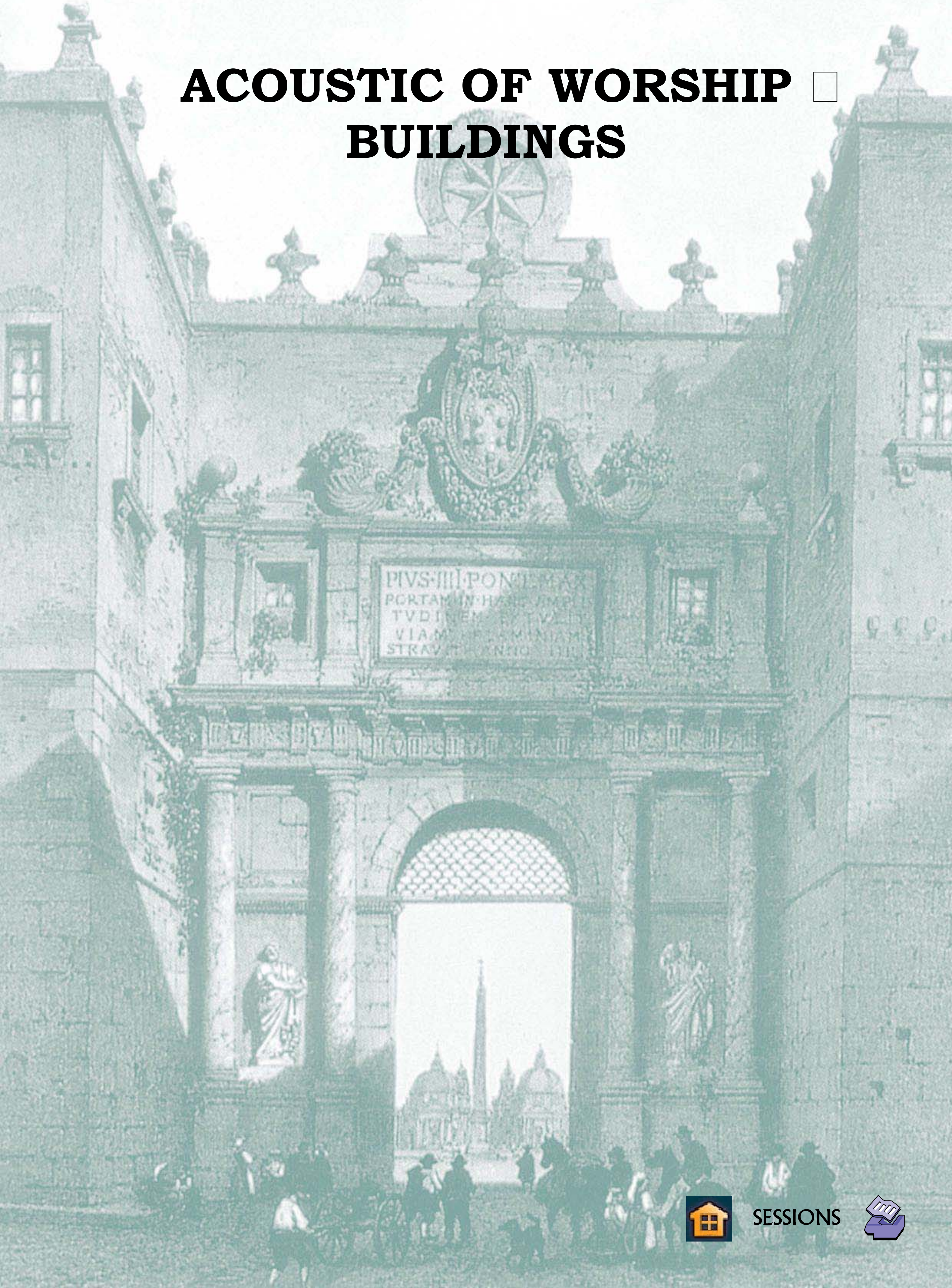

ACOUSTIC OF WORSHIP BUILDINGS

SESSIONS

The History of Western Civilization Told Through the Acoustics of its Worship Spaces

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Insights into the history and future of western civilization are found by applying information theory to the acoustical communication channel (ACC) of its worship spaces. Properties of the ACC have both influenced and reflected the choice of message coding (e.g., speech or music) at various times. Speech coding is efficient for acoustically dry ACCs, but hopeless for highly time-dispersive ACCs. Music coding is appropriate for time dispersive (reverberant) ACCs. The ACCs of synagogues, early Christian house churches, and many Protestant churches are relatively acoustically "dry" and thus well suited to spoken liturgies. The spoken liturgy, dominant in synagogues, was carried over to early Christian churches, but became unworkable in Constantinian cathedrals and was largely replaced with a musical liturgy. After a millennium, the cathedral acoustic was altered to suit the doctrinal needs of reformation churches with its renewed emphasis on the spoken word. Worship forms continue to change, and the changes are reflected in the properties of the ACC. The pulpits of electronic churches may be evolving into radio and television performance spaces and naves into worshipers' living rooms.

INTRODUCTION

The history of western civilization can be told through the acoustics of its worship spaces. The acoustics of any space are characterized by the properties of the acoustical communication channel between paired locations in the space. Communication takes place when a signal containing information is sent through the channel, and is received and accurately interpreted at the other end. Of primary interest here is the acoustical communication channel between the pulpit and nave in churches, and between the bima (lectern) and congregation in synagogues.

Information theory shows that channel properties influence the types of communication that are practical, and the ways that information is coded for efficient communication. Information theory assures that for every channel there exists an optimum signal coding which maximizes the rate at which information can be transmitted through the channel.

The main channel property of interest here is the degree of time dispersion. Channels with low time dispersion are said to be acoustically "dry" (low reverberation time.) Such channels are appropriate for the transmission of speech. Conversely, channels that are highly time dispersive are inappropriate for speech.

Speech is a poor coding for transmission on time dispersive channels because the information rate for speech transmission is very low. Music is an alternative way of coding a signal. Time dispersive channels can be very effective for the transmission of music, as all who enjoy resonant music performance spaces know.

For humans, speech tends to be more effective for communicating intellectual substance, whereas music tends to be more effective for communicating emotion. This paper suggests that at various times and places in western history; worship spaces were designed to favor either speech or music. There may be important cultural consequences for selective use of communication channels for worship over a long period of time.

Speech Communication in the Synagogue

From ancient times, the synagogue service emphasized a spoken liturgy. The centrality of "the word" in Hebrew worship forms is epitomized by the "Shema", a standing prayer containing the command to "Hear O Israel" The ancient synagogue building was used for worship, study and community meetings. Its very name means "a place of meeting." It is likely that the synagogue acoustic communication channel favored speech, though there was enough reverberation to support congregational singing

Early Christian worship adapted the liturgy of the synagogue. Worship spaces in the first Christian centuries were often synagogues or house churches. House churches too may be regarded as spaces with low time dispersion favorable to speech.

. Historical records support this idea. In the pre-Constantinian period before 313, Christian congregations were small and met in private homes. During the period before 313, congregations were small and met in private homes. Old and New Testament lessons were read by a lector and were followed by a sermon given by the presiding officer seated in a prominent chair.[1]. Following the custom of synagogue practices, a cantor would sing a simple recitation in an inflected monotone.[2] As early as 258 CE, as many as 40 large house churches were known to have existed in Rome.[3]

Post-Constantinian architecture led church liturgy from speech to music

The Roman emperor Constantine recognized the fledgling Christian Church as official in 313 CE. Soon After, Constantine's architects began constructing church buildings, modeled after Roman basilicas. These were large, roofed, and very resonant buildings. One large basilica, St. Paolo fuori le Mura in Rome dated at 386 CE, with double aisles and an open trussed roof measured a reverberation time of 9.1 seconds at mid-frequency in the nave.[6]

Important changes occurred in the liturgy during this time. One can speculate that acoustics was the dominant reason, for in these spaces reverberation must have made the spoken liturgy all but impossible.

The Christian church appears to have adapted to this challenge by largely abandoning the spoken liturgy in favor of a musical liturgy. The new musical liturgy creatively exploited the time dispersive properties of the new cathedrals. One can imagine how Gregorian chant began by recoding spoken utterances. The rapid recitation of consecutive vowels at the apse or chancel end of a cathedral would be heard as a blur in the nave because the signals overlapped in both time and frequency. A reasonable recoding would be to sing each syllable consecutively at a different pitch. This signal could be decoded clearly by listeners in the nave. This new method of coding speech by singing consecutive syllables at different pitches is a reasonably good description of the syllabic form of Gregorian chant.(It also appears to constitute an early form of frequency diversity coding!) But the Roman church had largely broken from the spoken liturgy of the synagogue and early church. This also led to important developments in western music. One might argue that it helped to shape the European mind.

By the 4th to 6th centuries greater formalism and ceremonial elaboration was practiced and sung services became normal.[4] By then, a highly melismatic (10 to 20 notes to a syllable) style of singing psalm verses had developed. The responses, originally sung by the congregation, began to be performed by trained choirs and both text and music became longer.[1] Furthermore, the reading of the lessons had been reduced and sermons were no longer preached.[4]

The acoustics of the new Gothic designs, in which sounds appeared to pile on top of one another, may have aided the development of polyphony. Organum, the earliest type of polyphonic music, which first arose in the 9th century[1], simply paralleled the Gregorian melody at an interval of a fourth or fifth above or below. Later polyphonic development saw more notes beginning to be written to each one of the original melodies. Reverberation times in York, Salisbury, Canterbury and Durham cathedrals, all built during the Gothic period, average 8 seconds at low frequencies and 5.5 seconds at mid-frequencies.[6].

Reformation churches – back to speech

Driven by the doctrinal need to understand sermons preached in the vernacular, the reformation church acoustic was made drier. Reformation church builders succeeded in reducing reverberation to achieve greater speech clarity. An unintended consequence was that the old polyphony, composed for a more reverberant space, did not work in the new, drier acoustic. A new musical liturgy was needed to suit the doctrinal needs of Protestantism. Here, church liturgy was the engine that drove church architectural acoustic design.

Luther introduced chorale tunes with simple, tuneful melodies. By the 16th century, the melody had moved to the top line over a simple chordal accompaniment. For example, to reduce reverberation, the pre-reformation Thomaskirche in Leipzig where J. S. Bach served as Kapellmeister added wooden paneling, hanging draperies and carving. These changes reduced the reverberation time to about 1.6 sec. when the church was fully occupied.

The reformation churches reached an acoustical extreme with the Quaker Meeting Houses in 17th and 18th century New England. They were so well suited to speech .that church service took new forms. Congregants could stand and "bear witness."

The electronic church

. A recent shift in architecture and worship style is the development of mega-churches. These Protestant churches are very large and very dry. Speech clarity tends to be high, but electronic sound reinforcement is needed to distribute speech and music throughout the church. The musical service tends to be electronically enhanced with guitars and with popular music sung by worship leaders and congregation. The acoustic resembles a theater or sound and television studio.

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On the prediction of reverberation time and strength in mosques

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The present study focuses on the prediction of reverberation time and on the distribution of sound level with distance inside mosques. Four sets of measured data have been compared with theoretical predictions obtained by sound absorption data of materials typically found inside mosques. Some peculiarities of the sound field inside mosques are pointed out.

INTRODUCTION

In the framework of the EU project CAHRISMA [1] acoustical measurements were collected inside some of the most important mosques projected by the architect Sinan in the XVI century and inside byzantine churches dating to the VI century. The mosques here considered are: Sokullu (SO), Selimye (SE), Suleymaniye (SU) and Kucuk Ayasofia, formely known as byzantine church of SS. Sergius and Bacchus (SB). These mosques show heights comparable with plan dimensions and are composed of a wide central volume, surrounded by partly uncoupled galleries and balconies. These buildings have a big slightly lowered dome, resting on pillars and on inferior orders of half domes. The materials covering the interior ceilings and walls are decorated plasters, marbles, stone and ceramics, all of them scarcely sound-absorbing. On the contrary the floor, though made of stone, is completely covered by carpets. They are ususally rested on a wooden chassis that maintains the walking plan raised from the ground by a few centimeters of air-backing. Table 1 summarizes the basic geometrical data of the buildings: volume (V), total surface (S_T), floor surface (S_F) and the ratio V/S_F. Even though the building typology is similar (especially among Sinan's mosques), the volumes vary considerably with a ratio of nearly 1/20 between minimum (SO) and maximum (SU).

EXPERIMENTAL MEASUREMENTS AND THEORETICAL PREDICTIONS

Table 2 reports the data concerning the positions of the sound source and of the receivers during in situ acoustical measurements. The source was placed in the usual positions of the leader of the congregation, whereas the receivers were located respectively in the central area of the ground floor (Centre of Mosque, CM), in the lateral galleries (GL) and in the balconies (BL). Both source and receivers were 1.15m above the floor.

Table 1. Basic geometrical data of the mosques.

Mosque	V [m^3]	S_T [m^2]	S_F [m^2]	V/S_F
SO	5700	2416	456	12.5
SB	14900	6701	761	19.6
SE	79300	12177	2625	30.2
SU	115000	22240	3594	32.0

Table 2. Number of source and receiver positions used.

Mosque	Source pos.	Receiver positions CM	GL	BL	Total
SO	3	4	1	3	8
SB	2	7	4	3	14
SE	3	6	1	3	10
SU	3	6	1	3	10

The delivered signal was a logarithmic sine sweep in the range from 80 Hz to 18kHz with a duration varying from 15 s to 20 s depending on the expected reverberation. The calculation of acoustical parameters was done with Aurora software in the octave bands ranging from 125Hz to 4 kHz. The parameter Strength was calculated as a single figure in the mid-frequency range, including the octaves from 500Hz to 2kHz. In order to obtain the correct calibration for this parameter , after each session a special measurement was done by putting the sound source and the receiver both at 2m above the floor and at 3m distance. By so doing it was possible to trace back the direct sound component with time-windowing and referring the level to a 10m free-field measurement. The second part of the work was focused of theoretical predictions. For the reverberation time eight formulas have been employed: Sabine (S), Eyring (E), Millington (Mi), Cremer (C), Kuttruff (K), Fitzroy (F), Arau-Puchades (A-P), Tohyama (T). Regarding the strength five formulas have been considered: Sabine (S), Eyring (E), Barron (B), Sendra, Zamarreno e Navarro (B-mod), Mueller (M). The implementation of the above formulas was pursued by using the geometrical data provided by 3D computer models developed by the partner Oersted - Danish

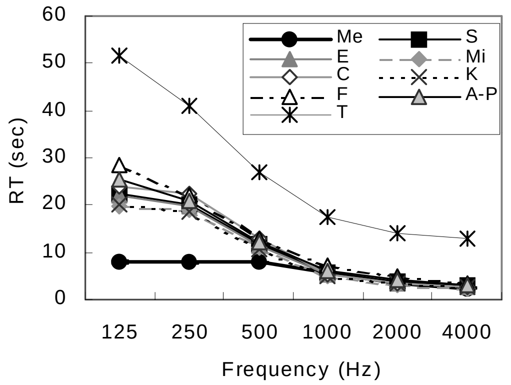

FIGURE 1. Comparison between exper. and theor RT curves.

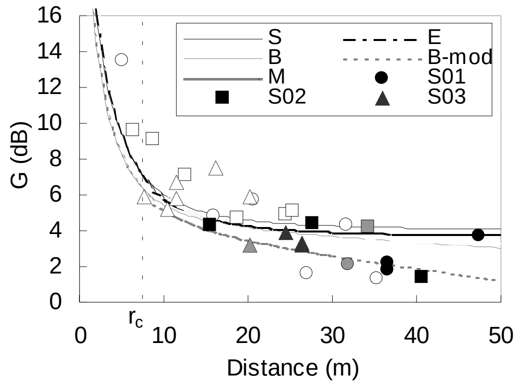

FIGURE 2. Comparison between exper and theor. G curves (bandpass from 500Hz to 2kHz oct.) .

Table 3. Percent deviation of RT.

△RT [%]	Frequencies (1/1 octave bands)						
	125	**250**	**500**	**1k**	**2k**	**4k**	**avg**
S	>100	>100	50	0	15	20	70
E	>100	>100	45	5	10	10	65
Mi	>100	>100	40	15	10	5	60
C	>100	>100	65	0	0	5	75
K	>100	>100	40	10	0	5	55
F	>>100	>100	65	30	55	45	>100
A-P	>>100	>100	55	10	30	30	85
T	>>100	>100	>100	>100	>100	>100	>100

Table 4. Deviations of G.

	S	**E**	**B**	**B-mod**	**M**
rms [dB]	1.70	1.67	1.78	1.94	1.51
avg [dB]	-0.12	0.15	0.47	1.23	0.27

Technical University and by sound absorption data of materials supplied by the partner Faculty of Architecture - Yildiz Technical University. In the case of the floor the sound absorption data were directly measured in the reverberation chamber as reported in [2].

DISCUSSION

Figure 1 reports the course of the parameter RT both measured (Me) and predicted and in Table 3 the respective percent deviations are grouped according to significative bounds. A similar comparison for the dependence of G with distance is shown in Figure 2 and Table 4 reports the respective average and rms errors. All of the data refer to the Selimye mosque but quite similar trends have been measured and predicted for the other three mosques. As regards RT, the parameter is overestimated by all the prediction formulas in the range of low frequencies (i.e. below 500Hz oct. band). The more accurate are those of Millington and Kuttruff. Above the 1kHz oct. band the dicrepancies are much reduced. Among possible causes it is supposed that the peculiar geometry of the rooms (partly coupled volumes, domes etc.) might introduce extra sound absorption not predicable by simple means. From Figure 4 related to G it is also seen that the prediction formulas seem to underestimate real values shortly after the critical distance and to overestimate the values for longer distances. The formula that gives a closer reproduction of the late course of the experimental data is the modified Barron's one. Lower avg errors are shown by classical formulas whereas the formula by Mueller has a slightly better rms behaviour.

CONCLUSIONS

This study pointed out the difficulties in making correct predictions of reverberation time and strength inside mosques. In particular reveerberation time shows dicrepancies in the lower frequency range where the effect of the peculiar geometry seems more marked. As far as strength is concerned it is necessary to develop a specialized model for mosques that can be worked out by fitting the collected experimental data.

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On the effect of floor inside mosques

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In this paper the impact of typical floor inside mosques has been studied by the comparison of in situ acoustical measurements taken inside very similar environments, namely SS. Sergius and Baccus in Istanbul (Turkey) and S. Vitale in Ravenna (Italy). In the work typical layouts of floors have been rebuilt and tested for sound absorption with standard procedures. Finally, some theoretical formulas have been tested to predict the influence of the mosque floor.

INTRODUCTION

This article deals with the comparison of the acoustic characteristics of two worship buildings, which are similar regarding architectural features but differ in the floor materials. Both rooms have been included in the acoustical surveys described in [1]. The former is the Basilica of S.Vitale in Ravenna, Italy (indicated as SV) and the latter is the Church of SS. Sergio and Bacchus in Istanbul, Turkey (referred to as SB). Both churches are byzantine-styled and date to the first half of VI century. They have a central plan and are characterized by a principal volume covered by a dome and surrounded by an ambulacre, which is surmounted by a balcony. But, while SV is conserved in its original state with a mostly sound-reflecting floor, SB is today used as a mosque and includes typical sound-absorbing carpets covering the floor structure. Table 1 reports the main geometrical data the two churches: volume (V), total surface (S_T), floor surface (S_F), and the ratios V/S_T and V/S_F. Finally, also the ratios between respective quantities in the two rooms is included (SV/SB). While V and S_T have the same ratios (with SV being biggest in absolute terms), the floor surface is proportionally more extense in SB. Moreover in Figure 1 the values of measured reverberation times for SB and SV are reported for the six octave bands from 125Hz to 4kHz.

Table 1. Basic geometrical data of the mosques.

Church	V [m^3]	S_T [m^2]	S_F [m^2]	V/S_T	V/S_F
SV	25800	11400	980	2.26	26.33
SB	14900	6700	750	2.22	19.87
SV/SB ratio	1.73	1.70	1.31	1.02	1.33

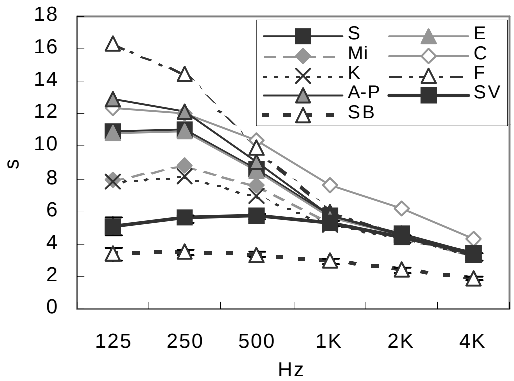


FIGURE 1. Experimental RT curves for SB and SV and theoretical RT curves for SB'.

THE MODEL OF THE FLOOR AND THE PREDICTION OF ITS IMPACT ON THE SOUND FIELD

In order to study more accurately the behavior of the floor, a specific model has been built and measurements of its sound absorption have been carried out in the reverberation chamber of the firm "*Modulo Uno*" based in Turin, Italy. The model, which keeps the stratification typical of the floor mosques, consists of a chassis of 12m^2 made by wooden panels 2.5cm thick. The structure has an air-backing of 4 cm and the face exposed to the sound field is entirely covered with carpets. The measures have been carried out with: wooden chassis only (A), carpets only – no chassis (B), complete structure (C). Figure 2 shows the results obtained for the sound absorption in the 1/3 oct. bands from 100Hz to 5kHz. It is to be noted how the structure is much absorptive in the medium-high frequency range where the carpets have a strong influence, while in the lower range the absorption is principaly due to the panel effect of the chassis with air-backing. The effect of the floor was also studied by calculating two sets of theoretical curves for reverberation time and strength and comparing them with experimental results. The former set was obtained directly by the geometrical data of SB and the latter by their modification according to the ratios in Tab. 1. In this second case a room equivalent to SV was

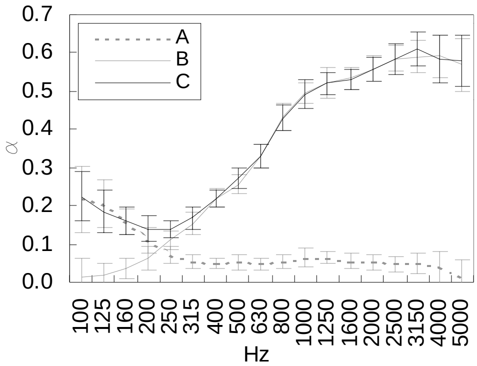


FIGURE 2. Absorbtion coefficients in 1/3 octave band for the three different configurations of material test.

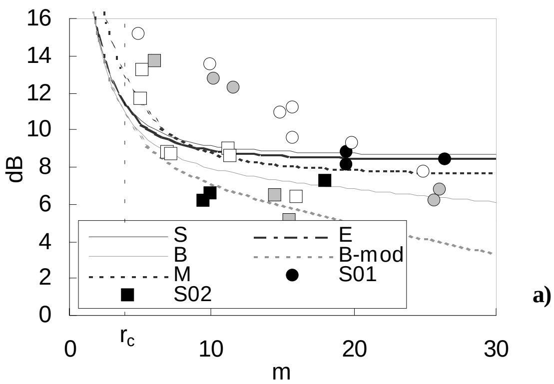
obtained (called SB`) but, differently from SB, the floor in SB` was considered sound reflective. Later the consistency of the theoretical predictions with the data collected in SB and SV was tested. In Figure 1 the RT measured in SB and SV is compared with predictions made after respectively Sabine (S), Eyring (and), Millington (Me), Cremer (C), Kuttruff (K), Fitzroy (F) and Arau-Puchades (AP) formulas. The Figures 3 a) and 3 b) report the comparisons for G in the oct. band from 500Hz to 2kHz. In particular the former shows data and predictions for SB and the latter compares measures in SV with theoretical predictions for SB`. The formulas used for predictions are those of Sabine (S), Eyring (E), Barron (B), modified Barron (B-mod) and Mueller (M).

DISCUSSION

From Fig. 1 it is noted that, for RT, the values of prediction for SB` in the lower frequency ranges are overestimated. This evidence is in line with the findings in [2], where the difficulty to predict correctly RT for mosques in the lower frequency range has been pointed out. This coincidence allows to exclude the floor structure from the causes of such problems, which seem more linked to the articulated geometry of the buildings. From Figures 3 it is shown that introducing the absorptive floor lowers the sound level in the reverberated field by 2dB (S and E) or even 3 dB (B-mod). A similar change is surely remarkable and can be problematic in bigger mosques, whose absolute G values are lower [2]. In Figures 3 it is also evidenced that the

Table 2. Deviations of G.

[dB]		S	E	B	B-mod	M
avg	SB	2.09	2.06	2.21	2.95	1.91
	SB'	0.98	0.96	1.13	1.82	1.21
rms	SB	2.52	2.52	2.76	3.49	2.33
	SB'	1.29	1.28	1.51	2.04	1.61



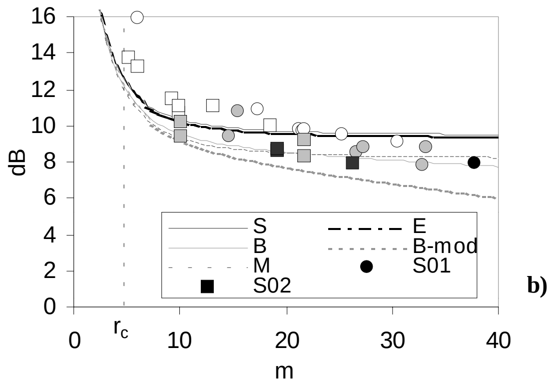


FIGURE 3 a)-b). Comparison between exper and theor. G curves for SB (a) and between theor. values for SB' with exper. values for SV (b) .

presence of the sound absorting floor causes a worse agreement with theoretical curves. This is also proved in Tab. 2 where the values of avg and rms errors for SB` are always lower than those of SB. Introducing such floor thus causes more scattered acoustical data and consequently more uneven listening conditions in the room.

CONCLUSIONS

The sound absorption data of a typical layout of floor inside mosques have been presented and the effect of introducing such a structure in a room has been discussed. The developed procedure can help in verifying the acoustical behaviour of a mosque during the different building stages by the simple use of its main geometric characteristics and of the data here presented.

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Acoustical Performance of Indonesian Mosque

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Responding to the complaint raised by many moeslem worshipper on the acoustic condition of mosques, an acoustics survey have been conducted on several mosques.The survey comprising of data collection on the geometry of the room,interior materials,loudspeaker characteritics and placement, measurement of reverberation time,ambient noise level and sound level distribution. Most of the mosques have square plan,high ceiling integrated into single construction with the roof,such as piramidal tier-roof,dome and flat roof.These geometry and interior materials produced acoustical defects suach as long reverberation time,echoes and sound concentration.Some of the defects will be potentially amplified by improper loudspeakers selection and placement. .The remedy could be by applying sound absorbing materials on the proper surfaces, but besides it could be expensive , it will also distracting the artistical interior.The other posibility is to replace the existing loudspeakers with more suitable characteristics and placement. Computer simulation has been conducted on several mosques using loudspeaker characteristics and placement as simulation parameter and the results be assesed with the intelibility criteria.

INTRODUCTION

Many moeslem worshiper have raised their concern for not being able to hear intelligibly of the prayer's leader voice or the Friday sermons in the prayer hall of Indonesian mosque. The hall is usually not fully occupied during five time daily prayers, but it is fully occupied during Friday congregation. The pray is conducted in Arabic, while Friday sermon is in Indonesian. In the unfavourable acoustical conditions the Arabic praying becomes more difficult to hear since the Arabic has more complex consonants. The acoustical problem of the Indonesians mosque is commonly related to the mosque design. The fact that Indonesian mosque is mostly built without considering the acoustics.Instead, the design is relied on the local conditions, such as climate and available materials and technology. .The objective of this study is to improve the quality of hearing conditions in the prayer hall of existing mosque without modification of the interior materials and construction, or distracting the artistical interior of the mosque
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ACOUSTICAL ASPECTS OF MOSQUES ARCHITECTURE .

In Indonesia, particularly in Java, the mosque can be classified according to the roof shape,that are [1] : (see Figure 1)(i).Pyramidal tier- roof or Javanese vernacular,characterized by three tiers, (ii).Dome or Indo-Arabic roof shape. These were common mosque built in the last nineteenth century in Sumatra and in the middle of the twentieth century in Java.(iii) Flat roof and other non-traditional shape.These mosque were mostly built in the last twentieth century, and called as modern mosque.The mosque usually has ceiling integrated into single construction with the roof, and has open corridors surrounding square- or semi square–shaped prayer hall,except the back side of the mosque.

According to hall sizes, the mosque can be classified as: (1) Great mosque, having approximately 50 m x 50 m prayer hall, is commonly built in the big city, and has functions not only for worship but also as a center of various related religious activities.(ii) Community mosque,with prayer hall area of approximately 30 m x 30 m. The mosque is usually used for both worship and other religious activities by surrounding community. (iii) Small mosque has prayer hall area of approximately 10 m x 10 m, and is built in the village and populated area.

The acoustical problem is commonly encountered in the Great and Community mosque, where the hall has of at least 7 m high ceiling, large open doors and windows. This is typical design of the mosque built in the humid and tropic area. It is so design to control the natural airflow and thermal conditions inside the hall. However, the hall is easily intruded by high ambient noise from outside The acoustical problem become worst for mosque located in the city, urban area or nearby the busy road. In some mosques there is additional noise generated by fan inside the hall. Unfortunately, almost no mosque installs air-conditioning system in the prayer hall. As for the interior material,ceramic tile and plastered on brick are used for wall. In some Great mosques, marble is used for floor, wall and columns. The ceiling, for dome or flat roof, is made of concrete or wood finished concrete. The ceiling of pyramidal tier-roof is made of wood board, asbestos sheet or gypsum board.

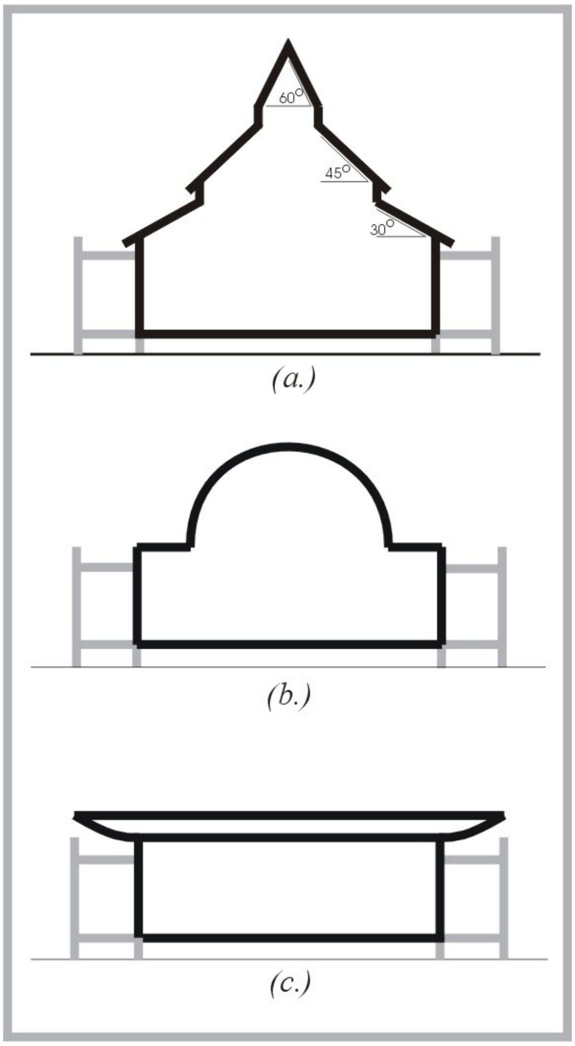

FIGURE 1 : Basic roof shape, (a) pyramidal-tier roof, (b) Dome-roof, (c) flat-roof

THE ACOUSTICAL PERFORMANCE

It was observed that most prayer halls have acoustical defeects, i.e. the observed reverberation time is longer than the required one, there were echoes, and non-uniformity of sound level distribution. These defects were caused by sound concentration and standing wave, and high ambient noise level. Some of these defects are potentially amplified by improper loudspeaker selection and placement inside the hall. Additional defect, such as loas of real source localization, may be generated.

Acoustical measurement of three similar size community mosques supported the observation. The reverberation time of the fully occupied hall, estimated from the measured empty hall at 1 k Hz were 1,7 ; 1.0 and 1.2 seconds,while the required reverberation time [2] were 0.9 ; 0.9 and 1.0 seconds respectively. This required reverberation time is the optimum reverberation time for speech hall The estimated reverberation time at mid-frequency is slightly lower than the low and high frequencies. The ambient noise level measured during the day time were between 45 to 50dBA, higher than that of recommended one, i.e. 40 dBA.

Computer simulation on hall with three different roof-ceiling shape indicates that the hall with dome and pyramidal tier-roof has high potential for producing sound concentrations and echoes.Further simulations were carried out to optimized hearing intelligibility..Loudspeaker directivity characteristic and placement were used as simulation parameters. The criteria of intelligibility is noted as the percentage of Articulation Loss of Consonant (% Al-cons. < 15 %), and the ratio of the early to late sound index C7 (> -15 dB) and C50 (> 0 dB). The results indicate that more than 80% areas of the prayer hall comply to one of those three criteria.

CONCLUSION

The acoustical performance of Indonesian mosque has been discussed. Without modification of the interior materials and structure, the acoustical performance of the prayer hall can be improved by proper selection and placement of the loudspeakers.

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Psycho-acoustic Evaluation of Sound in old Turkish Mosques

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Part of the European project CAHRISMA is to investigate the psycho-acoustic and subjective aspects that are characteristic of Sinan's mosques and Byzantine churches. The assessment of sound quality in the places of worship of the Ottoman cultural heritage in Turkey comprised two parts: a psychosocial survey by questionnaires, conducted among the users of the mosques, which is now complete; and a psycho-acoustic assessment, carried out in the laboratory, of sounds recorded inside the buildings as well as sounds modified using ODEON software, as stimuli, to determine which sounds are preferable to the listeners.

I. INTRODUCTION

This paper deals with the first step of the assessment of sound quality in mosques. This is one aim of the CAHRISMA project, although the main objectives of the project are the identification, conservation and restoration of architectural heritage of old Byzantine churches and Ottoman mosques. The basic approach is to evaluate both objectively and subjectively the sounds in the places of worship, and then to recreate an audio-visual 3D virtual image of the places of worship. The majority of this work is acoustical, which, until now, has been a neglected part of the architectural heritage. (Karabiber , 1)

The literature on sound quality in mosques is sparse; however a number of papers on sound in churches have been reviewed (Carvalho, (2); Magrini, (3); Ciao, (4)). The most interesting papers are those given by Desarnault (5) who studied, by social survey, the acoustical qualities of churches in Switzerland.

A possible analogy can be found in studies on room acoustics, especially in concert halls, such as the one by Gade (6) in Denmark, among many others.

Recently, the identification of the peculiarities of old Turkish churches and mosques has been carried out by acoustical measurements and computer aided modelling tools. The physical characterisation has been completed by an evaluation of the psycho-acoustical and subjective characteristics of these places of worship.

II METHODOLOGY OF THE QUESTIONNAIRE SURVEY

The survey comprises three steps: i) preparation after reviewing the literature and conducting open-ended interviews, ii) design of the questionnaire, iii) interviewing a representative sample of users of the mosques

2.1 A guide for the non-directive interviews

The guide focuses progressively on the main acoustical qualities of the mosques:

- choice of the mosque (good religious climate, few tourists, historical value),
- comparison with other mosques that the person knows,
- the interviewer then lists the qualities of the mosque (where the person prays).

The interviewer then directs the interview towards the **acoustical qualities of the mosques:** different purposes and acoustical qualities; the amplifier system, (is it a technical advance?); directivity of sound; homogeneity of sound; intelligibility of prayer, sermon, and speech; quality of music and songs; comparison with other mosques and/or large halls that the person knows.

2. 2 Analysis of the non-directive interviews

A preliminary interview was conducted by the whole team; the Imam of the Kadirga Sokullu mosque was interviewed for 45 minutes. After analysis of this first interview, 12 other people were interviewed by the Yildiz team, in various historical mosques in Istanbul. A draft questionnaire was written and modified to make it easier for future interviewees to understand. A second draft was written and tested in actual conditions on ten people after translation into Turkish. The extended survey was carried out in four mosques: the Selimiye mosque in Edirne and the Süleymaniye, Sultanahmet and Kadirga Sokullu mosques in Istanbul. The survey was carried in October 2000.

About 30 or more useful questionnaires were completed by men for each mosque, giving a minimum statistical sample per mosque. A coding plan was designed and the questionnaires coded. The data have been organised in an Excel file.

III RESULTS

Some of the more interesting results are presented below:

Q1-Reason of choice	Numbers	%
No response	0	0
Convenience	65	50
Religious practice	47	36.2

Historical or architectural value	86	66.2
Acoustical quality	4	3.1
Others	5	3.8
TOTAL/ Respondent	207	159.2

The importance of 'cultural heritage' is greater than convenience or even 'religious practice'.

Q2-Like	Numbers	%
No response	1	0
Acoustical qualities	13	10
Cleanliness	19	14,6
Decoration	77	59.2
All aspects appreciated	26	20
Others	39	30
TOTAL/ Respondent	164	133.8

The acoustical qualities of the mosques are identified spontaneously by 10% of respondents.

22% of respondents dislike something; this reinforces the confidence in the responses, which are not systematically positive: 30 to 40% of respondents note outdoor or even indoor noise.

Q5-Outdoor Q6 Indoor noise	Numbers	%
Bus, tourist, traffic, people	22	16.9
Children or sellers	15	11.5
Machines or other sources	3	2.3
Children	8	6.2
Whispering, breathing, voices	35	26.9
Tourists, cameras, guides	10	7.7
TOTAL/ Respondent	130	100

30% of people state that there is some outdoor noise.

The presence of children, tourists and guides creates some indoor noise; but the sound of unexpected voices is more significant, due to the intrinsic acoustical qualities of the ceremony of worship.

After performing analyses for each mosque, some cross analyses were carried out in an attempt to establish relationships between different acoustical parameters:

Q12-Intelligibility by Q7- sound quality %

	Bad	Average	Good	don't kn	TOTAL
bad	0.0%	0.0%	0.0%	0.0%	0.0%
rather bad	0.0%	0.0%	0.0%	0.0%	0.0%
medium	100.0%	22.2%	6.5%	0.0%	9.3%
rather good	0.0%	33.3%	44.9%	33.3%	42.6%
good	0.0%	44.4%	48.6%	66.7%	48.1%
TOTAL	100.0%	100.0%	100.0%	100.0%	100.0%

This table clearly indicates the relationship between intelligibility and the quality of sounds perceived in old mosques.

In these large places of worship we suspect that the exact location has some importance.

Q4-location by Q16-Annoying echo %

	first row	Back	Anywhere	Other	Total
No response	56.1%	66.7%	32.6%	44.4%	47.7%
yes	8.8%	0.0%	7.0%	0.0%	6.2%
most of the time	0.0%	8.3%	2.3%	5.6%	2.3%
no	35.1%	25.0%	58.1%	50.0%	43.8%
TOTAL	100.0%	100%	100.0%	100%	100%

The reflected sound perceived by people on first row or anywhere else can become annoying (9 and 7 % versus 0% at the back). So the placement, and not only the distance source listener, has an influence.

Q9-Acoustic qualities of sermon					
Q14-Reverberation	bad	medium	good	NR.	Total
bad					
rather bad	100.0				100.0
medium	6.7	20.0	66.7	6.7	100.0
Rather good		16.5	78.5	5.1	100.0
good		8.8	85.3	5.9	100.0
TOTAL	1.6	14.7	78.3	5.4	100.0

Q9Bis-Acoustic qualities of prayer					
Q14-Reverberation	bad	medium	good	NR.	Total
bad					
rather bad	100.0				100.0
medium		20.0	80.0		100.0
Rather good		5.1	94.9		100.0
good			100.0		100.0
TOTAL	0.8	5.4	93.8		100.0

78% of the subjects find the acoustical qualities of the sermon good whereas 94% them find the qualities of the prayer good. This shows that people can detect the acoustical difference between speech intelligibility and the perception of the religious musical activities (in spite of their general positive attitude towards those historical spaces). These results are in accordance with the measurement results made by other teams of the project (which shows that the reverberation times are long for speech activities).

CONCLUSION

Acoustical qualities in old mosques are recognised by 10% in spontaneous answers, and by more in elicited responses. Although there is still a risk that the responses have been affected by people's affection to religious spaces, different negative responses show that these results can be accepted as reliable. The location of the listener and the nature of the message (e.g. a sermon requiring intelligibility or prayers which do not) are the main factors to consider in rating the quality of the sound.

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Computer Simulation of the Acoustics of Mosques and Byzantine Churches

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The EU project **CAHRISMA** (***C****onservation of the* ***A****coustical* ***H****eritage by the* ***R****evival and* ***I****dentification of the* ***S****inan's* ***M****osques* ***A****coustics) investigates, among other things, the acoustics in some of the old churches and mosques in Istanbul, Turkey. The present paper deals with acoustic computer simulations of churches and mosques within this project. Three Byzantine churches and three mosques were modeled in the ***Odeon*** room acoustic program. These geometries are dominated by spherical and cylindrical (concave/convex) shapes; especially large domes dominating the ceiling. Another feature in the rooms is numerous columns and galleries obstructing the direct sound. In the models, calculation parameters such as transition order (***TO***), number of rays and the number of subdivision into plane surfaces of concave/convex surfaces are changed. This is done in order to investigate the effect on the results for the different room acoustic parameters (according to ISO 3382). The simulations are compared with room acoustic measurements made in the real rooms.

Introduction

From the six models made in ***Odeon*** of the buildings investigated in the **CAHRISMA** project, two of the models have been chosen for further investigation. These are; the Byzantine church ***Saint Irene*** and the ***Selimiye*** Mosque. Various calculation parameters have been changed and the simulated results have been compared with the measured results, to optimize the models. This is mainly done to examine the effect of concave/convex surfaces (domes, arches etc.), and to examine which of the two calculation methods; ray-tracing or image-source, are best suited for this purpose (***Odeon*** uses a hybrid method). The following is a listing of the altered calculation parameters.

1. ***Geometrical Resolution:*** Low, Medium and High. Number of plane surfaces used to model the concave/convex surfaces.
2. [1]***Transition Order (TO):*** 0, 1 and 2.
3. ***Number of rays:*** From approx. 100 to approx. 999.999 (maximum for ***Odeon***).

Comparing rooms and models

In order to compare the simulated with the measured results, an error value is calculated. This is done in the following manner:

$$Error = \frac{\left|AP_{measured} - AP_{simulated}\right|}{SL} \qquad (1)$$

Where,

$\boldsymbol{AP_{measured}}$ is the measured value of the current acoustic parameter.
$\boldsymbol{AP_{simulated}}$ is the simulated value of the current acoustic parameter
SL is a subjective limen for the current acoustic parameter (see ref. 1 – ex. one ***SL*** for EDT is 5 %)

This error is calculated for each position, frequency band (1/1 octave) and acoustic parameter. For each of the three models with different geometrical resolution, a reference model is made. This is done by adjusting the absorption of the surface material having the largest absorption area, so a global estimate of the reverberation time matched the measured values within one ***SL***. From this reference model, calculations were done using three different ***TO***, the three different geometrical resolutions and using 10 different number of rays for ***Selimiye*** and 11 for ***Hagia Irene***.

Results - The Selimiye mosque

The following diagrams (fig. 1) show the error values as a function of the number of rays used. The error is calculated from an average over the six acoustic parameters: EDT, T_{30}, T_s, C_{80}, D_{50} and LF_{80} (according to ISO 3382). Furthermore it is spatial and frequency

[1]Transition order determines when ***Odeon*** uses the ray-tracing method, instead of the image-source method. ***TO*** 0 = full ray-tracing.

averaged (125 – 4000 Hz). The diagrams show the error for the two ***TO*** 0 and 2, and the effect of the three resolutions are compared in each diagram.

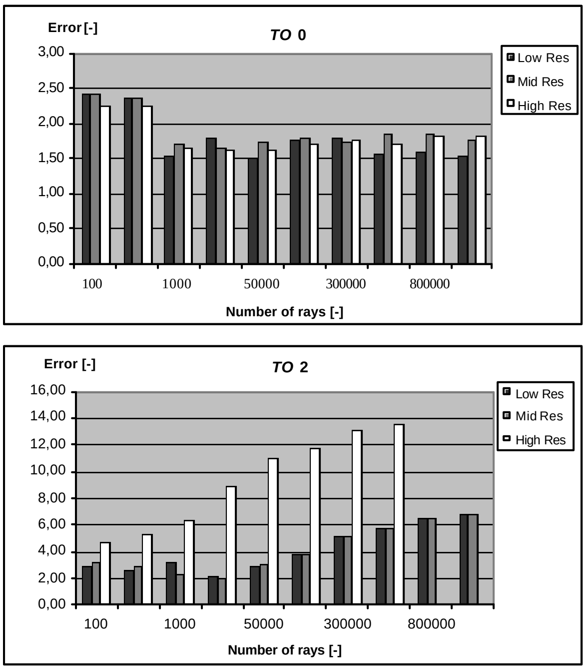

FIGURE 1: Average error for the six room acoustic parameters as a function of number of rays for ***TO*** 0 and 2, and the three orders of resolution. For high-resolution ***TO*** 2, ray-numbers 800.000 and 999.999 are not calculated due to long calculation times.

From figure 1 it is mainly seen that the higher the ***TO***, the higher the error. For ***TO*** 0 the three resolutions almost give the same magnitude error, and the lowest error is found at low geometrical resolution using 50.000 rays (error = 1,51).

Furthermore it is seen that using a ray number higher than 1000 does not improve the error. For ***TO*** 2 it is seen that high resolution gives a much higher error for all ray numbers compared to the two other resolutions The smallest error for high resolution is found at the lowest ray number, and increases with increasing ray number. Low and medium resolution almost show the same error values but also increases with increasing ray number.

From these results it is generally seen that using ***TO*** 0 and any of the three resolutions, and using 1000 rays or above gives the smallest error. To get the fastest calculation time and still get optimum results, it seems sufficient to use the lowest resolution and 1000 rays.

The fact that ***TO*** 0 generally gives the lowest error can be explained by the domination of the domes. The domes (mainly the center dome) are placed at a height, which gives the sound a large amount of diffusion, which can also be seen from the measured T_{30}, which has a spatial standard deviation of 0,16 sec. (freq. Average from 125 – 4000 Hz). The spatial average value is 6,21 sec., so it is within one ***SL***.

Results - Saint Irene Byzantine church

Below are shown the ***TO*** 2 results for ***Saint Irene***, in the same type of diagram as for ***Selimiye***. The ***TO*** 0 results looks like the one from ***Selimiye***.

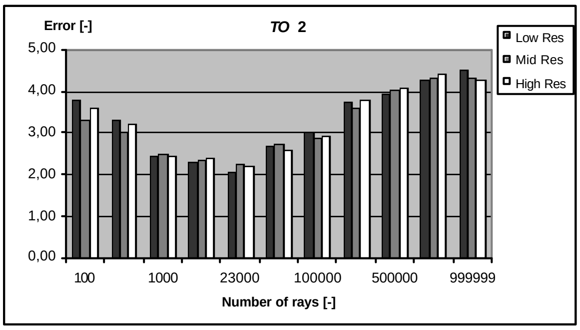

FIGURE 2. Average error for the six acoustic parameters as a function of number of rays for ***TO*** 0 and 2, and showing the three different geometrical resolutions.

For ***Saint Irene*** the error does not depend nearly as much on the resolution as for ***Selimiye***. For ***Saint Irene*** it is ***TO*** that determines the error. The higher ***TO***, the higher the error. For ***TO*** 2 the error decreases from 100 to 23.000 rays, where it reaches a minimum, and then it has a steady increase to 999.999 rays.

The numerous domes in ***Selimiye*** compared to ***Saint Irene*** can explain the fact that the error does not depend on the resolution as much as for ***Selimiye***. The domed surfaces in ***Selimiye*** take up a greater portion of the total surface area, than the ones in ***Saint Irene***.

Conclusion

This study generally shows that, for complex rooms with many curved surfaces, modeled with relatively small plane surfaces, the ray-tracing method yields the best results (***TO*** = 0).

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Acoustical Behaviour In Mudejar-Gothic Churches

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The aim of this paper is to point out some aspects of the acoustic behaviour of the Mudejar-Ghotic churches. The study focuses on a representative sample of this type in the city of Sevilla (Spain) but we attend to obtain more general conclusions from the measured-calculated data.

INTRODUCTION

This paper focuses on the study of the sound field in Mudejar-Ghotic churches. The Province of Seville, in the south of Spain, has a representative sample of these churches. D. Angulo [1], the famous specialist, called this type of church the "Seville parish type".

Mudejar churches were built in the Spanish Middle Ages, reaching their greatest splendour in the thirteenth and fourteenth centuries. They usually had a vaulted presbytery as a result of the stylistic evolution from Romanesque to Gothic, and the three naves had a timber roof trusses following Moorish tendencies. Many of these roofs have been lost to fire. All these churches are used today for worship. Both, estimations and measurements of acoustical parameters have been carried out, [3], [4], [6].

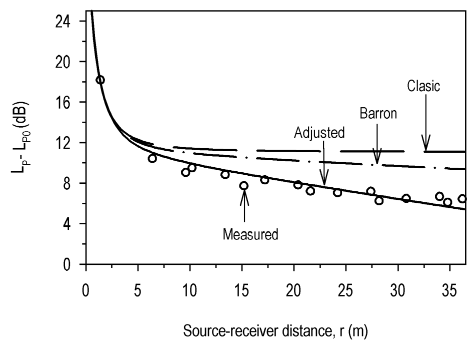

FIGURE 1. Sound pressure levels versus source receiver distance for the 2 kHz octave band in Sta Marina church.

The most significant geometric and acoustic parameters of the churches analysed are listed in table 1. The measured reverberation times, T, refer to unoccupied churches at 1 kHz octave band.

Steady state measurements

One of our objectives is to analyse how the reverberant field varies with distance for broadband and with the different frequency bands. To do this, we compare the measured attenuation of reverberant field over source-receiver distance with that predicted by Barron's model [2]. Taking this into account, Barron's model has been modified for Mudejar-Ghotic churches [3]. The modification was carried out by looking for the β_i parameter for the best adjustment to the experimental levels for each octave band studied and for broadband, in each church, according to the equation:

$$L_P - L_{P0} = 10\log\left(\frac{100}{r^2} + \frac{31200T_i}{V} e^{-\frac{\beta_i r}{T_i}}\right), \qquad (1)$$

where L_{P0} is the reference level produced by the source at a distance of 10 m in free field conditions. Fig. 1 compares Barron´s model and adjusted model with measured data for 2 kHz band in Santa Marina church.

From these adjusted values of β_i parameters we intended the elaboration of a typological model de-

Table 1. Significant data on Mudejar-Gothic Churches.

Church	Sta. Marina	S. Vicente	S. Julián	S. Gil	S. Pedro	S. Marcos	Sta. Catalina	S. Isidoro
Volume (m^3)	8700	6920	6230	6200	6110	4760	4360	3950
Nave length (m)	34	27	27	25	20	26	22	26
Width (m)	18	18	15	16	17	17	12	14
Mean height (m)	15	11	13	14	16	10	12	11
Volume/place (m^3/per.)	16.5	21.0	17.5	19.0	20.5	13.0	16.0	14.0
Reverberation time (s)	4.00	1.82	3.81	2.50	1.99	4.01	1.75	2.30
Interior *	(b) (c)	(a) (c)	(b) (c) (f)	(a) (d) (f)	(a) (c) (e)	(b) (c)	(a) (c) (e)	(a) (c)

(*) Side naves very adorned with altars, altarpieces and pictures (a), less adorned (b). Apse with brick or brick plastered (c), with curtains (d). Presbytery with carpets (e). Ceramic baseboard of about 1.50 m high (f).

scribed by mean values $\langle \beta_i \rangle$ of all churches for each octave band (table 2).

Table 2. Average adjusted β_i parameters.

Freq. (Hz)	250	500	1000	2000	4000
$\langle \beta_i \rangle$	0.06	0.11	0.08	0.12	0.12

Impulse measurements

From this modified model we attempt to analyse the correlation between the predicted and measured values (from the impulse response) of the objective acoustic clarity (C_{80}) and definition (D_{50}) indices, with the subsequent possibility of predicting their values in this architectural typology with no other premises than their volume (V) and T_i [4]. Fig. 2 compares predicted and measured values for C_{80} at Santa Marina church.

Although the modifications of Barron's model have helped us to develop a typological model that efficiently predicts stationary reverberant field attenuations over distance for different octave bands, we have found that such efficiency is much more limited for predicting indices based on early-to-late energy ratios. In fact, it seems sufficient to give the broadband set of values for these indices. Furthermore, Barron's model provides results similar to those of our model. They only show trends because significant variations of index values among relatively close positions are impossible to incorporate into simple analytical models such as Barron's one or this we have proposed. In contrast, we think that it is possible to simulate spectral and spatial variations by raytracing techniques using RAYNOISE [5].

Speech intelligibility

Finally, the scope is to show the relationships between two types of acoustical parameters (STI/RASTI and D_{50}) that are strongly connected to the speech intelligibility and that are obtained through two quite

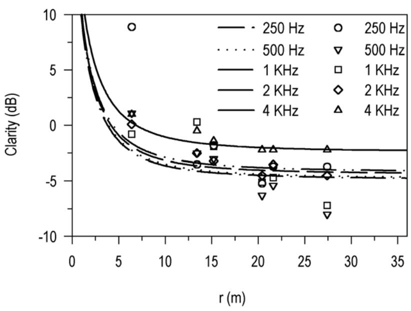

FIGURE 2. Clarity versus distance in Santa Marina Church. Symbols: measured data. Solid and doted lines: theoretical typological model.

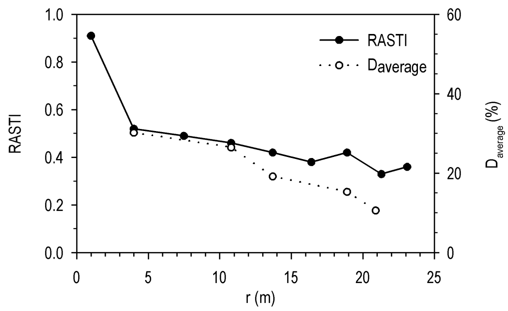

FIGURE 3. RASTI and $D_{average}$ versus source-receiver distance in San Gil church.

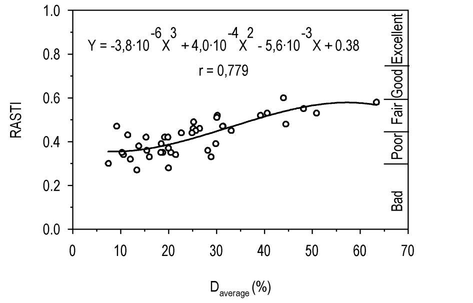

FIGURE 4. Relationship between RASTI and $D_{average}$.

different experimental techniques [6]. Fig. 3 compares RASTI and $D_{average}$ (D_{50} averaged over the 500 and 2000 Hz) versus source receiver distance in San Gil church and Fig. 4 the relationship between RASTI and $D_{average}$ for all measured churches.The correlation between RASTI and D is similar to that which Bradley [7] proposed between C_{80} and STI for classrooms, even though we must indicate that the RASTI values in these churches are smaller and the dispersion somewhat greater, as shown in Fig. 4. However, the regression curve that appears is also of third-order with a multiple correlation coefficient of 0.

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Serbian Orthodox Church - An Acoustical View

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Acoustical characteristics of Serbian orthodox churches are strongly influenced by their architecture and the type of religious service performed in them. The service consists of acapela chorus' polyphonic singing coupled with preachers' chant. Over the last decade, significant research efforts were conducted in churches across the country. Their acoustical characteristics were determined through measurements undertaken in 60 buildings of different sizes and dates.

INTRODUCTION

There are three important aspects that need to be distinguished in analysis of acoustical characteristics in Serbian orthodox churches:

1. The cultural heritage aspect - refers to historical and cultural significance of Serbian churches; research is focused on analyzing acoustical properties as they are.
2. The sound aesthetics aspect - the search for subjective preferences in acoustical response of worship space for contemporary orthodox service.
3. The engineering aspect - includes methods of church acoustical design and the achievement of optimal acoustical response using construction and interior design solutions and audio systems.

These aspects represent relatively independent research topic that need to complement each other.

Acoustic research in Serbian orthodox churches over the last decade has determined their existing acoustical characteristics [1,2,6]. The new research efforts aim to determine the subjective preferences in acoustical response for musical forms of contemporary religious service. Even today, the churches in Serbia are still built in the traditional way, without common acoustical interventions in their interior. Consequently, analysis of churches' existing acoustical state provides essential information relevant for engineering aspects of the topic

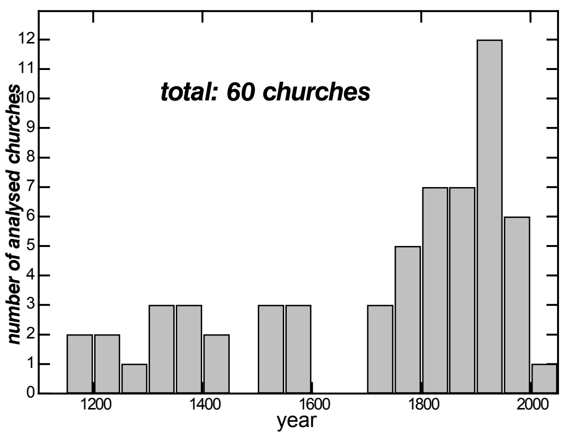

Fig 1 - Age of analyzed churches

RESULTS OF MEASUREMENTS

Acoustical research carried out over the past ten years involved measurements in 60 churches of different age and sizes. This sample included the prominent old churches as well as some that were built more recently, less than 200 years ago. Churches from the latter group were selected to satisfy various aspects of uniformity of relevant parameters. The age breakdown for the sampled churches is presented in Fig. 1. The distribution of their volumes and respective reverberation times is shown in Fig. 2. Churches with volumes greater than 5.000 m^3 are rare in Serbia.

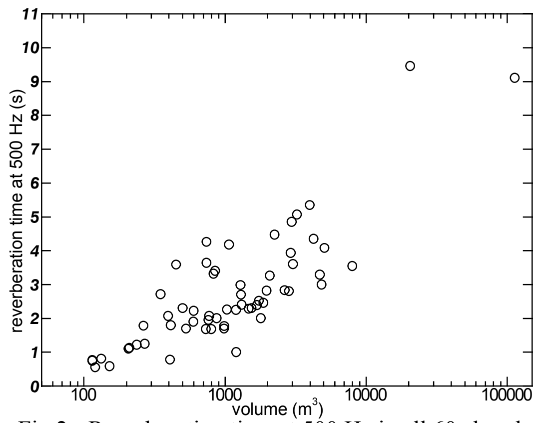

Fig 2 - Reverberation time at 500 Hz in all 60 churches

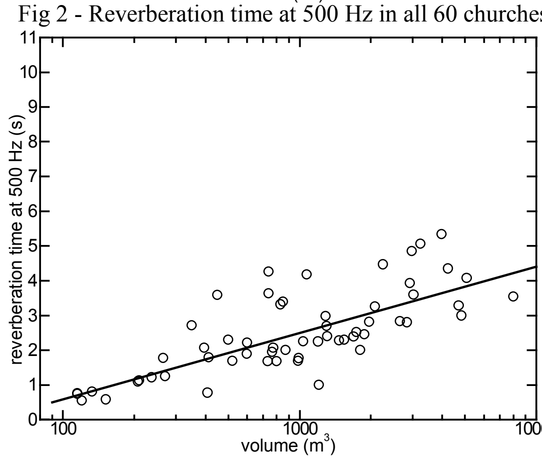

Fig. 3 - Reverberation time vs. church volume

The relationship between reverberation time and volumes in traditional churches is presented in Fig. 3.

They are characterized by a lack of significant fragmentation of the interior, and the use of only mortar or stone on interior surfaces. Therefore, the average reverberation time is longer than that of churches of other religions. Fig. 4 shows some comparisons.

The ratio of volume to floor surface is an important parameter for acoustical response prediction. This ratio is also an element of acoustical design because the sound absorption by people is a significant factor forming the response of worship space. The relationship of reverberation time and the ratio of volume to floor surface of traditional churches is presented in Fig. 5.

Due to relatively small volumes of Serbian churches, interior design elements, such as wood panels on the walls, altar partition, tables, carpets, and fabric decorations are important in acoustical design. Fig. 6 illustrates an example of the effect these elements can have on acoustical design. Two churches of the same volume (about 700 m^3) were selected, denoted as churches A and B. Church A is new and the measurement was made immediately after it was built (1998). Its interior was almost empty. Church B is an old church with the common considerable furniture and fixtures. The figure shows the difference in reverberation time caused by such difference.

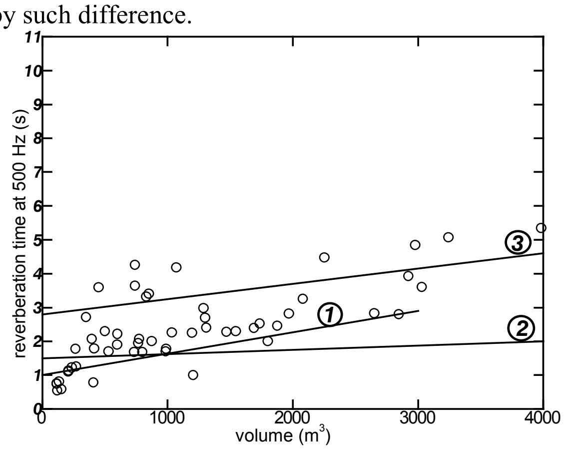

Fig 4 - Comparison with results from some other churches: circles - results from fig. 2; 1 - Buzantines churches [3]; 2 - English churches [4]; 3 - Catalan churches [4];

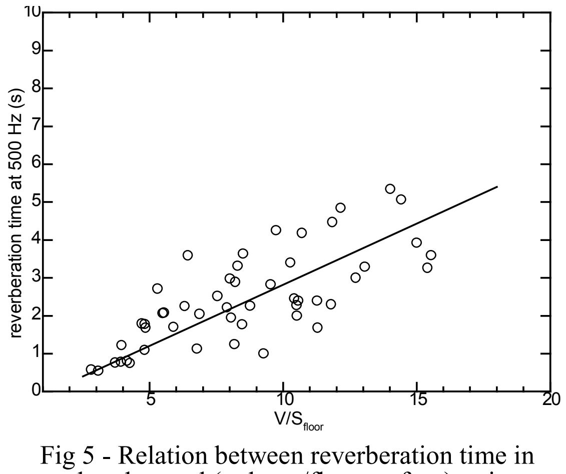

Fig 5 - Relation between reverberation time in churches and (volume/floor surface) ratio

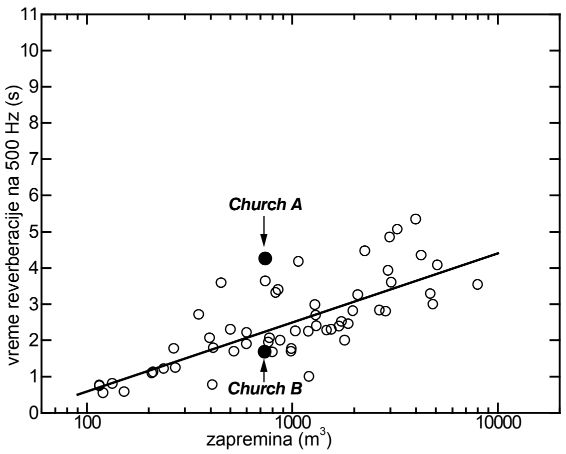

Fig 6 - Illustration of church furniture and fixtures influence

OPTIMAL ACOUSTIC RESPONSE

The contemporary service in Serbian churches consists of priests' chant and chorus' polyphonic singing. Priests move during the service, while the chorus is positioned on an inside gallery above the church entrance. Subjective preferences in acoustical response can be found using known theories [5]. The research included the analysis of autocorrelation of signals recorded during the religious service, as well as the subjective tests during services in churches.

Consequently, the churches with optimal acoustical response were found. It has been demonstrated that optimal response is achieved in churches built in a traditional way of about 2000 m^3 volume. In churches whose volumes exceed the optimal levels, a sophisticated sound reinforcement system is necessary, which can enhance both the sound level and aesthetic requirements in overall response.

METHODS OF ACOUSTIC DESIGN

The knowledge about subjective preferences in acoustical response of worship spaces are the starting point in acoustical design of new churches. Due to cannoning limitations in materials, the possibilities in acoustical design are very limited. For designers the following remain:

- Building the churches with acoustical active volume as near as possible to the optimal value;
- Making the furniture and fixtures in sufficient amount;
- Application of sound reinforcement systems to adjust the beginning part of overall impulse response according to subjective preferences.

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Acoustic effectiveness of pulpit reflector in churches

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Since the 12th century, pulpits and pulpit reflectors (canopies) were widely used in churches. This paper studies the acoustic effectiveness of such devices based on in site measurements (*STI* and *D50*) in four (unoccupied) churches with pulpits with and without the canopy. The pulpit reflector can remove the late reflection resulting from a high ceiling and makes possible to improve the listening conditions at medium distance from the pulpit. The pulpit reflector effectiveness decreases and becomes even unfavourable when the height of the ceiling drops (h < 10 m) and when the distance to the speaker increases. The absolute variations of speech intelligibility ratings are generally rather weak (average *STI* variation from +0.01 to -0.03), but can increase in the presence of an assembly.

INTRODUCTION

Since the 12th century, the use of pulpits, generally provided with a pulpit reflector (canopy) spreads in churches. A recent study [1] showed that in Switzerland, about 76% of the churches still have pulpits and half of those are provided with a canopy. The use of the pulpits, which remains traditional for preaching in the Protestant churches, is now in disuse (about 32% of the Swiss pulpits are never used). This paper presents a study on the objective acoustic effectiveness of pulpits reflectors for the speech intelligibility ratings based on measurements in four standard churches.

METHOD

Two indices of objective evaluation of speech intelligibility (*STI* and *D50*) were calculated from the impulse response, established on the basis of two measuring devices (Symphony with dBBati32 of 01dB and MLSSA). The use of a MLS sequence makes it possible to reduce the duration of in site measurements and to provide instantaneously various evaluations of speech intelligibility ratings.
The measurements were carried out in unoccupied churches in two situations: initially, placing the sound source on the pulpit under its canopy at about 1.5 m (measurements named "with canopy"), then at the same height but on the side of the pulpit not to have the effect of its canopy (measurements named "without canopy"). Measurements were carried out in four churches in Lausanne (Switzerland) whose main room and pulpit characteristics are presented in tables 1 and 2. In each church four measuring points were studied (table 3).

Table 1. Main characteristics of the churches studied.

Church, symbol	Volume (m^3)	Nave high (m)	Area (m^2)	RT avr. (s)
Cathedral, C	35000	20.0	2400	6.5
Allemande, A	1680	11.5	-	3.0
Terreaux, T	3600	9.5	380	2.4
St. Laurent, SL	3150	10.5	300	2.5

Table 2. Pulpit and canopy main characteristics (m).

C h.	Pulpit Position	Pulpit high	Canopy height	Canopy width	Canopy length
C	lateral nave	1.83	2.44	2.00	1.45
A	lateral choir	1.42	2.75	1.75	1.75
T	central choir	2.09	2.06	1.50	1.90
SL	central choir	2.15	2.00	1.00	1.00

Table 3. Measuring points - distance to sound source.

Church	1	2	3	4
C	4.0	8.2	10.1	15.5
A	3.2	8.6	7.8	12.5
T	4.5	10.0	15.0	18.0
SL	4.4	4.8	8.2	10.1

RESULTS

The results obtained with 01 dB for speech intelligibility parameters, expressed by the *STI* and *D50* with and without canopies, are presented in table 4. In the Cathedral (C) and in the church Allemande (A), that have a high ceiling, there is a beneficial effect of the canopy at medium distances (position 2). For the positions at long distance (positions 3 and 4) there is a slight deterioration. At short distances of the sound source (position 1) the speech intelligibility parameters are little influenced (C) or slightly underprivileged (A) by the presence of the canopy.

This last case can be explained by the displacement of the sound source for the measurement "without canopy" (increase in the distance source/receptor).
On contrary in the Terreaux and St. Laurent churches, that have a lower ceiling (h < 10 m), the presence of the canopy deteriorates the speech intelligibility parameters at short and medium distances of the sound source. In these cases, the sound reflection from the ceiling is useful for the speech intelligibility (delay with direct sound lower than 35 ms). The positions located at medium distances or apart from the pulpit axis, are those that present the most significant loss of speech intelligibility because they do not profit any more from a ceiling reflection neither benefiting from those from the canopy. Such churches do not benefit by the presence of a canopy.

Table 4: *STI* and *D50* values measured with and without canopy (%).

Situat.	Posit.	Cathed.		Allem.		Terr.		S. Laur.	
		STI	D_{50}	*STI*	D_{50}	*STI*	D_{50}	*STI*	D_{50}
with canopy	1	58	*54*	45	*29*	54	*42*	50	*39*
	2	55	*49*	49	*33*	51	*40*	48	*30*
	3	43	*26*	43	*22*	45	*24*	49	*32*
	4	38	*19*	46	*27*	47	*28*	48	*31*
	avg.	**49**	***37***	**46**	***28***	**49**	***34***	**49**	***33***
without canopy	1	59	*51*	46	*29*	61	*53*	53	*44*
	2	48	*38*	47	*32*	53	*36*	55	*46*
	3	43	*28*	45	*32*	49	*32*	52	*48*
	4	41	*24*	47	*31*	46	*26*	48	*30*
	avg.	**48**	***35***	**46**	***31***	**52**	***37***	**52**	***42***
"with canopy" - "without canopy"	1	-1	*3*	-1	*0*	-7	*-11*	-3	*-5*
	2	7	*11*	2	*1*	-2	*4*	-7	*-16*
	3	0	*-2*	-2	*-10*	-4	*-8*	-3	*-16*
	4	-3	*-5*	-1	*-4*	1	*2*	0	*1*
	avg.	**1**	***2***	**-1**	***-3***	**-3**	***-3***	**-3**	***-9***
	st.dev	4	*7*	2	*5*	3	*7*	3	*8*

DISCUSSION

The absolute variations of the speech intelligibility parameters are in general relatively modest (average *STI* variation from +0.01 to -0.03 according to church and standard deviation between measuring positions from 0.02 to 0.04) but can increase in the presence of an assembly. The variations of the *D50* values are coherent (slightly higher absolute values) with the *STI* values. These results are notably weaker than those obtained by Epstein [2] in the case of significant size canopies located in large Dutch churches, and slightly different from the predicted values obtained with a theoretical model and ray tracing simulations [3].
The detailed analysis of the *STI* modulation matrix highlights in certain cases (high ceiling without canopy) an increase, in certain bands of octaves, of the modulation coefficients between 6 and 8 Hz that corresponds to a late reflection. The correction of the *STI* predicted in these cases [3] would led to a reduction in the values from 0.8 to 1.4 and thus an additional increase in the effect of the canopy in the same proportions.
The measurement technique used does not seem well adapted for measurements at short distances. Indeed, the displacement of the sound source required for the measurements in the "without canopy" situation disadvantages these positions whatever the church.

CONCLUSION

Based on in site measurements in four churches, we can separate the churches according to their ceiling height (h ≥ 10 m as in the cathedral of Lausanne and the Allemande church or h < 10 m as in the Terreaux and St. Laurent churches). When the height of the ceiling and the size of the canopy are significant, a beneficial effect of this one is noted, mainly for the listeners located at medium distances from the pulpit. On the other hand, the effect of the canopy is almost non-existent at long distances. For short distances from the pulpit, a weak effect is noted that can be explained by a modification of the distance source-receiver. For churches with lower ceilings (< 10 m), an unfavourable effect of the canopy is noted at short and medium distances. In this case the presence of a canopy removes the early reflections from the ceiling church that are favourable for the listener. The presence of a canopy is thus not favourable in a low ceiling church, but it is interesting at medium distances in the higher ceiling churches. Whatever the ceiling height, the canopy does not have an effect at long distances.

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On the Distribution of Acoustical Parameters: Comparison between Experimental Results in Historical Christian Churches and Theoretical Models.

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Ancient worship buildings generally present an articulated space distribution (nave, aisles, chapels, transept, cupolas, volts) that leads to a very complex sound field. Since they represent a wide part of the Italian monumental heritage, the development of a rational measurement procedure could have a significant interest, aiming at obtaining a faster and simpler but exhaustive acquisition and post processing data.

A comparative analysis between theoretical models and experimental measurements carried out in 10 Italian churches (XI-XVI sec.) is presented. The geometrical characteristics of the considered environments do not lead to simple correlations: this may be related to preferential sound directions due to architectural elements (columns, arches, volutes, surfaces with elements in relief).

INTRODUCTION

Worship spaces represent a wide part of the Italian historical cultural heritage. Some of them often need restoration and in some cases a new destination may be considered with a different "acoustical" function from the original one (i.e. auditorium, concert hall). In this case they could present significant problems related to the acoustic quality. Therefore the development of a rational measurement procedure could be relevant to allow an accurate acoustical design with a minimum but comprehensive number of measurements. A survey of available theoretical models on the spatial distribution of some significant acoustical parameters has been carried out. The most suitable ones to worship spaces have been applied to some ancient Italian churches. A comparative analysis between theoretical models and experimental data is presented.

THEORETICAL MODELS

Barron, from '70s [1,2], proposed an analytical model for the evaluation of some significant acoustical parameters, based on the assumption of the linear dependence between sound decay and Reverberation Time (RT), using the volume of the hall (V) and the source-receiver distance (r).

However the model was conceived to be applied on concert halls and tested on 15 of them, as the Gade's one, in '90s [3] (verified on the basis of 32 concert halls), which gave empirical linear regression formulae to predict acoustical parameters with experimental RT. More recently, specific analyses were developed for worship spaces. A wide scientific research was carried out for Portuguese [4,5] and Spanish churches [6].

Carvalho [4,5] presents predictive equations to estimate acoustical parameters by using simple architectural data and, in some cases, also measured values, validated by an experimental survey on 41 churches ($V=299\div18674\ m^3$). Galindo et al. [6] modify Barron's equations, with β coefficients obtained by non-linear regression from experimental values measured in 8 Spanish churches ($V=3947\div8696\ m^3$).

The above considered models have been summarised in Table 1. In the determination of the Clarity Index (C80) and Definition Index (D50), the A Model considers the direct sound, the early reflected component and the late sound and it needs experimental RT values and geometrical parameters (V,r). In the present work also air attenuation coefficient (m) was taken into account. In the B Model the assumption of no influence of the direct field is considered (only V is needed). Two constant values (a,b) are taken into account to obtain a better

Table 1- Analysed Theoretical Models (A, B, C, D) for the evaluation of Clarity and Definition Indexes

Model	Clarity and Definition Indexes
A [1,2]	$C_{80}=10\ Log[(100/r^2)\ (H\ V/5023.2)\ (e^{0.248\ H\ r\ +6.8941})\ +(1\ -\ e^{-6.8941\ H})/(e^{-6.8941\ H})]$; H=0.161/(RT-4 m) $D_{50}=100\ \{1-[(5023.2/H\ V)\ (e^{-0.248\ H\ r\ -\ 4.31\ H})]\ /\ [(100/r^2)+(5023.2\ /\ H\ V)\ (e^{-0.248\ H\ r})]\ \}$;
B [3]	$C_{80}=a+b\ [10\ Log_{10}\ (e^{1.104\ /\ RT}\ -\ 1]$; $a=-0.4$; $b=0.9$
C [4,5]	$C_{80}=a+b\ [10Log_{10}\ (e^{1.104/RT}-1)]\ -0.025\ L_{max}$; $a=0.0576$; $b=1.045$ $D_{50}=100\ (0.347+0.048\ C_{80exp}+0.0016\ C_{80exp}^{\ 2})$; C_{80exp}= experimental value
D [6]	$C_{80}=10\ Log\ \{[V\ e^{(\beta\ r\ +13.82\ \tau)\ /\ RT}]\ /\ [(312\ RT\ r^2)+[e^{13.82\ \tau\ /\ RT}-1]\}$; $\tau=80$ ms; $D_{50}=100\ \{1-(31200\ RT/V)\ e^{-(\beta\ r\ +\ 13.82\ \tau)/RT}/[(100/r^2)+31200\ RT\ /\ (V\ e^{-\beta\ r\ /\ RT})]\}$; $\tau=50$ ms

correlation with experimental data in concert halls. Among the various models proposed by Carvalho in the literature, the C Model appears to fit better the experimental values considered in the present work. It evaluates C80 with measured RT, with an expression similar to the B Model (different a and b values), adding a correction depending on the maximum length of the church (L_{max}). His best correlation for D50 depends on the experimental C80 values. In the D Model, the β coefficients considered are averaged, for each frequency, among the values obtained from the analysis of the sound field in 8 Spanish churches.

DISCUSSION AND CONCLUSIONS

Clarity and Definition Indexes, measured in 10 Italian churches (XI-XVI sec.) [7], have been compared with the results of the analysed theoretical models, using as input data V, r, L_{max}, experimental RT and C80 of the examined churches (V=1500÷27.000 m^3). Experimental data have been divided into three ranges, depending on r and V. The statistical factor used for this comparison is the Intraclass Correlation Coefficient (ICC), as the ratio of variance between subjects to total variance (variance within subjects plus variance between subjects) [8,9], which is considered satisfying for values above 0.85.

Table 2 – ICC for the Clarity Index

r	V	A	B	C	D
< 23 m	**> 18000 m^3**	**0.71**	0.50	0.36	0.69
> 23 m	**> 18000 m^3**	0.29	0.25	0.49	0.21
< 23 m	**< 18000 m^3**	0.53	0.49	**0.59**	0.44

The ICC values obtained for C80 (Table 2) show a low satisfying correlation between experimental and calculated data. The highest value of ICC is reached by the A Model for V>18000m^3 and r<23 m, even though it can not be considered as a best fit; for r > 23m there is no accord. For V<18000m^3 the C Model seems to reach a slight agreement even if not completely satisfying. The D50 comparison is based on three available models (Table 1): the C Model shows the best ICC values (Table 3) although C80 experimental values are needed in the computation.

Table 3 – ICC for the Definition Index

r	V	A	C	D
< 23 m	**> 18000 m^3**	0.70	**0.94**	0.71
> 23 m	**> 18000 m^3**	0.42	**0.73**	0.29
< 23 m	**< 18000 m^3**	0.59	**0.88**	0.51

The comparison between experimental data and the models with better agreement is shown in Figures 1, 2.

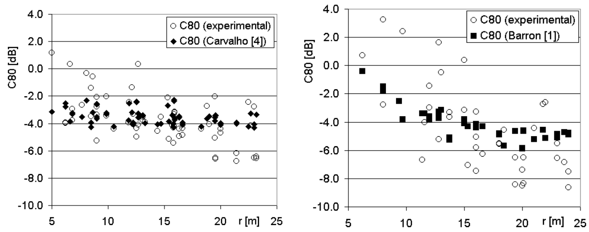

Figure 1 – C80 vs r of experimental data and the C Model (Carvalho [4]), for V<18000m^3 (left) and the A Model (Barron [1]) for V>18000m^3 (right) for r < 23 m.

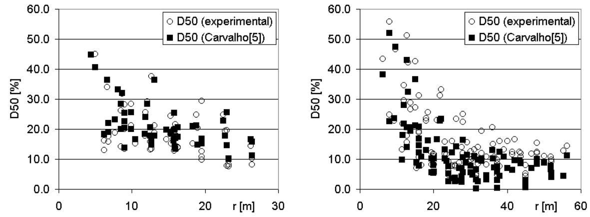

Figure 2 – D50 vs r of experimental data and the C Model (Carvalho [5]) for V<18000m^3 (left) and V>18000m^3 (right)

The geometrical complexity of worship spaces does not lead to simple correlations among acoustical parameters. This may be caused by sound paths influenced by architectural elements such as columns, arches, volutes and surfaces with elements in relief.

C80 and D50 are quite sensitive to early reflection components of sound and thus highly dependent on the building shape. The analysed theoretical models show a rather good agreement with experimental data in some cases, but none of them seems acceptable in the whole range of the considered buildings.

The experimental research about the sound field in worship spaces needs a deeper data collection, in order to formulate correlations applicable to a wider range of cases.

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Acoustical Design of Lake Avenue Church, Pasadena

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The sanctuary of Lake Avenue Church, completed in 1989, is unique among contemporary, American, Evangelical, Protestant churches in that it has preserved traditional ecclesiastic aesthetic elements while incorporating wall and ceiling surface forms that are usually reserved for concert halls. The sanctuary seats 4100 with one balcony and is fan-shaped. It includes a 104-rank Casavant pipe organ with moveable console, an orchestra pit, large choir loft and two performing balconies. The acoustical design and the design of a highly directional, high sound level, column loudspeaker system are described. Acoustical measurements are summarized for the completed sanctuary.

ACOUSTICAL OBJECTIVES

The new sanctuary of Lake Avenue Church, Pasadena, California was completed in 1989. It replaced the smaller chapel, which seats approximately 1200. Church committees under the direction of the acoustical consultant, Paul S. Veneklasen & Associates, established the following requirements:

- Acoustical ambience suitable for traditional and contemporary worship
- A sound reinforcement system capable of producing 116 dB peak over-all Sound Pressure Level with a minimum 10 dB acoustic gain. Loudspeaker response +1/-3 dB, 50 - 10,000 kHz.
- Greater than 90% speech intelligibility

SANCTUARY CONFIGURATION

The sanctuary is based upon one-quarter segment of a circle as shown in Figure 1. The total seating capacity is 4100, 2150 on the main floor and 1950 in the balcony. The choir loft, located at the front of the sanctuary, seats approximately 150. On each side of the choir loft are two performance balconies. The forward portion of the platform utilizes an electo-mechanical pit lift system with an orchestra pit. The sidewalls were configured to provide envelopment for the congregation seating area. The circular rear wall is configured to avoid echoes back to the platform.

The longitudinal section taken along the centerline of the sanctuary is shown in Figure 2. The ceiling was contoured to provide co-planar sound reflections to the audience area to augment the direct sound.

The total volume of the sanctuary is 37,000 cubic meters. The overall length is 59.7 meters and the width is 63.4 meters. The maximum height is 19.8 meters. The walls and ceiling are constructed of 50 mm plaster. Carpet is restricted to the aisles only. The pews in the audience area are upholstered on the backs and seats to help stabilize the reverberation time.

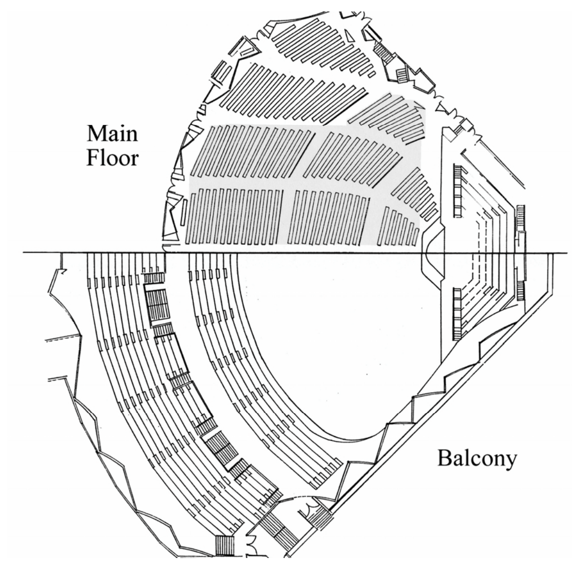

FIGURE 1. Plan view of the sanctuary.

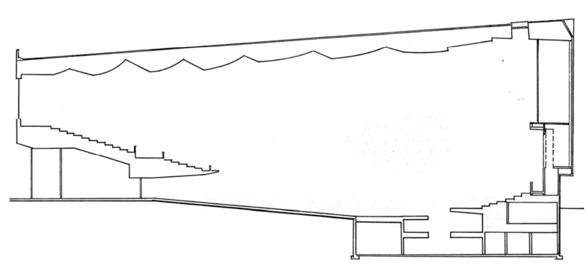

FIGURE 2. Longitudinal section through the sanctuary.

A 104 rank, 5842 pipe Casavant organ is located behind the choir loft as shown in Figure 3. The organ stops were specifically selected by the Church Organ Committee of the Church for their inspirational sounds for the worship service and for concert performances.

FIGURE 3. View of the chancel and the Casavant Organ

LOUDSPEAKER DESCRIPTION

In order to meet the very high sound pressure levels required by the church Technical Services Committee and maintain a high degree of speech intelligibility throughout the sanctuary, a custom column loudspeaker system was developed as shown in Figure 4.

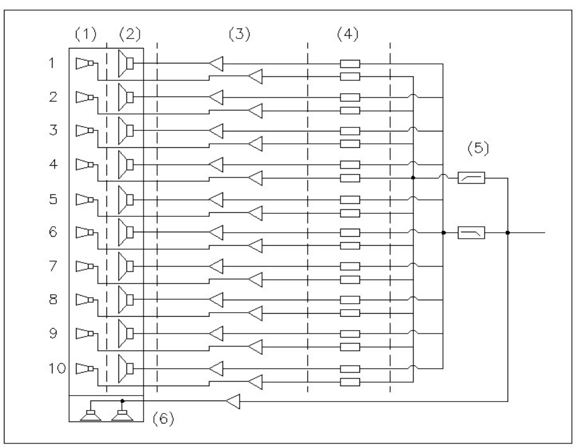

FIGURE 4. Column Loudspeaker System

The column array includes 10 compression drivers connected to 800 Hz. multi-cellular horns (1) and 10 nominal 380 mm diameter low frequency cone loudspeakers (2). Each of the transducers is driven through a power amplifier (3) connected to a digital delay line (4) and an electronic, 18dB/octave crossover network (5). The high frequency horns are aimed independently to provide uniform coverage throughout the audience seating area. Two wide-range, nominal 200 mm diameter, cone loudspeakers in the base of the array are for the choir (6). The loudspeaker array is 4.57 meters high, 0.51 meters wide and 1.42 meters deep. The total amplifier power available is 12,000 watts r.m.s.

MEASUREMENT RESULTS

Reverberation time measurements were performed in the unoccupied sanctuary shortly after its completion in 1989. More recent acoustical measurements were performed using MLSSA [1]. The results are shown in Table 1 without the aid of sound reinforcement.

Table 1. Summary of Acoustical Measurements

	Frequency, Hertz					
Parameter	**125**	**250**	**500**	**1000**	**2000**	**4000**
C80 *	-2.9	-2.1	0.8	3.5	1.8	3.1
C80 †	-4.2	-2.7	-2.0	-1.2	-1.8	1.5
EDT	2.2	2.2	2.2	2.0	1.6	1.4
RT (1989)	2.6	2.5	2.2	2.0	1.7	1.0

* Average of four positions on main floor
† Average of two positions in the balcony

The sound reinforcement system was equalized to ± 2 dB from 50 to 10,000 Hertz. The system is capable of producing a peak over-all Sound Pressure Level of 117 dB. The system achieved a system gain of 10 dB with the sound source 1 meter from the microphone.

Speech intelligibility tests were performed using the sound reinforcement system in the unoccupied sanctuary. Verses from Proverbs in the Old Testament from two talkers were read to 23 participants who moved to a total of 30 positions. Overall, 96.5% of the verses were understood correctly.

ACKNOWLEDGMENTS

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Evaluation of Acoustical Characteristics of Cenabi Ahmet Pasha Mosque: Simulation and Measurements

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In this study acoustical analysis of a XVI century Ottoman Mosque is performed by using ray tracing technique. Highly precise three-dimensional geometry of Cenabi Ahmet Pasha Mosque is developed by using photogrammetric plotting. Ray tracing simulations for different source and receiver combinations are carried. Simulation results are found to compare favorably to experimental results obtained through a set of measurements. Early decay times obtained through simulations and experiments characterize acoustics measurements for such spaces. Long mid-frequency reverberation characteristics are also underlined

INTRODUCTION

Ray tracing technique is implemented in this study in order to characterize acoustical behavior of a XVI century mosque. Three-dimensional model of the mosque is generated by photogrammetric plotting technique using stereo photograph pairs taken inside the mosque. Early decay times and impulse responses at different receiver positions inside the mosque are calculated from the ray tracing analysis. Results are justified by means of experiments. These experiments are performed on a real time frequency analyzer through acoustical measurements taken at an early time in the morning (i.e., 4 am) in order to minimize background noise.

HISTORY OF THE MOSQUE

According to the inscription panel above its entrance portal, the mosque of Cenabi Ahmet Pasha was built in 1565-66. The donor Cenabi Ahmet Pasha was a well-known state's official of the period and during the reign of Sultan Suleyman the Magnificent. The XVI. century is the period when the Ottoman architecture reached its classical period and is especially reached in the construction of single buildings or complexes with religious, educational and civil functions.

The common appearance depicted to the mosque in XVI. century was once again provided by the domination of a great dome over a cubical body. The dome of Cenabi Ahmet Pasha Mosque has a diameter of 14.40 m. The transition of dome structure to square base is provided by squinches. At the skirts of dome a small gallery takes place. Windows around the gallery and on the walls supply a great extent of light so as to create space of transparency.

ANALYSIS TECHNIQUE

Due to complexity of the geometry and deformation through centuries, it is required to use advanced measuring techniques. Photogrammetric measurement is applied in order to obtain accurate and precise results. Computer controlled P3-Planicomp analytical plotting system by Zeiss is used to digitize the stereo photographs that are taken inside the mosque. The three dimensional model is developed with digitized coordinates.

The ray tracing technique is used to analyze the acoustical response of the mosque. Reflecting surfaces of enclosed space are removed conceptually and replaced with sound rays progressing in free field. Consequently, the problem of a sound source and a reflecting surface is transformed into a free field problem. The process of sound propagation is assumed to be linear allowing superposition of contributions by valid rays in the receiver sphere [1].

Sound pressure contributions by valid rays are superimposed to obtain the sound pressure at a chosen receiver point. Phase differences among valid rays are ignored in the superposition. An echogram that represents the reflection pattern of sound waves inside the enclosure is obtained when superposition is performed along the time axis by recording the arrival times of valid rays at receiver locations. The acoustical impulse response in an octave band can be deduced by filtering the resulting echogram.

IMPLEMENTATION

Implementation of the ray tracing technique involves two stages. In the first part, techniques are provided to develop the room geometry and to determine the valid rays for a specified source and receiver configuration. The second stage consists of procedures to perform acoustical analysis in the form of impulse response, energy decay curve, reverberation and early decay times, clarity and room response indexes.

An acoustical ray tracing program is developed for the analysis [2,3]. The program can trace any number of randomly generated rays inside an enclosed space.

For a given source position, 16000 rays are generated and traced by their five successive reflections from boundary surfaces of enclosed space. Wall surfaces and the dome are made of plaster, *mimber* and balcony are marble and floor is covered by carpet. History of each ray is stored in a disk file containing reflection plane index and coordinates of reflection point on that plane. All of the acoustical response characteristics are calculated by this data.

The experimental part of the study involves the measurement of certain acoustical properties of the mosque in order to compare with theoretical results obtained by the ray tracing technique. Acoustical measurements are performed with Brüel & Kjær 2143 real time frequency analyzer. A wide band noise generator is used as a sound source. A 1/2 inch microphone and preamplifier are located at different receiver locations during measurements.

RESULTS

Early decay time (EDT) is a measure of the rate of sound decay expressed in the same way as reverberation time, based on the first 10dB portion of decay. In a highly diffused space where the decay is completely linear, the two quantities would be identical. The early decay time has been shown to be better related to the subjective judgment of the reverberation than the traditional reverberation time.

In this study early decay times in 1 kHz octave band are obtained for different receiver positions experimentally by a real time frequency analyzer and theoretically by ray tracing approximations. Results are shown in Figure 1 and 2. It is seen that EDT values obtained from measurements and simulations are in harmony with each other.

Echograms and impulse responses for different receiver positions are displayed in Figure 2. If these impulse responses are investigated it is apparent that there is always an echo almost at every receiver position inside the mosque. These echoes are caused by the dome. It is evidently seen that the dome is focusing sound onto the receiver. Echo phenomenon reduces speech intelligibility inside the mosque. It is shown again the clarity and the room response values obtained for large volumes with short record times will not give satisfactory results in simulations. Sampling rate of 12000 Hz is used in simulations. For a mosque with a volume of $4000 m^3$, the record length for all valid rays is not enough to specify clarity and other room response indexes.

In holly spaces like churches, long reverberation times in the order of 2.5 - 4 seconds are quite common. Mosques are also found to have comparably long reverberation times. Bigger mosques like Suleymaniye in Istanbul are found to posses EDT in the order of 6-8 seconds.

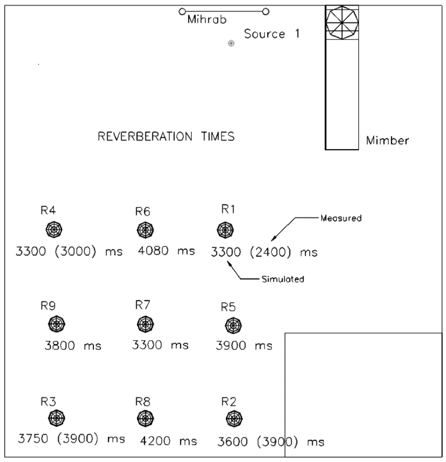

FIGURE 1. EDT of both measurement and simulation

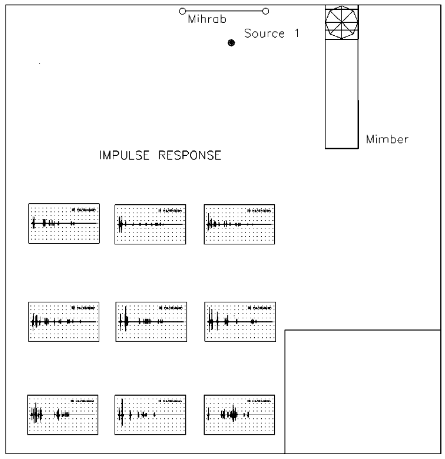

FIGURE 2. Impulse responses at different locations

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Acoustic Properties of a Few Cistercian Abbeys Historical Aspects and Measurements

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In XII century the Cistercian monks performed a reform in the Benedectine Order renewing the monastic rules and returning to the former "Rule of Saint Benedictus". This reform affected the cultural and historical events very strongly in the following centuries and had also a large influence on Monastic Architectural design. The new characteristics in a few Cistercian Abbeys show particular effects in the field of architectural acoustics. In this communication the results of experimental measurements of reverberation time carried out in three Cistercian Abbeys in the Southern part of France, among the best preserved today (Le Thoronet, Silvacane and Senanque), are presented and discussed. The results show a higher value of resonance in comparison with other churches of almost the same volume, in the range of frequency of the liturgical chorus, the main kind of music played by Cistercian monks.

HISTORICAL ASPECTS

The reform carried out by the Cistercian monks since the XII century, inside the Benedictine Order, had the purpose to return to the strict Rule of St.Benedictus "ora et labora". The Cistercian Order spread widely from France. About one century after their early foundation the Cistercians ruled about 700 abbeys all over Europe mostly connected among themselves. Their influence on the historical events of the time was very deep. From Cistercian Abbeys Popes, politicians, high members of the Church came out. Their inner organization was quite efficient; the production of goods and therefore their economic power, fed by wide donations, was very high. The reform had great influence on the lifestyle, on the liturgy, on the way of life, and even on the architecture and on indoor decoration of the Abbeys.

The Cistercian Abbeys present particular characteristics in the values of acoustical parameters in comparison with other religious buildings. The resonance produced by the sound inside gives higher values of reverberation time RT than the one in other Churches of almost the same volume. In the three Cistercian Abbeys here examined the values of RT are always rather high mainly in the range of frequency of Gregorian songs, the only musical performance permitted.

The presence of only stone smooth-faced and therefore reflecting the sound mainly at low frequency is suitable to the liturgical functions. The three Abbeys arrived to us in the best way of maintenance. They are called the three "Provençal Sisters" and lie in the South of France at short distance from one another. They are: the Abbey of Silvacane, Senanque and Le Thoronet. The building structure is quite similar as to the plants, elevation, transept, vaults, nave, aisle etc.(see Figure 1). The beginning years of construction seem to have been: Silvacane 1144, Senanque 1148, Le Thoronet 1160.

In the three Abbeys measurements of RT have been carried out in the nave and in the aisle, with two different source points (Figure 1), with the operating procedure and apparatus described in the following. The results obtained appear of remarkable interest both from historical and technical point of view.

PREVIOUS WORK

Some AA [1,2] hold the hypothesis that the Cistercian architects, in order to reinforce the sound and to maintain an adequate sound distribution for chorus performances, operated following the fundamental concepts of the Acoustic principles. The results of our measurements allow to observe that, in the range of frequency of choral and liturgical song, the RT is remarkably reinforced. That seems to agree with the AA [1,2] and with the hypothesis that the acoustic effects obtained are the direct consequence of an aware acoustic design of Cistercian architects, even with no document available.

MEASUREMENTS

In the various points shown in Figure 1 for the three Abbeys, E.D.T., the early decay time, RT20, related to the decay from -5 dB to –25 dB and RT30 from –5 dB to –35 dB, with the extrapolation to - 60 dB of the medium slope of the RT curves versus time, in the octave bands of frequency, have been measured. The source of sound, following the I.S.O.3382-1975, was a pistol-shot using blank cartridge. The impulse was recorded by using a chain of instruments consisting in a noise meter connected to a computer. The data acquired were processed by means of a software using the Schoreder method of integration [4].

RESULTS OF THE MEASUREMENTS

Figure 2 reports the average values of RT in the range 500-1000 Hz, vs volume, in the three Abbeys, in comparison with other (not Cistercian) Churches, obtained from literature [5].

In Figure 3, for the three Abbeys, the averaged RT values, among E.D.T., RT20 e RT30 are presented, with sound source in the centre of the transept (S1, Figure 1).

DISCUSSION AND CONCLUSIONS

The reform developed by the Cistercians regarded all the aspects of the monastic life, liturgy, customs, indoor decoration and furnishing. They returned to absolute simplicity of life; also the architecture of the Abbeys was strongly affected. In the three Abbeys here examined mainly smooth faced stones were used as building materials. Pavement, vault and cover also in stone, shortage of wooden surface The peculiarities that arise from experimental results are the following: the three Cistercian Abbeys present a medium value of RT, in the whole field of frequency, remarkably higher if referred to Churches with almost the same volume (Figure 2). It can be noticed a light increase in the value of RT in the range of human voice (between 125 and 800 Hz). In the Abbey of Le Thoronet such effect is particularly clear (Figure 3).

The topics that interest the AA, in the lack of documentation, regard the question if all these effects are casual or a consequence of an acoustical design. The AA [1,2] have supported a deep knowledge of Acoustic Technique by the Cistercian architects.

The high values of RT and particularly their increasing in a few cases in the range of frequency of Gregorian chorus, the main kind of music played by the Cistercian Monks, the reinforcement and the concentration of sound observed also by other AA, allow to suppose the acquaintance of the fundamental principles of the acoustic technique from the Cistercian architects.

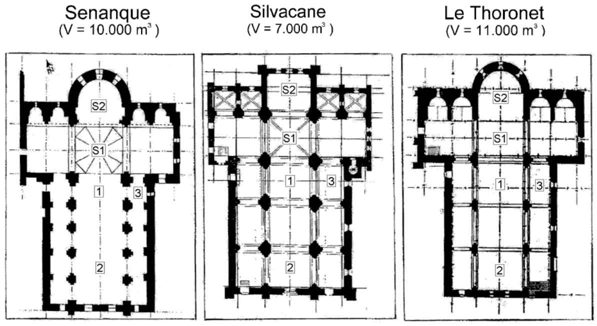

Figure 1 Plane of the three Abbeys

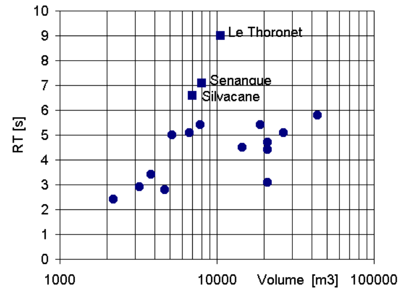

Figure 2. Reverberation time (RT) versus Volume

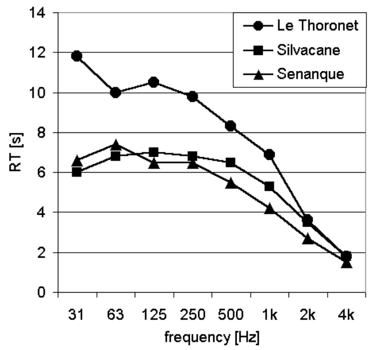

Figure 3. Reverberation Time (RT) versus Frequency

AKNOWLEDGMENTS

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Preferred Reverberation Time of Serbian Orthodox Churches

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This paper presents the results of an investigation of the preferred reverberation time in Serbian Orthodox churches. The research started from the results of a previous investigation of the subjective preferences of sound field, especially subsequent reverberation time which can be obtained from the effective duration of the normalized autocorrelation function (ACF), as well as by the minimum value of the effective duration of the running autocorrelation function of music signals after passing through the A-weighting network. The architecture of several types of churches has remained the same during the history, differing mostly in volume. However, the type of religious service performed in them was changed in 19th century. The preferred subsequent reverberation time obtained from ACF was defined for various types of sounds which now represent religious service consisting of acapela chorus polyphonic singing and preachers' chant. Preliminary results show that the preferred subsequent reverberation time for present-day services is shorter than the value proposed in the literature. Values of reverberation time obtained in this analysis are in a good correlation with the results of the preliminary subjective tests performed by sound engineers in a few of 60 analyzed churches in Serbia.

INTRODUCTION

This paper presents a part of the main project performed during the past decade in the Laboratory of Acoustics at the Belgrade Faculty of Electrical Engineering. The aim of that project is to analyze the acoustical properties of the Serbian Ortodox churches as they are, and to determined the optimal conditions according to the specific religious services performed in them today, always with respect to the all distinctive qualities of this kind of buildings [1]. Due to differences between religious practices and places of worship, obtained results are not universally applicable in all confessions.

There are few important fact that must be taken in account when investigating the acoustical properties of the Serbian Ortodox churches. Architectural design has remain roughly the same through the history, until now. Several types of church designs can be recognized, differing only in size and volume. On the other hand, the type of religious services performed in them has changed. Service consists of the acapela chorus polyphonic singing, as well as preacher's chant.

As a first step, the measurement of the reverberation time was performed in approximately 60 churches, differing in age and size (volume). Results of that measurements show that values of reverberation time varied significantly, it ranges between 1 s and 10 s, depending primary on the church volume. Frequency characteristics of the reverberation time are not flat, it monotony decreases with frequency.

Identification of the preferred reverberation time in Serbian Orthodox church is based on the theory of the subjective preferences of sound field [2,3,4,5,6]. For several musical signals which represent religious services preferred subsequent reverberation time is calculated by the effective duration of the long-time autocorrelation function τ_e and by the minimum value of the effective duration of the running autocorrelation function (ACF) $(\tau_e)_{\min}$.

RESULTS AND DISCUSSION

In order to determine preferred subsequent reverberation time after early reflection, several types of different religious services were recorded. Nine signals are considered: five of them represent acapela chorus polyphonic singing and four represent preacher's chant. All recordings are 30 s - 35 s long. Effective duration of the normalized long-time ACF (2T=30-35 s) as well as the minimum of the effective the running ACF (2T=2s, 100 ms) were determined for all signals after passing through the A-weighting network. Figures 1 and 2 shows the examples of the calculated normalized ACF for two different type of signals.

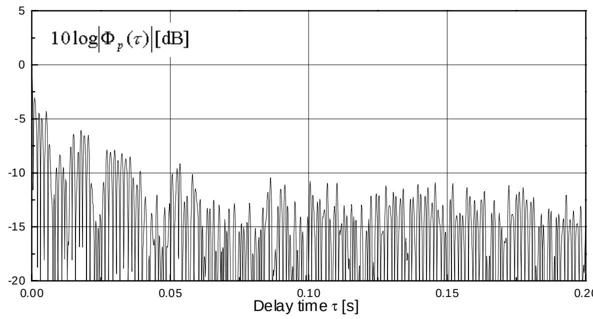

FIGURE 1. Example of normalized ACF for the one signals with acapela chorus polyphonic singing.

SESSIONS

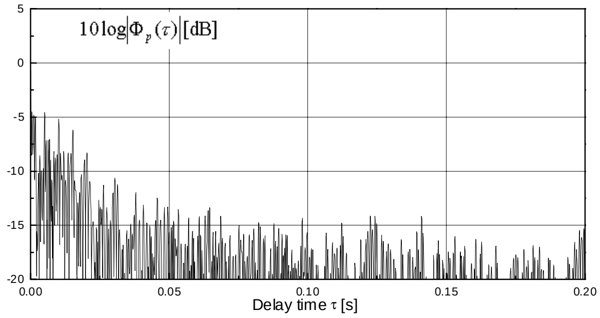

FIGURE 2. Example of normalized ACF for the one signals with preacher's chant.

Calculated values of the effective duration of long-time as well as minimum values of the running ACF are presented in the Table 1. The obtained values for the $(\tau_e)_{\min}$ are smaller than τ_e in all cases. For different types of religious services mean values for $(\tau_e)_{\min}$ and τ_e are calculated (Figure 3).

Table 1. Music used and the effective duration of the long - time ACF and the running ACF

Music signal	No.	Long-time ACF 2T=30-35 s τ_e [ms]	Running ACF 2T=2 s $(\tau_e)_{\min}$ for 30s
acapela chorus polyphonic singing	1	40	35
	2	32	19
	3	70	39
	4	28	26
	5	99	40
preacher's chant	1	62.6	43
	2	110	90
	3	43	29
	4	44	31

The preferred subsequent reverberation time $[T_{sub}]_p$ is described simply by the effective duration of ACF by:

$$[T_{sub}]_p \approx 23\tau_e \tag{1}$$

According to the results obtain for the τ_e, $[T_{sub}]_p$ would be approximately between 1.2 s and 2 s, for the religious services as they are today. To proof this values, simplified subjective tests (performed by sound engineers) carried out in a few of 60 analyzed churches in Serbia. The aim of such subjective tests was to obtain a simple classification of churches, according to something that can be expressed as "good acoustical conditions". This correspondence between the two analyses confirmed again the validity of the calculation of the preferred reverberation time on the basic of the ACF

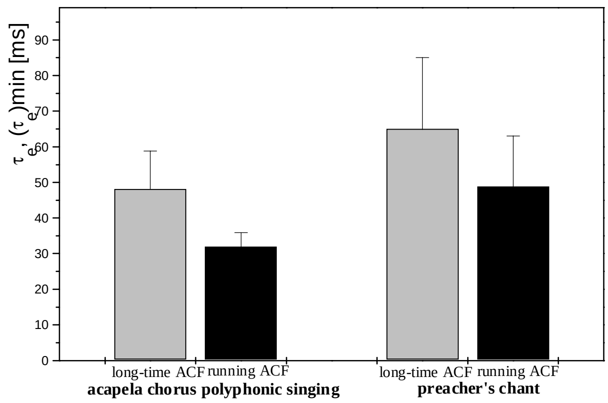

FIGURE 3. Mean values of the measured τ_e and $(\tau_e)_{\min}$ for different type of religious services in Serbian Ortgodox church

CONCLUSIONS

The results obtained in this analysis shows that subjective preferred reverberation time in Serbian Ortodox churches, with respect to the today's religious services would ranged 1.2 - 2 s approximately. These values are shorter that values proposed in the past, but they are in a good correlation with the results of the simplified subjective tests carried out in a few analyzed churches. Although, the subsequent reverberation time is one of the subjective attributes which is important for the good acoustical conditions in sound fields, the results mentioned above give the basic recommendations for the Serbian Ortodox church design. Additional investigation is needed to evaluate subjective preferences of the church sound space. The focus would be to identify the presence of specific acoustics sensations in such spaces.

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Acoustics Survey of Ancient Chilean Churches

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The churches of the island of Chiloé (Chile) belong to the small group of architectural style of XVIII century, completely constructed with native wood and wood wooden plugs instead of nails. Recently fourteen of them were declared Patrimony of the Humanity by UNESCO. Such nomination has originated several studies and restoration initiatives. Objective measurements were made in six of them to evaluate their acoustics performance. Between evaluated parameters were [1][2]: T60, C80, D50 and RASTI. Results indicate that the speech intelligibility is in the range of poor to fair; reverberation time fluctuate between 1.8 seconds to 2.4 seconds (empty room). Clarity and Definition had few variations being located around 9 dB and 0.07 respectively.

INTRODUCTION

The motivation of this work had, on the one hand, to the absence of acoustic studies of the call Escuela Chilota de Religious Architecture and, by another one, to the postulation of appointment of Patrimony of the Humanity, granted by UNESCO.

Architecture Chilota

The churches of the island of Chiloé (Chile) belong to the small group of architectural style of XVIII century, completely constructed with native wood and wood wooden plugs instead of nails.

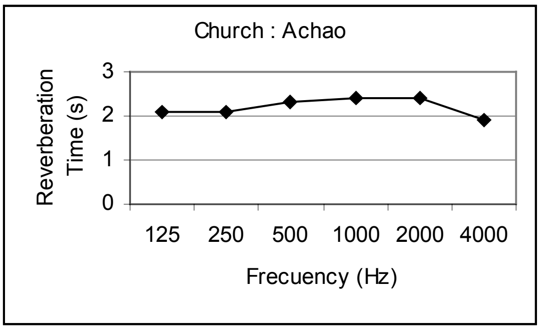
As much the techniques as the structural and constructive systems remain in the knowledge of the constructors chilotes of today, those that dominate in addition, the different properties from the different existing native wood species in the archipelago. In this sense, the inherited knowledge of generation in generation, assures the survival this school of religious architecture that gathers centuries of experience.

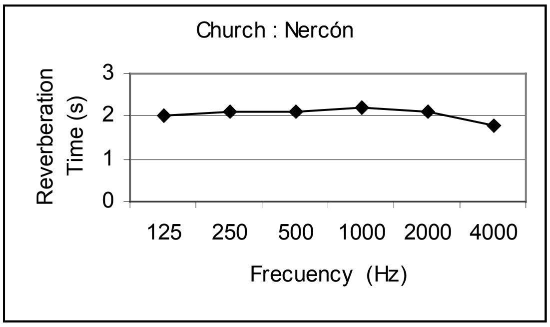
RESULTS

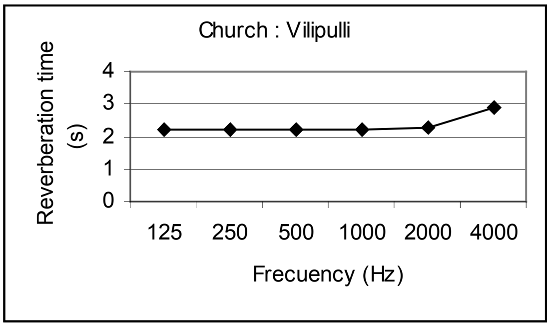
The measurement of time of reverberation took place according to norm ISO 3382 (empty room) and measurement RASTI according to norm IEC 268. In both cases of it came to register the signals in situ with DAT. The results were obtained in laboratory. Only the background noise directly was measured in situ using a sound level meter. In Table 1 the obtained results of the acoustic measurements for each one of the five studied churches are seen.

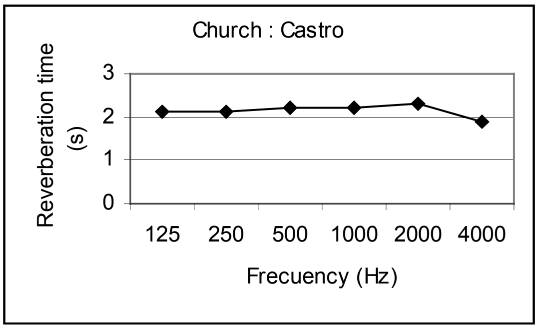
	Date			Bac.noise	RT (empty)	
CHURCH	constr.	Vol. (m3)	seat	NC	500 (Hz)	RASTI
Achao	1730	3400	6800	8484	2.3	0.43
Castro	1912	7300	14600	18234	2.2	0.43
Chonchi	1893	4800	9600	11984	2.2	0.45
Nercón	1897	3800	7600	9484	2.1	0.48
Vilipulli	179?	2100	4200	5234	2.2	0.46

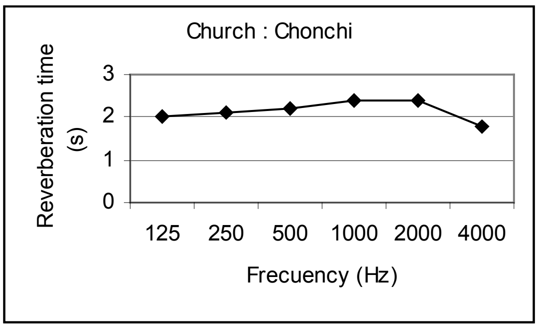
Table 1 : Essentials facts and acoustics results.











CONCLUSIONS

The preliminary results produce a paradoxical interpretation. It can see that neither the time of reverberation nor the background noise too much are elevated like so that the intellibility it has been classified like poor man to regulate. As the measurements were made with the empty room, he is expectable (and thus we hoped to verify in a new stage of measurements) that with hearing objective value RASTI increases significantly. The low reverberation time in low frequencies is due to the massive use of wood forming effective resonators.

ACKNOWLEDGMENTS

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