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A METHOD FOR ACOUSTIC MODELING OF PAST SOUNDSCAPES

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Abstract

This paper investigates the use of geometric simulation algorithms to model the acoustics of a church as it would have sounded in the late 16th century. Based on measured acoustic parameters, an average absorption parameter is developed for the heterogeneous walls of the Church of the Ospedaletto, obtaining a good match between the simulated model and modern acoustic measurements. Using these data, the model is altered to simulate the church's acoustics before the large organ gallery was installed in the late seventeenth century. This method allows a high degree of confidence in the model's ability to reconstruct accurately the soundscape as it would have been experienced during the Renaissance.

Keywords

Acoustic Simulation, Archaeological Acoustics, Architectural History

1. Introduction

The Centre for Acoustic and Musical Experiments in Renaissance Architecture (CAMERA) is an interdisciplinary project investigating the connections between architecture, acoustics, and music composition in Renaissance Venice. Following an analysis of acoustic measurements of ten churches from this period, it was concluded that a comprehensive analysis would require knowledge of the acoustic parameters of the churches as audiences would have heard them during the Renaissance. Since it was not feasible to recreate the past layout of these churches *in situ*, virtual models were developed as the spaces would have existed 400 years ago.

Obtaining an accurate rendering of a nonexistent acoustic space is very difficult as such a method provides no clear way of checking for errors or even determining where errors may be introduced into the model. An earlier simulation of the demolished Church of the Incurabili was based on good information about the space's geometry, but little was known about the church's material composition. The model predicted a reverberation time of six seconds, which is inconsistent with subjective accounts of the church's fine acoustics [1]. Without objective material data, blind modeling techniques rely on guesswork, and there is no way of measuring the accuracy of the simulation.

A different approach was adopted to model earlier versions of spaces that still exist. Using modern acoustic measurements, a model of the present Church of the Ospedaletto was constructed that correctly reproduced the present-day acoustics of the church. The acoustics of the earlier Renaissance-era church were then simulated by restoring the interior of the church to its known structure using a calibrated virtual model.

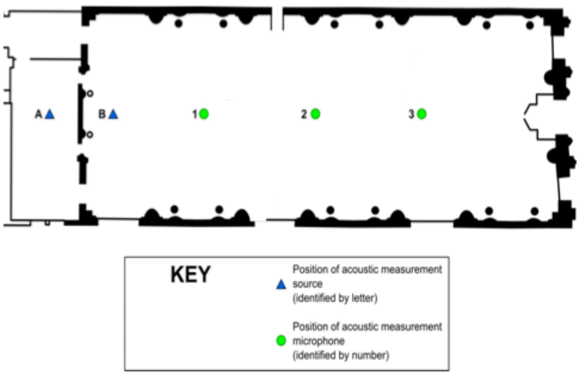

Figure 1 – Source and receiver locations for acoustic measurements in the Ospedaletto.
A and B are source positions. 1, 2, and 3 are receiver positions.

2. Acoustic Measurements

The acoustic measurements for the CAMERA project were carried out by Davide Bonsi of the Musical and Architectural Acoustics Laboratory of the Fondazione Scuola di San Giorgio in Venice. Source and receiver locations were determined using historical evidence for the locations of singers and audience members for each church studied. The Ospedaletto was measured for sources in the organ gallery and at the high altar, with three receiver locations in the middle aisle of the church (Fig. 1). The measurement source was a log sine sweep, produced through a dodecahedral loudspeaker with a nearly flat frequency response from 60 to 16000 Hz. The measurement receiver was a Microflown® probe, an acoustic device that records sound pressure as well as air particle velocities in x-, y-, and z-directions [2]. The principal acoustic parameters used in this analysis are the reverberation time (T30), the early decay time (EDT), and the clarity index (C80), each measured at one-octave frequency bands from 63-8000 Hz.

3. Modeling the Current Church

3.1 Background to the current church

The Ospedaletto was a hospital church, known throughout Europe for the excellence of the performances of the choir of orphan girls resident there. Since the girls' performances contributed significantly to the church's finances, acoustic considerations may have played a significant role in the design of the current church in the 1570s. The church's geometrical layout is essentially a long, rectangular 'shoebox' (Fig. 2) with a high organ gallery that was added in the 1670s by Baldassare Longhena [1]. The church's small volume combined with its diffuse parallel-wall reflections allow the church to score highly in audience surveys for both 'envelopment' and 'intimacy,' subjective categories that are often in conflict with one another [1, 3].

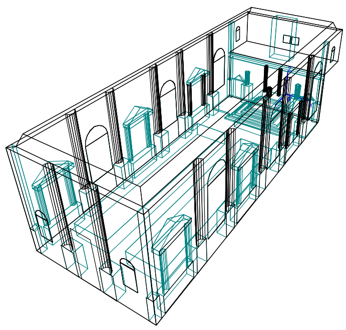

Figure 2 – Geometrical layout of the present day Ospedaletto in Odeon

3.2 Geometrical Modeling

The church was modeled using ODEON 10.0 Combined Edition. Odeon is an acoustic simulation program that uses a hybrid of image-source modeling and ray tracing for early reflections and late-field reverberation, respectively. Odeon's algorithms generate impulse responses corresponding to each source-receiver combination in its virtual model. The church's geometry was modeled using Odeon's parametric coordinate modeling system based on detailed plans and photographs of the church made available by Deborah Howard and Laura Moretti.

The geometry was modeled first as the airtight 'skeleton' of the room, and then altars, columns, windows, and seating were added. Though round surfaces such as columns are approximated with multiple planar surfaces, Odeon's algorithms treat these surfaces as a single entity, preventing each individual surface from generating scattering by edge diffraction [4]. The only surface that seemed impractical to model adequately piece-by-piece was the heterogeneous mixture of plaster, paintings, and ornamentation of the main walls of the church.

The authors of Odeon suggested taking advantage of the software's scattering system to simplify complex geometries into planar surfaces with higher scattering coefficients when these simplifications do not affect early reflection paths or overall room absorption [4]. A recent study asserts that a simplified Odeon model of a church ceiling with high scattering provided worse simulated results for T30 than a complex model that contained wooden vaults [5]. However, the study's complex model contained more surface absorption than the simpler model, which suggests that the simplified version's error was introduced by the removal of the absorption, not by the added scattering.

With the understanding that Odeon's scattering method does not inherently introduce error, the main walls of the Ospedaletto, that is, everything on the walls except the altars, windows, and columns, were modeled as planar surfaces and assigned a high scattering coefficient of 0.4, corresponding to a surface roughness depth of up to 0.3 meters, based on Odeon's recommendations [4].

3.3 Material Absorption Coefficients

As the acoustic measurements were completed before the virtual modeling project had begun, the Microflown probe could not be used to measure material absorption coefficients on-site. Nevertheless, the majority of the church's materials, such as marble, wood, glass, and carpeting, had absorption coefficients that were well characterized in existing databases. The only surface that did not have a pre-measured absorption coefficient was the simplified wall surface discussed earlier. Though the church's walls are plastered brick, their dampness and ornamentation make them very unlike an unadorned plaster wall. Our databases had a variety of absorption coefficients for the various materials composing the walls and so we adopted maximum and minimum values to characterize the walls' average absorption coefficient. Since we were confident in the coefficients for all other surfaces, the average absorption coefficient for the simplified wall surface was reverse-engineered from the measured values of T30 for each frequency band (Tab. 1).

Table 1 – Ospedaletto's average wall absorption coefficients, by frequency band

F (Hz):	63	125	250	500	1000	2000	4000	8000
AC:	0.08	0.08	0.1	0.2	0.2	0.2	0.2	0.1

3.4 Simulation Accuracy

All Odeon simulations were carried out in precision mode, which uses the highest ray count recommended for a given room volume, increasing the accuracy as well as computation time. To evaluate the accuracy of the model's simulated acoustic parameters, the model's output values were compared with the measured values for each source-receiver position. T30 and EDT were found to be similar for both sources and at all receiver positions, since the space's small volume and high diffusion gives a fairly uniform sound distribution. C80 is higher for receivers closer to the source, but values are similar for sources A and B. Consequently, this paper will focus on source B.

The simulations were compared with the measured data using auditory difference limens, or just-noticeable differences (JNDs), which represent the smallest change in a given parameter that a listener notices more than 50% of the time. The accepted JND for T30 and EDT is 5%, or about 0.1 seconds for a reference value of two seconds [6]. As shown in figures 3 and 4, the simulated values are within about 3 JNDs of the measurements at all frequency bands. The dotted lines above and below the red boxes show the standard deviation of the simulated values.

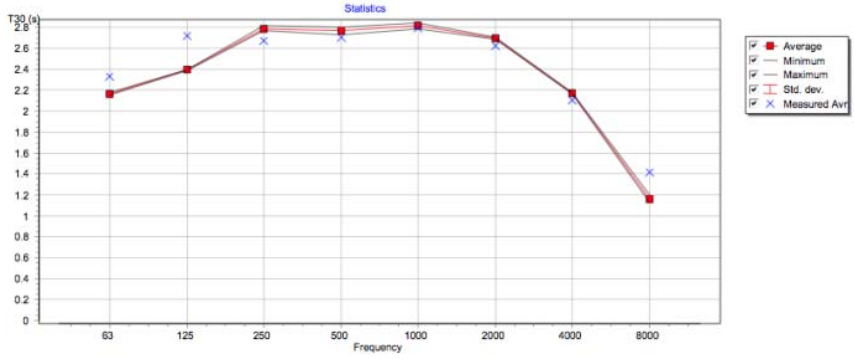

Figure 3 – Average T30 values from Source B to all receivers, simulated vs. measured

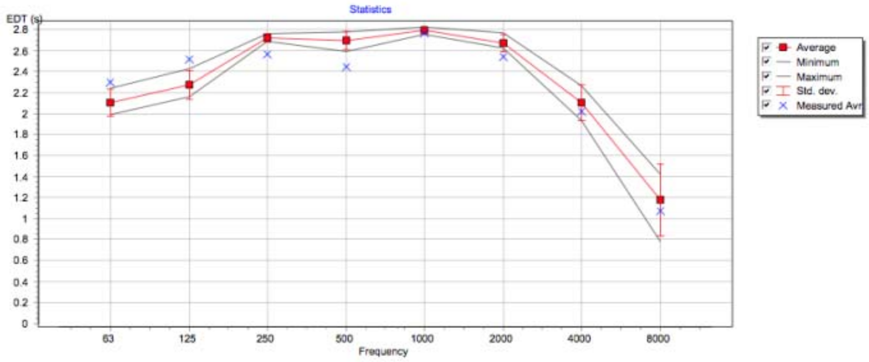

Figure 4 – Average EDT values from Source B to all receivers, simulated vs. measured

The JND for C80 has been shown to be 1 dB or greater for reverberant spaces [7]. As shown in figure 5, the model's simulations for C80 are also within 3 JNDs of the measured values. In principle a perfect simulation should be within 1 JND of measured values, but since the most accurate blind modeling attempts yield results with an accuracy of about 5 JNDs [8], we considered that our calibrated version contained a satisfactory level of accuracy based on current computational power and material data.

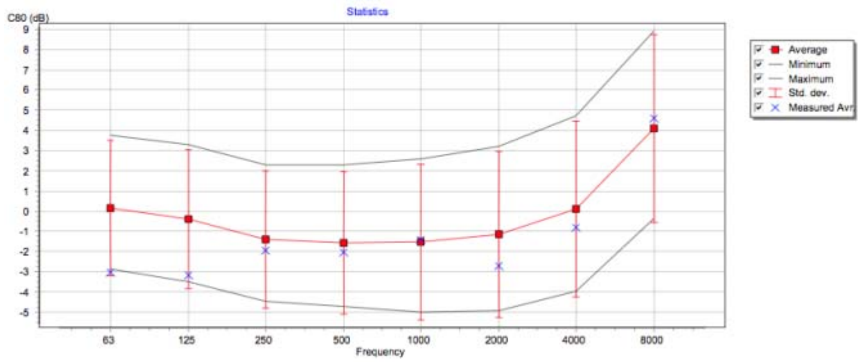

Figure 5 – Average C80 values from Source B to all receivers, simulated vs. measured

4. Modeling the past church

We modeled the effects of changes both in geometry and material composition that would have changed the past church's acoustic properties from those of the current church. The model's geometry was altered to reflect its sixteenth century layout by extending the wall behind the high altar up to the ceiling. This extended wall was given the same absorption coefficients as the averaged data of the main walls.

The model's material data were also altered to reflect the presence of a reasonably large audience in the church's pews. Though the space was empty when the measurements were taken, humans are among the most efficient sound absorbers at mid-frequencies and must be taken into account in order to obtain a good model of the past church. The top surface of the pews was assigned absorption coefficients corresponding to an "Audience on wooden seats," assuming a density of two people per square meter.

To study the impact of these changes, four models were compared: the original model of the current empty church, a model of the current church with an audience, the empty church without the gallery, and church without the gallery but with an audience. As expected, the addition of an audience has a large effect on T30 at mid-frequencies (Fig. 6). The removal of the organ gallery, however, has almost no effect on T30, suggesting that the smaller room volume negates the lower overall surface absorption.

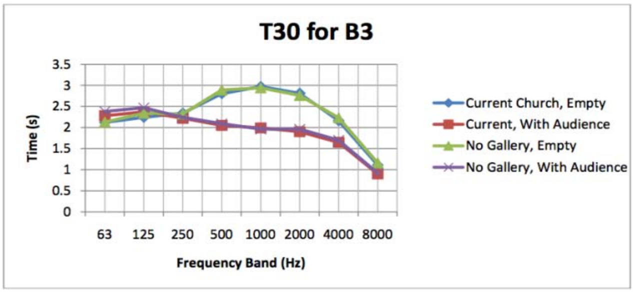

Figure 6 – Changes in T30 in the four different models, source B to receiver 3

EDT and C80 also show strong changes in the mid-frequency bands for the versions of the church with an audience. These parameters, which are more-position dependent than T30, both show increases of up to 2 JNDs for the empty pre-gallery model in the frequency bands at 2000 and 4000 Hz (Fig. 7 & 8). This suggests that a strong reflection off the original wall would have increased musical clarity somewhat compared to the current church, where sound takes longer to travel into the gallery and back to the floor. Although the increase in EDT is not simulated when the audience is present in the pre-gallery church, the C80 increases whether or not the model includes an audience.

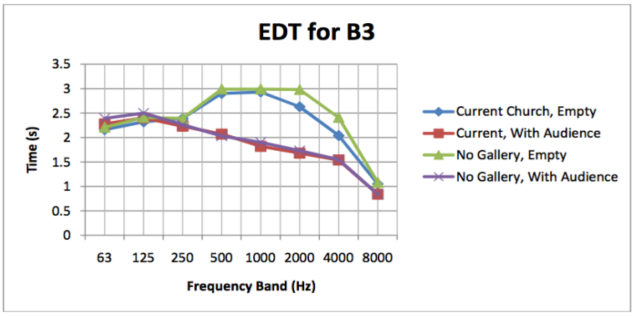

Figure 7 – Changes in EDT in the four different models, source B to receiver 3

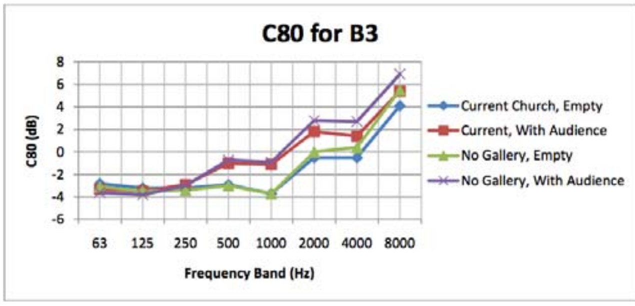

Figure 8 – Changes in C80 in the four different models, source B to receiver 3

5. Discussion

The method outlined here seeks to obtain the best acoustic model for the past configuration of a space for which present measured parameters are available. Though specific absorption coefficients were not available for the main walls of the church, the heterogeneous composition of these surfaces made it more straightforward to model their average value based on reproducing the measured values. This method may introduce some error due to its assumption of uniform absorption and scattering across the entire surface. In addition, this method assumes that the single set of measurements is accurate, although ideally multiple sets of measured values should be used to establish an accurate present characterisation. Finally, this method relies upon the accuracy of Odeon's hybrid algorithm to obtain a good simulation for the amount of data available.

Despite these possible sources of error, computer modeling allows great flexibility in making large changes to an acoustical space that would not be possible in the physical space. Computer modeling algorithms also offer consistent repeatability, allowing the use of experiments testing the effect of a single change on the room's acoustic parameters. The model of the current church was very accurate in comparison to measured values, and it seems likely that any errors present would be equivalently simulated in the past versions of the church, such that changes between models are still informative.

An intriguing example of the power of the modeling procedures was to understand the origin of the phenomenon of the sound appearing to "descend from above", an effect noted by many of the listeners present during the acoustic experiments discussed by Howard and Moretti [1]. With the organ loft present, the simulations clearly showed that, when the source was in the organ loft, reflections inside that volume resulted in the wavefront of the sound reaching the audience at an angle of about 45 degrees to the vertical direction. This attractive feature of the acoustic design of the building is indeed a real phenomenon.

6. Conclusion

The church of the Ospedaletto has been simulated with a high degree of accuracy. Measured acoustical parameters were used to estimate average absorption coefficients of wall surfaces with unknown properties. Once this model was satisfactorily calibrated, the model was altered to reflect the configuration of the church during a performance of its choir in the late sixteenth century. The introduction of an audience had by far the biggest impact on the church's acoustics, reducing T30 by up to one second in middle frequency bands. The removal of the current organ gallery was simulated to have a slight impact on EDT and C80 in high frequency bands, suggesting that the reflection from the earlier wall may have increased musical clarity for sources at the high altar.

The method developed here has been used to reconstruct past configurations of other Renaissance Venetian churches, such as the Basilica of San Marco, the church of San Francesco della Vigna and Palladio’s Redentore, for which acoustic data and simulations can help inform important architectural and musicological questions. Many such questions have thus far been treated as unanswerable, given the manifold uncertainties involved in reconstructing such information. Our work suggests that, with the best available modern simulation technology, acoustic models can provide valuable quantitative evidence to further inform the historical discussion.

7. Acknowledgements

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