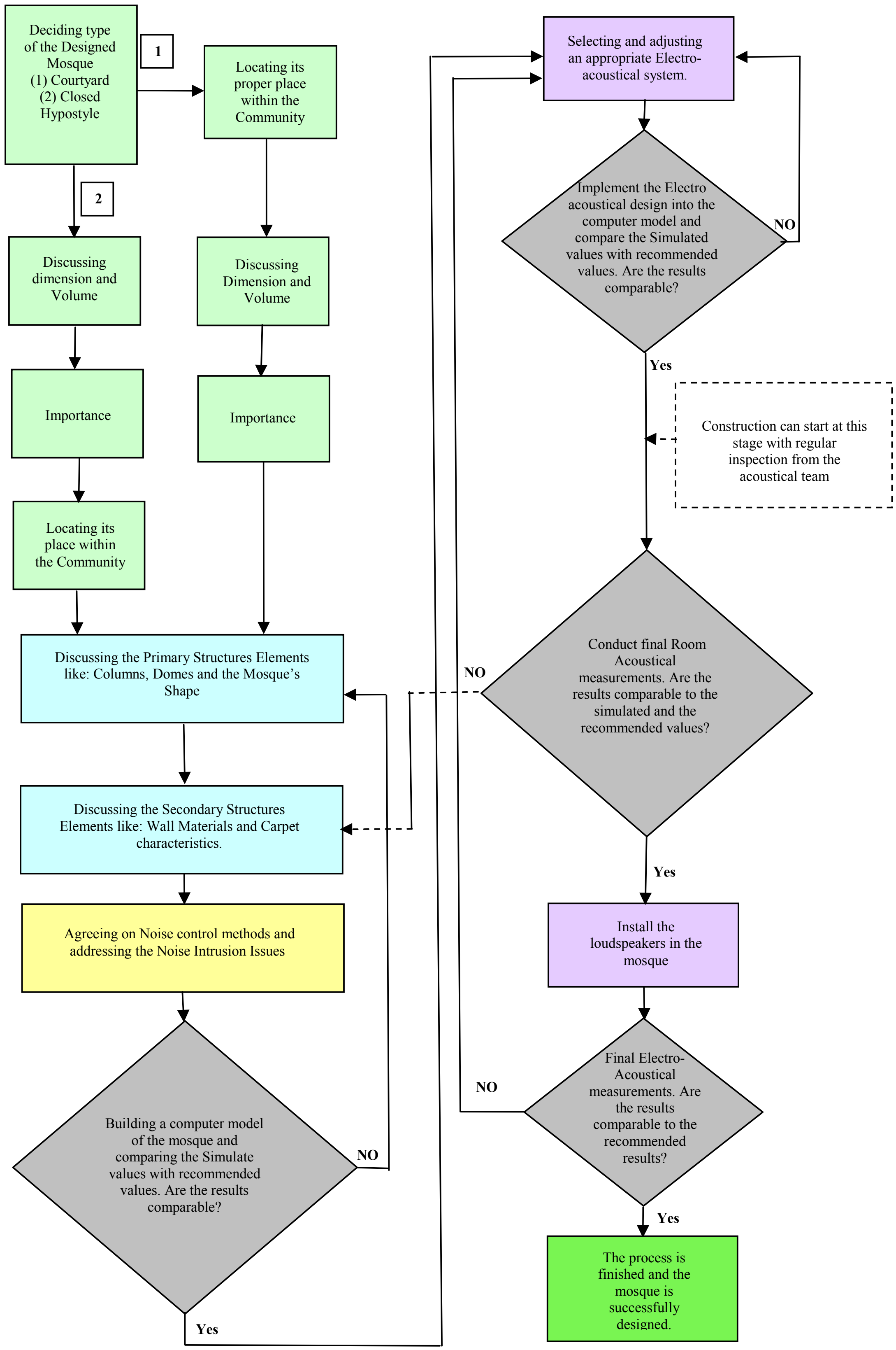



*Figure 109 Flow Chart of Acoustical and the Electro-Acoustical Design for Mosques*

All designing phases are shown in the above flowchart with different colours. The acoustical issues shown in Light Green boxes, Room Acoustics (Turquoise), Building Acoustics (Light Yellow) and Sound Systems (Light Lavender) are consider major designing phases. The architects and the acousticians as one team should follow the flowchart step by step to avoid future complications and to achieve the recommended designing results.

This part of the work has introduced designing Guidelines to achieve good acoustics and intelligibility in mosques. Architectural designs, Room Acoustics, Building Acoustics and Electro-Acoustical Designs were considered major design phases. The architect and the acoustician as one team should consider all phases systematically as was shown in the flow chart diagram. One of the aims of this chapter is to show both professions what and when to consider each phase. Accordingly, they will discover how they will be better aware of each other fields. This will reflect on the design quality of the mosque.

# Chapter 8

## 8.1: Conclusion:

This work came as a result of strong belief that acoustical design literature related to mosques has to be augmented. Neither churches acoustical parameters nor auditoriums designing approach are applicable to be used to design the acoustics of a mosque. Consequently, this work has been initiated to investigate all subjects related to the acoustical environment in mosques. It enriches and grants the acoustics of mosques accustomed acoustical parameters. Mosque's acoustics have been defined in this work as having a standalone identity compared to other structures. The acoustical environment in such structures needs new designing approach according to its worshipping modes and worshipper expectation.

At the beginning, the influence of the architectural identities of churches on architectural design of mosques was discussed. Also, the architectural development of both of them and the interrelation between them including their types and classifications were argued. Here how the mosque inherited some of its basics architectural identities and elements were illustrated. The definition and functionality of a Mosque's Basics Elements were provided. At this point all the terminology and the historical background needed to read further this work were introduced to the reader.

Then, the acoustics of mosques and churches were briefly conversed. Here the acoustics and sound system development for both structures were highlighted. So, the question **"what happened throughout the history of acoustic in the church?"** was answered. On the other hand, Mosque's acoustics were introduced by means of worshiping modes and adequate room acoustical parameters. Regarding Sound System in mosques no series of developments can be traced back through out the last century. This means that no organised scientific work or systematic modern development took place in this field. This was a strong reason to instigate this work.

Chapter 2 was the reader's gateway to more technical work and the marking end of the introductory part. It gave a brief description of the topic and the contents of this work. The subsequent chapter 3 studied the influence of the Primary and the secondary structures of mosques. In the Primary Structure part the influence of the dimension on the Reverberation Time and the Clarity of Speech were discussed. Here simulated results of shoebox models for different sizes and measured results of the same sizes mosques were compared. In the shoebox models no architectural details or basic elements were included. This way we were able to study their influence. Also, the relationship between reachable Critical Distance $r_R$ vs. *S/N* ratio was devolved as a function of different directivity values C of the source. The effect of the Mosque's shape (as a primary structure element) and the adopted design of its Basic Elements on the acoustical environment were evaluated, too. Here different geometrical shapes and position of the basic elements and mosque's common features on the sound quality were assessed. To prevent sound focusing, a relationship between Focusing Height of domes and sound source height were developed. This will assist the architect to make a decision about the dome radius and the height of the loudspeakers. Also, all points of weakness and strength were highlighted for the different architectural forms. Different acoustical parameters were tested and simulated for different models at different preaching modes, different demands for speech, ensuring the needed intelligibility and other acoustical measurements.

Fortunately, Secondary Shape design may be used to solve the acoustical problems resulting from the Primary structure problems of a mosque. Wall treatments or what so called "passive treatments" of the worship space are implemented in most cases to overcome the effect of some fundamental architectural design contradictions, which degrade the sound quality in such a space. The Secondary Shape was presented as wall material treatment and wall's structure influence. Here the benefits of treating the carpet in contrast to other surfaces were highlighted by presenting a real life example. The acoustical parameters in King Abdullah Mosque in Amman/Jordan were evaluated after using two approaches. Large scale wall treatments as a first approach (provided in the literature) were compared to especial carpet treatments (suggested in this work). Different treatment materials and approaches to the floor surface were suggested to ensure diversity. Treating only the carpet floor has an advantage of being effective, advantageous to the worshippers and has a lower cost compared to treating other surfaces. The effect of Wall's Ornaments as sound diffusers was investigated.

It was important to evaluate the present acoustical and electro-acoustical situation in mosques before starting to recommend adequate sound parameter and systems. Therefore, chapter 4 was devoted to an Electro-acoustical survey for a number of mosques. Its aim was to assist the used sound system in mosques and their effect on sound parameters. Also, Background Noise inside each mosque was measured. All mosques seem to be reverberant compared to the recommended RT for the same volume structures. The Background Noise level was as a high as RC-48(R) where (R) stands for "Rumbly" as a subjective measure. In all the visited and chosen mosques in the survey, small conventional loudspeakers were adopted. Such loudspeakers have low front-to-random factor and almost omni-directional directivity which is not in favour of intelligibility level inside these structures. Therefore, the intelligibility levels were measured to be low compared to the recommended values. An example of one of the surveyed mosques was adopted were all of the above mentioned factors which degraded intelligibility was eliminated. An improvement of the overall intelligibility levels and sound coverage were noticed.

In chapter 5 general acoustical rules were generated for designing and constructing mosques. New quantities of the applicable acoustical quality parameters (RT, Alcons, C50, STI) were produced according to the understanding of the worshipping modes and acoustical environments expected in mosques. In newly constructed mosques some sort of designing parameters were described. Here generating some acoustical advises to avoid acoustically unpleasing designs was the main aim. It was recommended that things like curved surfaces, big columns, huge domed, parallel walls and noise sources should be eliminated.

In courtyard mosques, constructing a moveable dome or glass roof is beneficial since it isolate the courtyard from the external noise. On the other hand, different treatment solutions by means of transparent micro-perforated foil or especial stuffing material were introduced to eliminate its drawback.

In closed structure mosques, treating the floor surface compared to other surfaces was highly recommended for its considerable positive influence. Two recommended carpet treatment materials were introduced. Also, another alternative solution for the concrete under the carpet was found. Such a treatment would be beneficial in case treatment of the carpet material is rejected. It involves adding especial white foam bubbles to the concrete mixture to increase its absorption.

Once the mosque is acoustically tuned, appropriate sound system solution should be installed if needed. Chapter 6 was dedicated to investigate appropriate sound systems according to mosque's size. Therefore, after introducing the modern sound system, mosques were divided to small, Mid-size and Big mosques. It was found that worshipping ceremonies in mosques which have a volume less than 1500 m3 can be conducted without sound reinforcement system. In small mosques (< 3000 m3), one loudspeaker column with proper length should be sufficient to cover the whole worshipper area evenly. The advantages of using such columns compared to distributed conventional loudspeakers or Classical columns were demonstrated. Here the improvement of intelligibility levels and sound pressure level coverage were shown.

In Mid-Size mosques (between $3000m^3$ and $6000m^3$), an adequate number of loudspeakers columns installed only in the Qibla wall should be sufficient. Using modern digitally controlled loudspeaker columns will make it possible to address different worshipping modes and to obtain appreciated results.

Sound systems in Big and Prestigious mosques are challenging according to their volume and architectural design. Here more distributed loudspeaker columns with appropriate delay times are required. Because of their complicated architectural design they need more sophisticated loudspeaker arrangements. By using digitally controlled and high-directed loudspeaker columns the needed numbers of speakers will be substantially decreased. Consequently, less cabling, power and installation efforts will be needed as compared to conventional sound systems.

Using “Beam controlled sound radiation Method” as a controlling method makes it possible to control the Elevation Angle, Focus Distance and the Opening angle of the radiated beam. These parameters can help to address different needs in a mosque environment like different worshipping modes heights. In more complicated worshipping areas “Predefined listener area Method” is useful. Here the designer will find it easier and more efficient to obtain acceptable radiation results.

At the end of this work a guidebook for good acoustics and intelligibility in mosques was provided. Here a systematic design procedure which organizes the cooperation between the architects and the acousticians were discussed. If these designing procedures are followed as provided in the given flow chart future necessary manipulation of implemented architectural designs could be avoided. All issues related to acoustics in mosques were placed in organised methodical order to achieve this objective. Starting from Architectural Issues until the recommended sound system is installed all were considered.

# Appendix:

### Sound Level in the Direct Field:

Sound level intensity in the areas covered with direct sound can be described with following equation:

$$I_{dir} = \frac{\gamma_L P_{ak}}{4\pi r^2} \text{.............(1)}$$

Where, γL is the effective front-to-random factor.
The notation level equation of the sound intensity in the direct field:

$$L_{dir} = \frac{I_{dir}}{I_o} dB \text{.............(2)}$$

By substituting equation 2 in 3 and replacing $I_o = 10^{-12}$ W/m$^2$ the result is:

$$L_{dir} = 10 \log \frac{\gamma_L P_{ak}}{4\pi r^2 \times 10^{-12}} dB \text{.............(3)}$$

Since the A=0.163V/T, the final equations that relate the direct sound field level to the critical distance radius *r* is:

$$L_{dir} = 10 \log \frac{\gamma_L P_{ak} P_o}{4\pi r^2 \times 10^{-12} P_o} dB \text{.......... ...(4)}$$

$$L_{dir} = 10 \log \frac{\gamma_L P_{ak}}{4\pi r^2 P_o} dB \text{.......... ...(5)}$$

$$L_{dir} = 10 \log \frac{p_{ak}}{p_o} + 10 \log \frac{1}{r^2} + 10 \log \gamma_L + 10 \log \frac{1}{4\pi} dB \text{.............(6)}$$

$$L_{dir} = L_w - 20\log r + C - 11dB ........ ...(7)$$

Where *C=10 log* $\gamma_L$ is the front-random-factor index. By saying that sound power level of a human loud voice at 1m is 80dB and C=2, thus:

$$L_{dir} = 71dB - 20\log r ........ ...(8)$$

**Maximum Achievable Sound Level in Diffused Field:**

An equation to start with is the Intensity level in the diffused field:

$$I_{diff} = \frac{4P_{ak}}{A} ............(9)$$

the notation level equation of the sound intensity in the diffused field:

$$L_{diif} = 10\log\frac{I_{d\,iff}}{I_o}dB ............(10)$$

By substituting equation 10 in 11 and replacing $I_o = 10^{-12}$ W/m$^2$ the result is:

$$L_{diff} = 10\log\frac{4P_{ak}}{A\times10^{-12}}dB ............(11)$$

Since the A=0.163V/T, the final equations that relate the diffused sound field level to the V/A ratio is:

$$L_{diff} = 10\log\frac{4}{0.163\times10^{-12}} + 10\log\frac{P_{ak}P_o}{P_o} - 10\log\frac{V}{T}dB ........ ...(12)$$

$$L_{diff} = 10\log\frac{4}{0.163\times10^{-12}} + 10\log P_o + 10\log\frac{P_{ak}}{P_o} - 10\log\frac{V}{T}dB ............(13)$$

$$L_{diff} = 10\log\frac{4P_o}{0.163\times10^{-12}} + 10\log\frac{P_{ak}}{P_o} - 10\log\frac{V}{T}dB ........ ...(14)$$

Where $P_o$=$10^{-12}$ W ;

$$L_{diff} = 10\log\frac{4}{0.163} + 10\log\frac{P_{ak}}{P_o} - 10\log\frac{V}{T}\,dB............(15)$$

$$L_{diff} = L_w + 14dB - 10\log\frac{V}{T}\,dB............(16)$$

By saying that sound power level of a human loud voice at 1m is 80dB:

$$L_{diff} = 94dB - 10\log\frac{V}{T}\,dB............(17)$$

**Total Sound Level of Direct Field and Diffused Field levels in real Rooms:**

In sound field of rooms, the resulting sound pressure from the Direct and the Diffused sound field is additive. The resulting total energy density is:

$$w = w_d + w_r............(18)$$

Where $w_d = \frac{\gamma_L P_{ak}}{4\pi r^2 C}, w_r = \frac{4P_{ak}}{CA}$ ;

thus, the total energy density is:

$$w = \frac{\gamma_L P_{ak}}{4\pi r^2 C} + \frac{4P_{ak}}{CA}...........(19)$$

Where, I=w.c (c is the sound velocity)

Thus the total intensity level is:

$$I = \frac{\gamma_L P_{ak}}{4\pi r^2} + \frac{4P_{ak}}{A}...........(20)$$

The notation level of the intensity in a room is as follow:

$$L = 10 \log \frac{I}{I_o} dB \text{..........} \text{...}(21)$$

Substituting 20 in 21,

$$L = 10\log \frac{P_{ak}}{I_o}\left(\frac{\gamma_L}{4\pi r^2} + \frac{4}{A}\right) \text{..........}(22)$$

Where A=0.163V/T and by multiplying the nominator and the dominator by $P_o$

$$L = 10\log \frac{P_{ak}P_o}{I_oP_o}\left(\frac{\gamma_L}{4\pi r^2} + \frac{4}{A}\right) \text{..........}(23)$$

$$L = 10\log \frac{P_{ak}}{I_o}\left(\frac{\gamma_L}{4\pi r^2} + \frac{4RT}{0.163V}\right) \text{..........}(24)$$

$$L = 10\log \frac{P_{ak}}{P_o} + 10\log\left(\frac{\gamma_L}{4\pi r^2} + \frac{4RT}{0.163V}\right) \text{..........}(25)$$

$$L = L_w + 10\log\left(\frac{\gamma_L}{4\pi r^2} + \frac{25RT}{V}\right) \text{.........}(26)$$

by introducing the critical distance $r_R$ (here $w_d = w_r$) and with

$$r_R^2 = r_H^2 \times \gamma_L \text{......}(27)$$

$$r_H^2 = \left(\frac{A}{16\pi}\right)$$

$$A = 0.163\left(\frac{V}{T}\right)$$

Thus;

$$r_R^2 = \left(\frac{0.163V}{16\pi RT}\right) \times \gamma_L \text{......}(28)$$

$$r_R^2 = \left(0.00326\frac{V}{RT}\right) \times \gamma_L ......(29)$$

Thus;

$$\frac{RT}{V} = \left(\frac{0.163\gamma_L}{16\pi r_R^2}\right)......(30)$$

by substituting equation 31 in 27:

$$L = L_w + 10\log\left(\frac{\gamma_L}{4\pi r^2} + \frac{25(0.163)\gamma_L}{16\pi r_R^2}\right).........(31)$$

$$L = L_w + 10\log\left(\frac{\gamma_L}{4\pi r^2} + \frac{0.163\gamma_L}{2r_R^2}\right).........(32)$$

$$L = L_w + 10\log\left(\frac{0.163}{2}\right)\left(\frac{\gamma_L}{r_R^2}\right)\left(\frac{2r_R^2}{(0.163)4\pi r^2} + 1\right)......(33)$$

$$L = L_w + 10\log\left(\frac{0.163}{2}\right)\left(\frac{\gamma_L}{r_R^2}\right)\left(\frac{r_R^2}{r^2} + 1\right)......(34)$$

Writing the equation in levels notation:

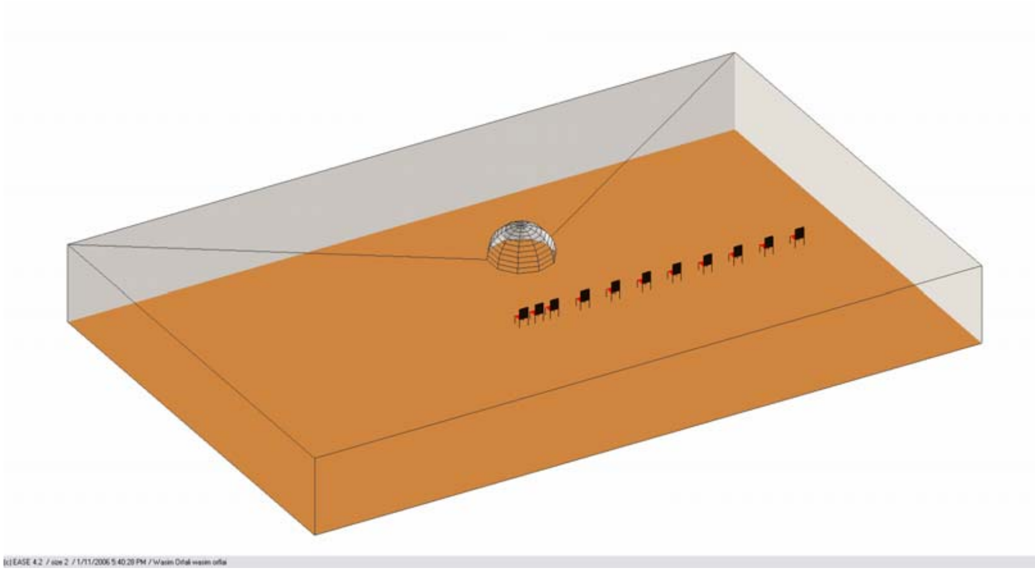
$$L = L_w - 20 \log r_R + C + 10 \log ((\frac{r_R}{r})^2 + 1) - 11\, dB ......(35)$$

By saying that sound power level of a human loud voice at 1m is 80 dB and C=2:

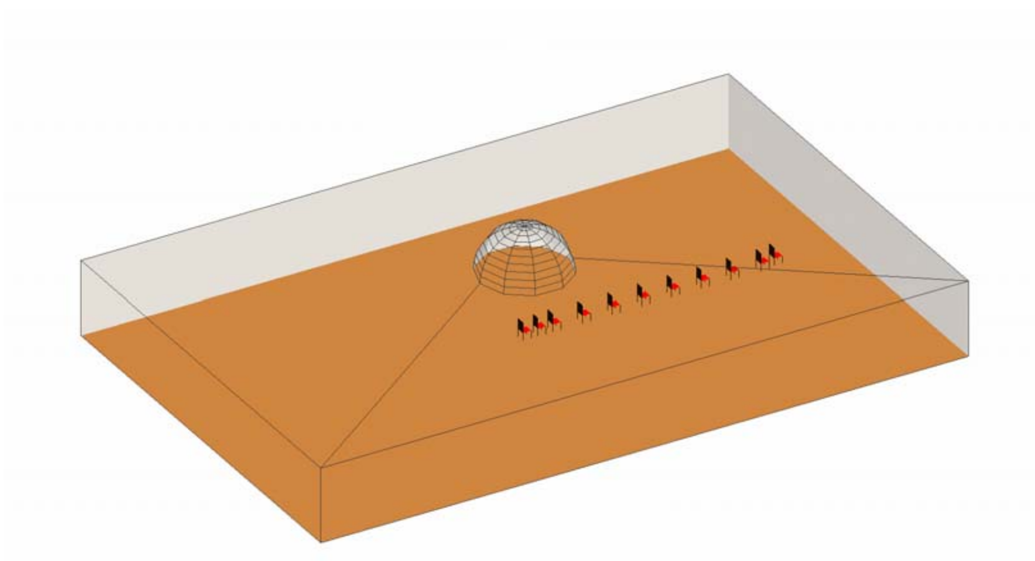
$$L = 71 - 20 \log r_R + 10 \log ((\frac{r_R}{r})^2 + 1)\, dB .........(36)$$

## Domes Effect:

2m radius:




3m radius:



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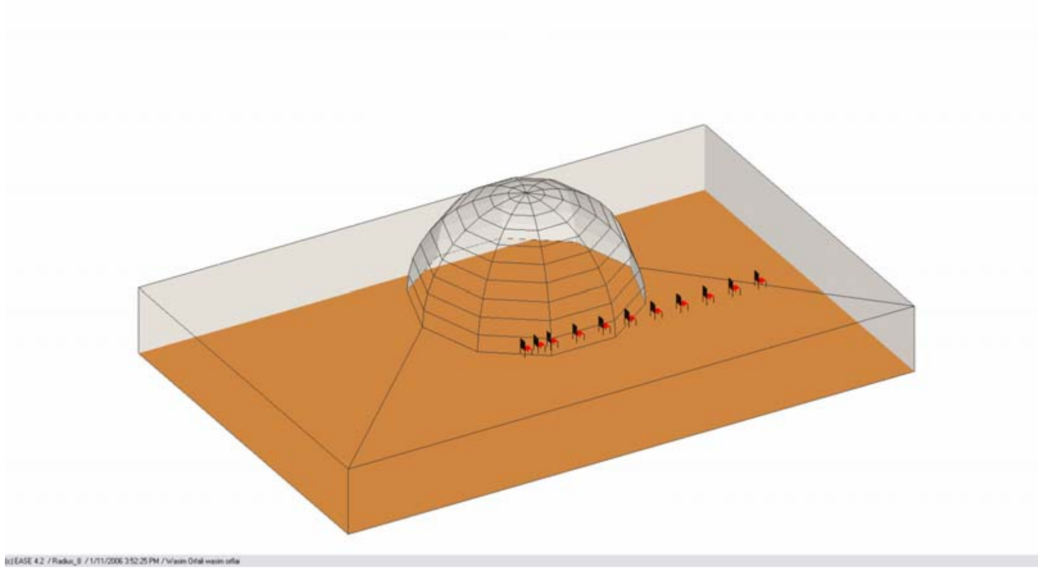


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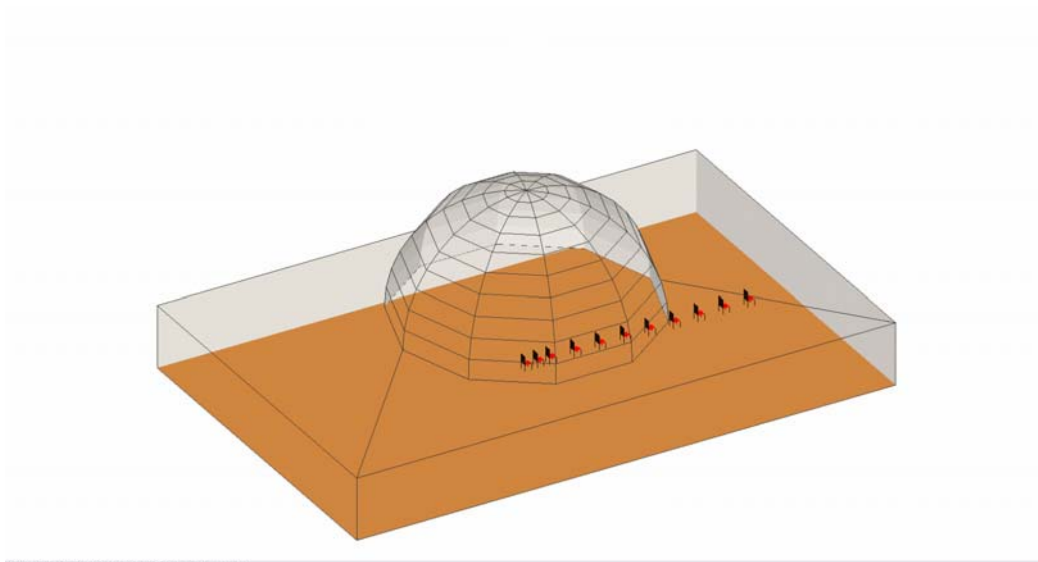

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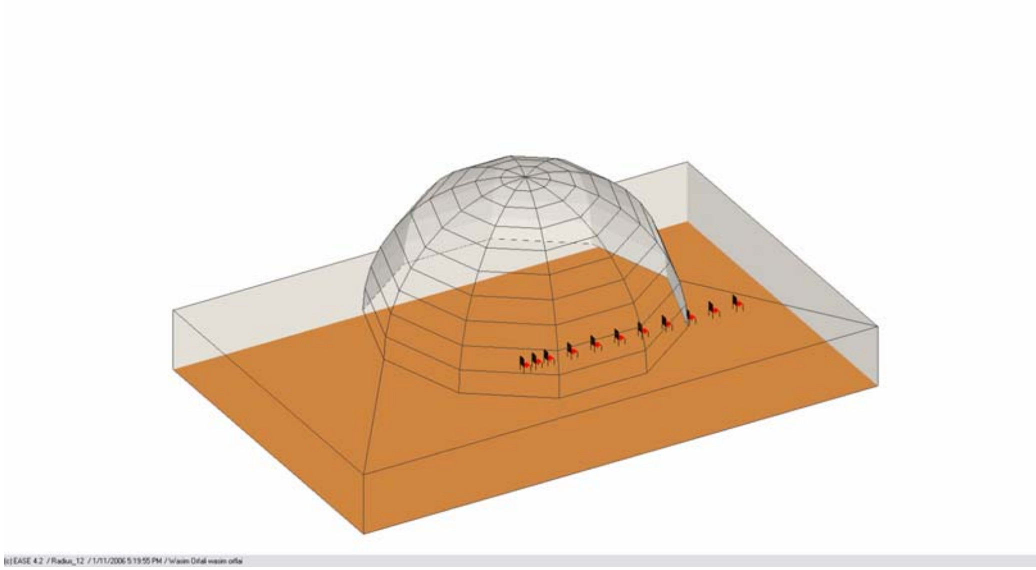
(c) EASE 4.2 / Radius_12 / 1/11/2006 5:19:55 PM / Wasim Orfali wasim orfali

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