A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL OF THE UNIVERSITY OF FLORIDA (USA) IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

CHAPTER 8
CONCLUSIONS

This investigation revealed one critical area of acoustics in churches: the relationships of basic architectural styles, dimensions and materials of churches to detailed acoustical measurements made at multiple locations within each room. The results of this work permit several conclusions.

A) - One of the major contributions of this study is the development of a comprehensive method of analysis of room acoustic measures in churches. This work provides important knowledge regarding basic methodology to use in this particular environment.

A large group of 41 heterogeneous but representative churches (in size, shape and architectural styles) was chosen. The number and locations of sound source and receivers was defined. Two sound source positions were established near the altar and in the middle of the congregation seating area. Five or six receiver locations were set as a reasonable number depending on the width of the church. For the RASTI measurements a slightly large number of locations may be needed. A frequency averaging method to calculate a representative single-number average was determined. The two octave frequency bands centered on the 500 and 1000 Hz were calculated to be the most useful regarding the analyses with architectural parameters. For the analyses among acoustical measures the six octave frequency bands (125 - 4000 Hz) were used because no real improvement was determined to exist with any of the other six averaging options tested. A comprehensive set of acoustical measures and simple architectural parameters was also defined.

Three groups of related acoustical measures were found in this study: RT/EDT/TS, C80/D and L. RT and EDT present a very high correlation ($|R| > 0.99$) as expected because they are similar quantities with comparable physical meaning. EDT and TS also show a strong relationship between them ($|R| > 0.94$). These two factors suggest that any of those three measures (RT, EDT or TS) can be used to predict the other two. The RT is a reasonable choice due to its clear physical meaning and traditional use in this area. However EDT is considered to be a better predictor of the sense of reverberance and is more useful if subjective analysis is desired. C80 and D are highly correlated ($|R| > 0.94$) mainly due to their comparable physical and mathematical design. The correlation between L and the other five measures is markedly low ($|R| < 0.37$) confirming the individuality of this measure among those six and indicates that this quantity should be included as one of the acoustical measures. From the acoustical measures used, the most significant or useful to characterize the acoustical environment of churches are: RT (or EDT if subjective studies are involved), C80 and L.

B) - Another major contribution of this study was the calculation of several prediction equations that will have a real impact as a useful tool in the acoustical design of churches. Prediction formulas were defined for relationships among acoustical measures, between acoustical measures and architectural parameters and for the RT using the Sabine equation with a proposed new algorithm for coupled spaces.

1 - Relationships among the acoustical measures were defined and prediction equations were calculated to estimate measures taken at individual locations within each room as well as the mean values in each church. It was found that nonlinear models give a slightly better prediction line than the linear models in the majority of the cases studied (70%). Among these, the logarithmic smooth presents a better fit in many cases, especially in those with the C80 measure. This is due to the logarithmic mathematical characteristic of many of these measures.

There are significant differences between the correlation coefficient $|R|$ results (1 to 68% higher $|R|$ in the averaged data option) depending upon whether all the data or just room average data were used. Depending on the situation been studied, a single point measure or a room average value, the corresponding prediction equation should be used.

2 - Within and inter church differences in the data for the six acoustical measures and the effect of sound source position were also analyzed. The within church variation in RT and EDT data were found to be much smaller than the variation of other measures. The variation was four times smaller than the variation of the C80 or D measures. This agrees with the findings of similar studies in concert halls (Barron 1994). In general, the spatial variation in the acoustical measures made in churches shows important similarities among all churches. Nevertheless, there are differences among churches that may be attributable to the architectural characteristics of each room, especially to differences in size. It was found that the differences among the mean values of the acoustical measures made in churches were significant in nearly 80% of the cases for the RT and EDT data and 61% to 75% in C80, TS and L data. However, there were only significant differences in the mean values of D in less than half of the churches because the internal variation of their values was relatively higher than the spatial variation of other measures. Therefore RT was found to be the most significant single measure to characterize a church as it is for concert halls (Barron 1994).

3 - The effect of fifteen architectural parameters on these acoustical measures was investigated. Prediction equations were calculated to estimate mean acoustical measures. Simple nonlinear models gave only a slightly better ($DR^2 < 0.14$) prediction fit than the linear models in the majority (70%) of the cases studied. Among these, the logarithmic smooth presents a better fit in many cases (C80, D and L). This is due to the logarithmic mathematical characteristic of many of the measures.

General linear models using only two to five architectural parameters were calculated to predict the six main acoustical measures with 71% (RT and EDT) to 85% (C80) of the variance explained and relatively small standard errors of the estimates. The bass ratios could not be reasonably predicted with the use of this set of architectural parameters (R^2 £ 0.35). The use of the expected values for some acoustical measures found by the use of the classical diffuse field theory equations largely increased the fitness of the predictions models from $R^2 = 0.944$ (for C80) to $R^2 = 0.996$ (for EDT).

4 - The use of the classical reverberation time equations (Sabine and Eyring) was tested to estimate the measured reverberation times in this sample of churches. The Eyring equation gives slightly better results than the Sabine equation in predicting the RT when the effect of coupled spaces is not considered. Two trends were clearly distinguishable in the RT values indicating a need for a coupled spaces' analysis in the prediction of RT in churches that could better explain that difference between predicted and measured RTs.

The effect of coupled spaces was analyzed and a new algorithm for the application of the Sabine equation in churches was developed producing an average of 16% in the differences between the predicted and real RTs compared to a 71% difference using the standard Sabine equation. Coupled spaces (CS) were found to act as windows with a characteristic a depending on their dimensions $\{a_{CS} = \tanh[a\,(l/w-b)]\}$. The recesses in churches were grouped in three types: main altar area, chapels and lateral aisles. Each type of coupled space has a particular acoustical behavior with different *a* and *b* parameters in the equation above. It was found that those recesses only acted as coupled spaces if their length/opening_width > 0.6 or if the aisle_width/opening_height > 0.4 in lateral aisles.

The remaining differences found between the RTs predicted with this new algorithm and the measured RTs were hypothesized to be related to what was called a reverberant ceiling effect which is presumed to be due to a two-dimensional reverberant sound field that builds up near a very tall ceiling.

The new algorithm for the use of the Sabine equation in this type of building accounting for several distinct types of coupled spaces should allow much greater accuracy of estimated reverberation times.

C) - A new understanding of several topics unique to churches was also achieved as the effect of changing architectural styles in the values of several acoustical measures, the analysis of RASTI or the effect of pulpits or the definition of a new binaural parameter to assess subjective quality regarding music.

1 - An innovative study in this research is the historical analysis of how the values of several acoustical measures changed over time, through the evolving architectural styles, reflecting important changes in Church history. The churches were grouped in eight architectural styles. From the acoustical measures tested, conclusions were drawn on the effect of the evolution of the architectural styles through the last fourteen centuries. In general this study suggests that some changes in the acoustical measures in churches are related to changes in architectural styles. Statistically significant differences were found in churches regarding their architectural styles for the RT, EDT and TS measures and a visible trend seems to be present in their variation through time. An increase in the mean values of RT (or EDT) was found through the first five styles with a decrease in the Baroque style (Reformation period) and again a negative slope in the last two styles (the Vatican II period). The TS data behave similarly but with inverted slopes due to its physical characteristics. Changes in church music and other church practices and changes in the mean values of some acoustical measures seem to have occurred in the same historical periods. RT and EDT appeared as the most suitable acoustical measures to identify differences in churches regarding their architectural styles.

2 - The use of RASTI in churches was studied and the relationships with acoustical and architectural parameters identified. It was found that the vast majority of churches have RASTI values below 0.45 giving a poor rating in the quality of speech intelligibility.

New relationships of RASTI with other acoustical measures were identified eliminating the previous idea that this index was an independent test among other measures. RASTI values within churches, in positions not in the direct field of the sound source, can be predicted by the use of TS at 1000 Hz (TS_1k) in the same position, with a $R^2 = 0.80$. The EDT_500 and RT_2k are almost as effective in that task with $R^2 = 0.78$ or 0.76, confirming the findings of the previous correlation analysis among measures. If the assumption that RASTI is a good predictor of speech intelligibility is correct (Brüel & Kjær 1986), then TS_1k will also be an accurate predictor of speech intelligibility. Regardless of the receiver position within a church, RASTI was found to be easily predicted (with $R^2 = 0.74$) by the use of C80_2k. Loudness (L) does not appear as an important characteristic regarding RASTI values with $R^2 < 0.17$ supporting the idea that the intelligibility of speech, under reverberant conditions does not depend on Loudness. This agrees with the idea that speech intelligibility is related to the direct sound being at greater intensity than the reverberant sound. A prediction equation using three architectural parameters (nave width, nave height and the average absorption coefficient) was calculated to estimate (with $R^2 = 0.73$) the average RASTI in churches.

The effect of the architectural styles on RASTI values was found to show a negative trend regarding the first five styles, i.e., speech intelligibility generally decreased until the Renaissance with a strong improvement in the Baroque style (Reformation period). There were no statistically significant variations in the last two styles. The Renaissance appears as the style with the lowest RASTI values and the Visigothic and Baroque are the ones with the highest RASTI values. The use of pulpits without large canopies was found to increase the RASTI values. This was justified only by the decrease of the distance between the receiver and the source. Using unoccupied churches, pulpits were found not to be a direct acoustical resource but only an indirect way to increase the intelligibility of speech by decreasing the distance from the speaker to the listener.

3 - The definition of a new binaural acoustical measure is believed to be an important step in studying the interaction between personal feelings regarding musical performances in this type of environment and a physical quantity to measure it. Using binaural measurements and subjective information collected in these churches, BACH a new binaural measure (Binaural Acoustical CoHerence), was presented as a ratio of coherence values (1/3 octave bands) between low (50, 63 and 80 Hz) and high (3.15, 4 and 5 kHz) frequencies. It was found to be orthogonal among the other 104 acoustical measures and architectural parameters ($R^2_i < 0.3$). A linear correlation coefficient near 0.7 was found between the BACH measure and a five point subjective quality rating regarding music in churches, supporting the hypothesis that this measure can be useful in predicting the subjective quality of music heard in churches. A three point (bad, normal, and good) method of rating the subjective quality of music in churches was found to be more acceptable than the five points used (very bad, bad, normal, good, and very good).

The results of this study provide designers and researchers the basic information and tools to predict several acoustical measures in churches during the early stages of design and without the need of measurements in real buildings. Though this work has considerably increased the understanding of the acoustics of churches, much exploration is still needed to answer more quantitatively some of the questions posed in this field.