The Acoustical History of Hagia Sophia revived through Computer Simulation

PACS REFERENCE: 43.55.Ka

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ABSTRACT
The present paper deals with acoustic computer simulations of Hagia Sophia, which is characterized not only by being one of the largest worship buildings in the world, but also by – in its 1500 year history – having served three purposes: as a church, as a mosque and today as a museum. The investigation is done as a part of the EU project - CAHRISMA.

The room acoustic differences in the three periods have been investigated by creating three different computer models each including the particular furnishing as reported in the historical archives. For all the configurations simulations and auralizations have been made, with and without people occupying the rooms.

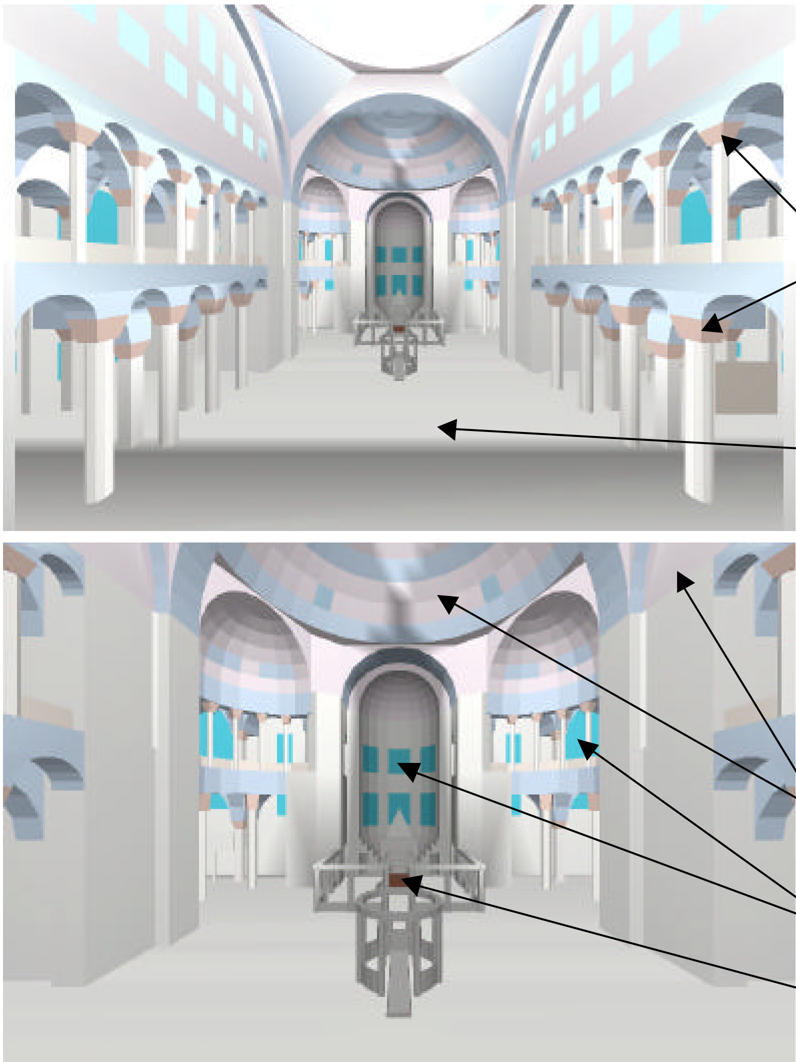
INTRODUCTION
This paper deals with the virtual restitution of the acoustics of the Hagia Sophia Byzantine church. This is done as a part of the CAHRISMA project that investigates, among other things, the acoustics of some of the old mosques and churches in Turkey. Three mosques are investigated in the project: Sokollu, Süleymaniye and Selimiye (two in Istanbul and one in Edirne), and 3 churches: Saints Sergius & Bacchus, Saint Irene and Hagia Sophia (all in Istanbul – the churches are no longer used as churches). This church, and the other two churches, has been used for different purposes through their 1500 years of history. Hagia Sophia was built in 537 A.D. as a church in the Byzantine Empire. In 1453 A.D. it was converted into a mosque in the Ottoman Empire, and finally it was converted into a museum in 1934 A.D.

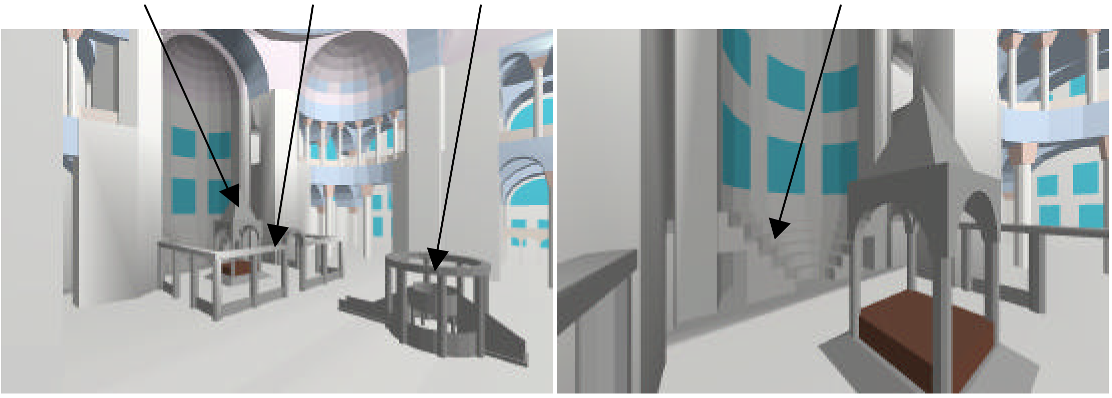
Using the ***Odeon*** computer simulation program three different acoustic models of Hagia Sophia has been made representing the three different time configurations mentioned above. This has been done using historical information and drawings of the building (1). A number of room acoustical parameters have been calculated for numerous positions and auralizations have been made for selected positions. Calculations and auralizations have also been made with people occupying the room. Since little is known about the absorption characteristics of the materials in Hagia Sophia, calculations of the model of the present configuration (Museum) have been compared with measurements done in the real room (2), and the calculated reverberation times have been adjusted to match the measured reverberation times.

DESCRIPTION OF THE DIFFERENT TIME CONFIGURATION MODELS

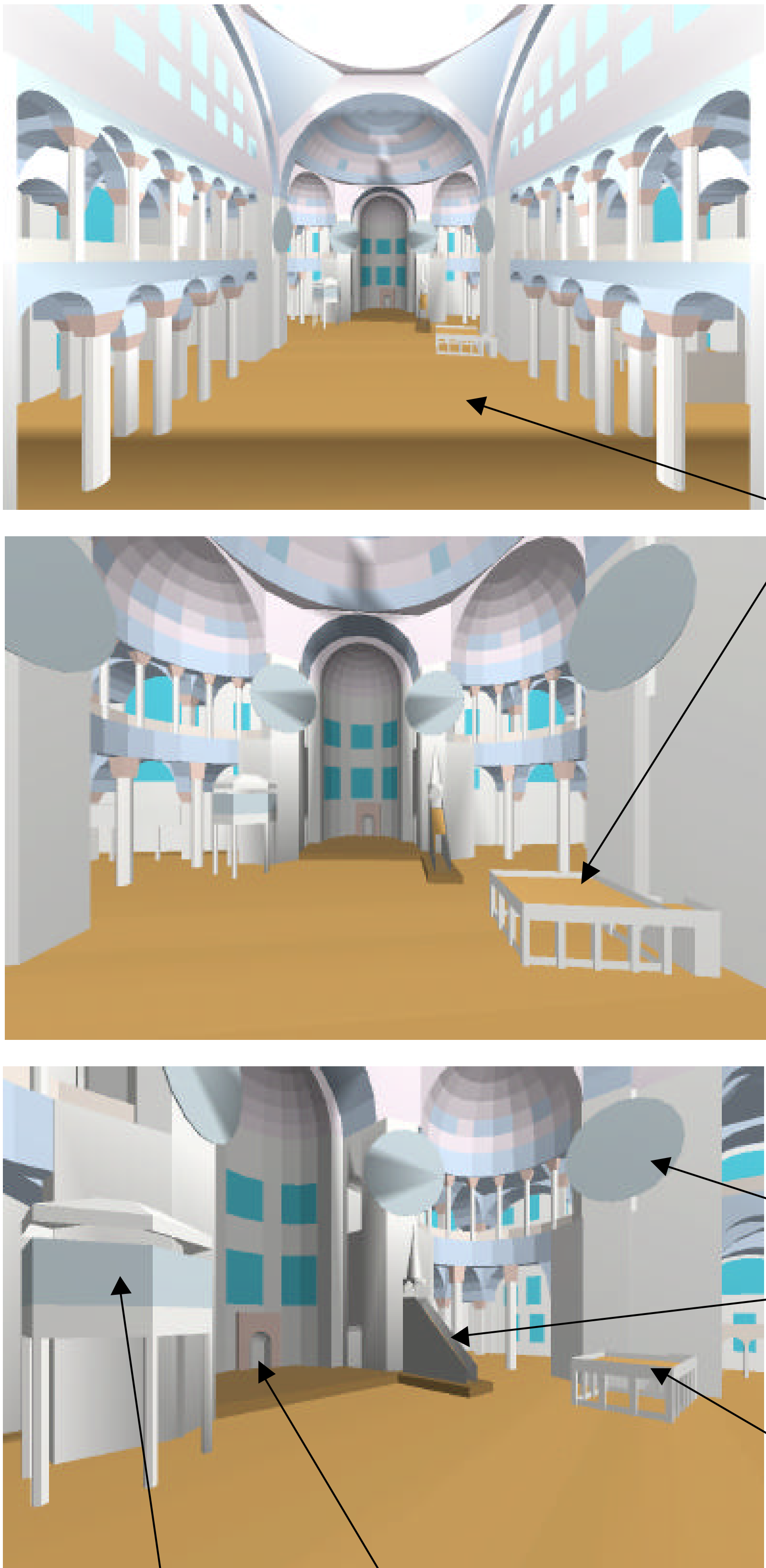
In the following, the three different time configurations of the model of Hagia Sophia are described. Below are seen pictures of the different ***Odeon*** models. The colours of the materials represent their different absorption characteristics. A material with a red colour absorbs mainly in the high frequency range. A blue colour absorbs mainly at low frequencies. A dark colour has a high absorption value, and a bright colour has a low absorption value. A grey colour absorbs equally in the frequency range.

Figures 1 - 4:
Odeon model of Hagia Sophia as a **Church**.





Figures 5 - 7:
Odeon model of Hagia Sophia as a **Mosque**.



Main materials

Carpet

Artifacts

Wooden panels with Arabic inscription

Minber

Mahfel

Sultan’s loggia

Mihrab

Figures 8 - 10:
Odeon model of Hagia Sophia as a **Museum**.

The Museum configuration looks very similar to the mosque configuration. As far as historical archives tell, only the lack of carpet shows the difference.

A view from the first floor balcony.

As seen from the pictures above (figures 1 – 10), the main differences between the three configurations are the artifacts and the materials. The main acoustic difference lies in the floor, where the mosque is covered with carpets, and the church and museum has a marble floor.

CALCULATION RESULTS AND DATA

Data and selected calculation results for the three different configurations of Hagia Sophia are shown below.

Volume [m^3] (Estimation from the ***Odeon*** model)	No. of surfaces in the model (average for the three configurations)	No. of sources	No. of receivers
255.800	5.937	3	12

Table 1: Selected data for Hagia Sophia

Reverberation time (T_{30})

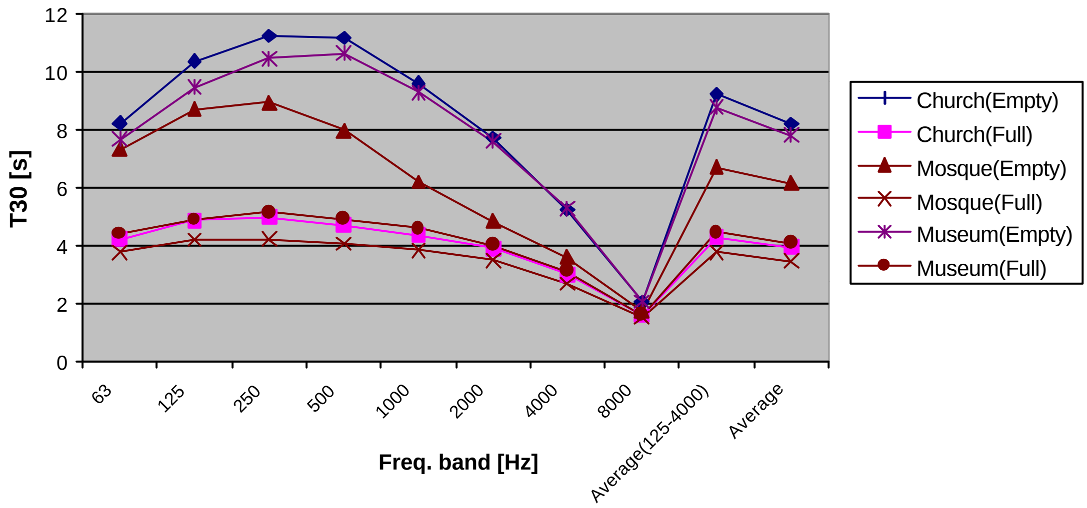


Figure 11: Calculated reverberation time (T_{30}) as a function of 1/1 octave frequency band for Hagia Sophia averaged over all positions. Also seen are frequency averaged values from 125-4000 Hz and from 63-8000 Hz.

Clarity (C_{80})

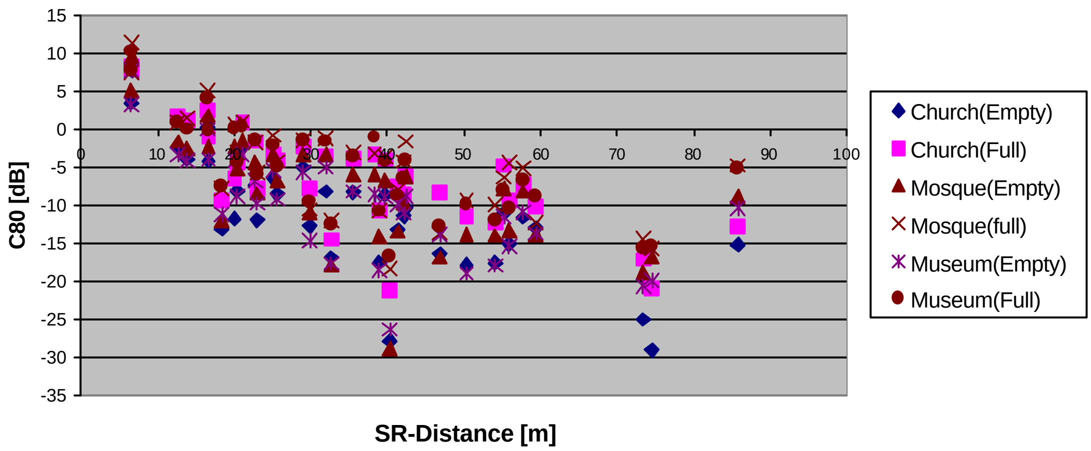


Figure 12: Calculated C_{80} (freq. Averaged from 125 – 4000 Hz) as a function of source-receiver (SR) distance for Hagia Sophia.

DISCUSSION

In figure 11 T_{30} for the different time configurations (**empty** and **full**) of Hagia Sophia is seen as a function of 1/1-octave frequency bands. For all the time configurations T_{30} is seen to follow almost the same envelope, peaks between 250 and 500 Hz, and has a minimum value at 8 kHz. The **empty** configurations are seen to give the highest T_{30} values, and the biggest difference over frequency compared to the **full** configurations. The **empty** configurations have a T_{30} value of approx. 8 sec. for 63 Hz, with the **mosque** giving the lowest value and the **church** giving the highest. When the frequency increases the difference between the **mosque** and the two other configurations becomes bigger, until they reach almost the same value at high frequencies. The small difference between the **church** and **museum** configurations can mainly be explained by the absence of the wooden panels with Arabic inscription for the **church**, which gives slightly larger T_{30} values.

The **empty mosque** peaks at 250 Hz with a value of 8,9 sec. The **empty church** peaks also at 250 Hz with a value of 11,2 sec, and the **museum** peaks at 500 Hz with a value of 10,6 sec. All configurations attain their lowest value of approx. 2 sec at 8 kHz, which is due to the domination of air absorption. The carpet covering almost the entire floor causes the generally lower values of the **mosque**.

The **full** configurations gives T_{30} values that are more than halved for low frequencies, and they do not differ so much between the different configurations as the **empty** ones. This is due to the similar absorption characteristics of the people occupying a large area of the rooms.

The relatively large reverberation times are caused by the very large volume (more than 250.000 m^3) and the very hard surfaces (marble, stone, glass etc.).

In figure 12 C_{80} is seen as a function of the distance from the source to the receiver. It generally shows that C_{80} decreases with increasing distance. It also shows that the **empty** rooms have the lowest C_{80} values, which shows C_{80}'s dependency of T_{30}. Some closer distances are seen to have lower values than large distances. At these positions there is no direct sight to the source. The direct sound is obstructed by walls, columns etc. Furthermore it is seen that the values of C_{80} have a great span from approx. 11 dB (close to the source) to –29 dB (mainly far from the source). This is mainly due to the great difference in distance, the room size and reverberation time, and because some positions are placed with no direct sight to the source, which in many cases lowers C_{80} substantially.

CONCLUSION

This study shows different acoustic time models of Hagia Sophia situated in Istanbul, Turkey. Calculations and auralizations have been carried out using the ***Odeon*** software. Three different models were made of Hagia Sophia: As a Church, as a Mosque and as its present configuration, a Museum. An average of 5937 surfaces was used to make the three different models. In the present paper, values for reverberation time (T_{30}) and Clarity (C_{80}) are presented as function of frequency and source-receiver distance, respectively. The difference in T_{30} for the three different time configurations is mainly seen between the mosque and the two other configurations, which is mainly due to the carpet on the floor. The values of clarity is seen to cover a large range, mainly due to the great distances and the fact that some positions do not have direct sight to the source. Furthermore pictures of the three models from ***Odeon*** are seen with their different furnishing and materials.

REFERENCES

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2. Christoffer A. Weitze, Claus Lynge Christensen, Jens Holger Rindel and Anders Christian Gade. Computer Simulations of the Acoustics of Mosques and Byzantine Churches. 17th ICA, Rome, Italy, September 2 – 7, 2001.