Acoustic Simulation of Renaissance Venetian Churches

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ABSTRACT

The large churches of the Venetian Renaissance have very long reverberation times and provide poor clarity for appreciating the complex polyphonic music composed for these spaces. Geometric acoustic simulation techniques have been used to provide insights into the acoustics of two large Venetian churches, the Redentore and San Marco, as they would have existed during the Renaissance. Using the ODEON® acoustic simulation programme, virtual models were constructed that accurately matched recently measured acoustic data at a number of source-receiver combinations. In consultation with architectural historians, evidence has been assembled on the structure and layout of the Redentore and San Marco on festal occasions, when large crowds, extra seating and wall tapestries would have provided extra absorption. The models were then adjusted to reflect these changes. The simulations demonstrate that under festal conditions these churches would have had significant improvements in $T_{30}$, EDT and $C_{80}$, making them suitable for the performance of polyphonic music. The Doge’s position in the chancel of San Marco has particularly good clarity for sources in the galleries, or pergoli, supporting Moretti’s conjecture that these galleries were installed by architect Jacopo Sansovino for enhanced appreciation of polyphonic split-choir music.

1. INTRODUCTION

This study of the acoustics of Renaissance churches in Venice is a follow-up to a research project carried out at the University of Cambridge, UK. The Centre for Acoustic and Musical Experiments in Renaissance Architecture (CAMERA) is an interdisciplinary project investigating the connections between architecture, acoustics and musical composition in the Renaissance, and has involved architectural historical and musicological research, in situ choral experiments and the quantitative acoustic characterisation of eleven Venetian churches [1]. The main questions to be addressed were:

- How far did architects consider acoustic needs when designing new churches in Renaissance Venice?
- How far were different types of churches adapted to the particular use of sacred music in the liturgy?
- How far did composers take account of the acoustics of church interiors when writing sacred music?
- How could complex polyphony be appreciated in churches with very long reverberation times?

The first three questions were discussed in detail in the book Sound and Space in Renaissance Venice by Howard and Moretti [1] and in the studies by Bonsi et al. [2, 3]. This paper concerns the virtual reconstruction of the acoustics of two of the great churches studied by Howard and Moretti in order to discuss the fourth question and to cast further light on the first three.

2. BACKGROUND

During the sixteenth century, there were remarkable developments in architecture and music in Venice. At the church of San Marco, cori spezzati, or split choirs, were probably introduced into Venice by composer Adriaan Willaert and later exploited by Andrea and Giovanni Gabrieli and Claudio Monteverdi. There were innovations in the architectural design of churches by the most eminent architects of the time, in particular, by Jacopo Sansovino and Andrea Palladio. Howard and Moretti’s comprehensive survey of
the many different aspects of the interactions between music, architecture and acoustics addressed all the issues listed above and at the same time raised questions about how the complexities of innovative polyphonic music could be fully appreciated in the large acoustic volumes of the great celebratory churches for which some of the greatest music was written.

Howard, Moretti and their colleagues carried out an extensive programme of acoustic measurements of 11 surviving Venetian churches: San Marco, two monastery churches, three friaries, three parish churches and two hospital churches. Sansovino’s surviving churches were included, as well as Palladio’s two Venetian masterpieces, San Giorgio Maggiore and the Redentore. The details of the programme of measurements are described in Appendix 1 of Howard and Moretti [1]. The combinations of source and microphone positions were chosen on the basis of architectural historical and musicological research. Sufficient measurements were taken to provide an excellent quantitative characterisation of the acoustic properties of the various spaces within each church. This paper describes how these acoustic data were used to create virtual acoustic models of four of the churches studied, the emphasis being upon the results for the Redentore and San Marco. Once these models were calibrated by providing satisfactory agreement with the measured acoustic data at the present day, they could be modified to recreate the acoustic conditions in the 16th century, using the evidence of architectural and musicological history.

3. THE MODELLING PROCEDURES - THE CHURCH OF SANTA MARIA DEI DERELITTI (THE OSPEDALETTO)

This project uses an approach developed to reduce the speculation involved in ‘archaeo-acoustic’ research. It involves first developing models for spaces that still exist and for which acoustic measurements are available. Assumptions about geometrical relationships, coupling effects and material content can then be tested against quantitative data. Once a virtual model has been obtained that accurately reflects the present state of a space, the simulation may then be adjusted to reflect its earlier form [4].

The modelling approach was tested through an analysis of the orphanage church of Santa Maria dei Derelitti, commonly known as the Ospedaletto, which has a simple geometric ‘shoe-box’ form and which had the best acoustics properties of all the churches studied. Acoustic data were secured for it as part of the CAMERA project by Bonsi and Moretti [2]. Construction of the church began in 1570 with some design input by Palladio. It was modified in the 17th and 18th centuries and was renowned throughout Europe for the girls’ choir and its excellent acoustics.

The modelling was carried out using Odeon® v.10.0 Combined Edition [5, 6]. We benefited greatly from the advice of the originators of the Odeon® programme, Jens Rindel and Claus Christensen. In summary, the Odeon® software uses image-source modelling for first- and second-order specular reflections. For diffuse reflections, it uses a ray-tracing approach with oblique Lambert scattering. Diffraction effects are also taken into account [5]. The virtual acoustic space was built using the programme’s parametric editor and then materials, sources and receivers assigned in the main window of the programme.

In the modelling procedures, we sought to create a good model, not an alternative reality. Some of the materials assignments were straightforward - the floors and columns were marble and the ceiling lath and plaster. The walls were a mixture of paintings, ornamentation and damp plastered brick. We adopted an empirical approach to the average absorption, reflection and scattering properties of the walls, starting with an absorption coefficient of 0.1-0.2 as a reasonable initial guess. The parameters only needed to be mildly adjusted to obtain values of EDT and T60 that were in satisfactory agreement with the acoustic measurements. A similar approach was adopted for the Redentore and San Marco.

Since the primary interest was in the perception of the music as experienced by period audiences, auditory just-noticeable differences (JNDs) were used to assess the agreement of the simulations with the measured values. The accepted JND for T60 and EDT is 5% [7]. The JND for C50 has been shown to be 1 dB or greater for reverberant spaces [8]. In principle, a perfect simulation should be within 1 JND of measured values, but since the most accurate blind modelling attempts yield results with an accuracy of about 5 JNDs, it was considered that the calibrated model had attained a satisfactory level of accuracy when the simulations were within 3 JNDs of the measured data [6].

A number of anechoic recordings were made of choral pieces composed in the 16th century, and these were used in auralisation experiments for the virtual model of the Ospedaletto. Listening tests convincingly demonstrated the excellence of the acoustics of the Ospedaletto for the performance of complex polyphonic music with excellent clarity and reverberance of about 2 seconds. Among the interesting results was the demonstration of the origin of an effect noted by the audience who responded to the questionnaires that
accompanied the live choral experiments [3]. Several listeners remarked on the fact that the sound seemed to ‘come down from on high’, providing an ethereal effect. The acoustic modelling showed that this is a real effect associated with reflections of the sound within the organ gallery. The resulting wavefronts arrived at an angle of about 45° to the audience in the nave.

The fourth church studied was San Francesco della Vigna, the objective being to study the effect of different roof types and heights on the preaching of sermons. The results of that study are discussed in a companion paper [3].

4. THE CHURCH OF THE REDENTORE

4.1. Background

Palladio’s Redentore, like the other large churches, exhibited long reverberation times that reduced complex polyphonic music to a muddied wash of sound. In his study of the decoration of Venetian churches on great festive occasions, Hopkins inferred that the spaces would have sounded very different on these occasions, when ‘ephemeral ornament increasingly transformed church interiors … during feast-day celebrations and processions.’ [9]

As a votive church funded by the Republic, the Redentore was built for the city’s annual festival of the same name. For the rest of the year, the austere Capuchin friars who lived there would have experienced the acoustics of the empty church. The Capuchins disapproved of the extravagance of the church’s main body, prompting Palladio to design a plain friars’ choir behind the high altar (see Fig. 1), more in keeping with the Capuchin order’s life of simplicity [1].

4.2. Modelling the Current Church

The Redentore’s internal acoustic volume was modelled in Odeon®. The church is composed of marble floors and altars, some high clerestory glass windows, stone columns and plastered brick walls and ceiling. While the absorption data for marble and glass windows are fairly uniform, plastered brick is more variable. Since the latter constituted a large fraction of the church’s interior surface area, absorption coefficients were selected within measured ranges to match the model’s simulated data to the physical acoustic measurements.

Fig. 1 shows the source and receiver locations in the Redentore, as well as the listening locations of audience members who participated in the choral experiments.

Figs. 2(a) and (b) compare the simulations with measurements of $T_{30}$ for source A within the friars’ choir to receivers 3 and 5 in the main body of the church. The simulations are within 3 JNDs of the measurements at every frequency except 8000 Hz, where the shorter T30 value decreases the JND significantly. The decrease in $T_{30}$ is caused by the extreme lowpass filtering effect of air absorption in this band, making $T_{30}$ less dependent on the material composition of the space. Since $T_{30}$ is less salient at high frequencies, it was decided that this level of precision was acceptable for the 8000 Hz band. The model estimates of EDT and $C_{60}$ were also found to provide a satisfactory match to the measured values at receiver positions 3-5 in the main body of the church.

The friars’ choir is separated from the chancel by a colonnaded screen, consisting of a curved wall about 3 meters high and four large columns extending to the ceiling (see Fig. 1). This screen acted as a ‘semi-permeable barrier’ with the friars’ choir acting as a ‘church within a church’, but still coupled to the main acoustic volume. The acoustic measurements supported this conclusion. With the source at A and the receivers at positions 1 and 2 in the choir, very
significantly lower average values for the EDT of 1.6 seconds and of $T_{30}$ of 3.7 seconds were found, as well as values of $C_80$ greater than 2 dB. Thus, the friars had excellent acoustics for the performance of plainchant within their choir.

The coupling of the acoustic volumes of the choir and nave resulted in a double-slope decay within the choir (Fig. 3) - the early part of the decay is determined by the acoustic volume of the friars’ choir while the later part is associated with the much longer decay constant of the main acoustic volume of the church [10, 11]. Because of this coupling effect, single-slope quantifiers such as $T_{30}$ are inadequate to characterize these decay curves, although the EDT is well matched to the early decay. Odeon® recommended using a larger number of rays for coupled volumes, but increasing the number of rays used in the simulation by a factor of 5 did not affect the result. Thus, care is needed in interpreting the parameters derived from geometrical acoustical simulation algorithms. The long decay tail seen in Fig. 3 matched well the values of $T_{30}$ for the main body of the church, and it was therefore concluded that the model gave a satisfactory account of all the acoustic volumes of the Redentore.

4.3. Sound Visualisation

Computer modelling also allows a visual analysis of sound propagation within the church by showing a spherical sound wave that gradually expands and reflects from surfaces in its path. The most striking geometrical feature of the acoustic volume is the extreme height of the dome above the chancel, as can be seen in Fig. 4. Previous Venetian churches had a tradition of false outer cupolas supported by wooden trussing, as was the case at San Marco. Palladio broke with this custom by instead using a cradle of thin wooden ribs to support the dome, allowing the inner curvature to be much greater, nearly matching the outer dome of the church’s roof [12].

Visualizing the propagation of sound with a source at location C in the centre of the chancel (see Fig. 1), the effect of the dome on the acoustics of the church can be assessed. As expected and demonstrated by the model, the almost spherical dome causes focusing effects above the radial centre of the dome (Fig. 4(a)). After the wavefront spreads out from the first focusing point, there is a concentration of secondary focusing farther down resulting from reflections within the cylindrical drum supporting the dome (Fig. 4(b)). Because of the height of the drum, these secondary focal points are still many meters above the floor. Had Palladio constructed a shallower dome at a lower height, the secondary focal point could have reached the floor level causing unpleasant comb filtering effects in the chancel. Although Palladio probably had no acoustical effect in mind when he designed the dome, the immense cylindrical acoustic volume acts as a diffuser spreading the sound uniformly through the main volume after passing out of the dome.

4.4. Modelling Festive Occasions

Once a year, the Doge and his entourage would take part in a formal procession across the canal between the main island of Venice and the Giudecca on a bridge of boats to celebrate the delivery of the city from the devastating...
plague of 1575-6 which caused the deaths of one third of the population of the city. On these major celebratory occasions, the Redentore would have been packed with the citizens of Venice. Hopkins has suggested three ways in which the acoustics would have been significantly modified on these occasions [9]. On the basis of his studies of similar celebrations in the church of Santa Maria della Salute [13], there would have been wall hangings and tapestries covering the columns in the nave and most of the sanctuary, the congregation would have been in their heavy robes, and temporary wooden bleacher-like seating called palchi would have been placed in the chancel for the Doge and his entourage. It has been recorded that on the great festal occasions, thousands of Venetians were present in the Redentore, filling the floor area of most of the acoustic volume.

In modifying the virtual Redentore, we aimed to produce the largest reasonable acoustic change using the properties of measured materials in order to understand how significantly the acoustic parameters might have changed on the great festal occasions. The absorption coefficients for Renaissance tapestries and wall hangings were taken to be those of heavy drapes, which are very absorbent at high frequencies but less so at lower frequencies.

One of the most absorbent materials was the audience itself. Based on the descriptions of the massive crowds flocking to the church, we modelled a large congregation in the church. The nave floor was covered by a ‘surface’ of people 2 meters above the ground, though the side chapels were left empty. The chancel would have been occupied by the clergy, the Doge, and his entourage. This area would probably have been less crowded and so was less densely populated in the model. Since the database included different absorption coefficients for individuals based on the thickness of their clothes, this was incorporated into the model: the audience in the nave were given slightly less absorbent clothing, while the nobility in the rear of the chancel were given higher absorption coefficients corresponding to their heavy ceremonial robes.
The original high altar was less tall than that in the church today. Although the marble altar provides almost no absorption and was not found to contribute to the coupling of the friars’ choir, the original altar was incorporated into the virtual festal church. In addition, two *palchi* were added to the model’s chancel and were filled with the same heavily-robed nobility as at the rear of the chancel. Virtual images of the festal Redentore from the Odeon® simulations are available on line [14].

The four changes to the virtual church were added separately to ascertain the impact of each. As expected, the shortened altar had no effect on any acoustic parameter. The addition of an audience gave significant damping at mid-frequencies. The tapestries provided additional absorption at high frequencies. While the wooden parts of the *palchi* added low-frequency absorption, their surface area was too small to affect the overall reverberation time, though the *palchi* did slightly affect EDT at nearby receivers in the chancel.

When these changes were combined into a single model, the overall changes were considerable. Figs. 5(a) and (b) show the averaged $T_{30}$ across all receivers from source B in the left chancel apse. Low frequencies are dampened somewhat, since the audience (absorption coefficient 0.15 at 62.5 Hz) is still much less reflective than the marble floor (absorption coefficient 0.01 at 62.5 Hz). $T_{30}$ at mid and high frequencies is, however, decreased to roughly half of that of the empty church. As would be expected based on the earlier analysis of the friars’ choir, while the EDT decreased for the receivers in the main body of the church, receivers in the choir were unaffected since absorption behind the screen was unchanged.

Reducing the reverberance of the main body of the church also increased significantly the $C_{80}$ values. For a source under the dome in the chancel, the $C_{80}$ value for a listener in the centre of the nave was very low for the empty church (Figs. 6(a)). But in the virtual festal church (Figs. 6(b)), $C_{80}$ was significantly increased in

![Figure 5](image1.png)

*Figure 5.* (a) Comparison of the simulations for $T_{30}$ averaged over all receivers with the source at B in the left chancel apse for the empty Redentore. (b) The averaged $T_{30}$ simulations as in (a) for the festal Redentore.

![Figure 6](image2.png)

*Figure 6.* (a) Comparison of the $C_{80}$ simulations (red boxes) with the acoustic measurements at C5 (blue crosses) for the empty Redentore. (b) $C_{80}$ simulations for C5 in the festal Redentore (red boxes) compared with measurements of C5 for the empty Redentore (blue crosses).
the mid- and high-frequency bands. Reaching values greater than 0 dB, this region of the spectrum experienced a dramatic increase in clarity. The added clarity of the festal church does not come without cost, however - there is a decrease in overall sound intensity. The simulated impulse response for C5 in the empty church is 4-8 dB louder than that of the festal church from 250-8000 Hz, the frequency bands in which C80 increased the most.

These conclusions were substantiated by auralisations of the anechoic recordings made by the choir of complex polyphonic music. Whilst the empty church was unsuited for such music, the festal church would have provided all listeners wherever they were located with a clear and satisfying musical experience.

5. THE CHURCH OF SAN MARCO

5.1. Background: The Doge’s Chapel

Until 1807, the church of San Marco was the private chapel of the doge. As a state church, it developed its own liturgy, distinct from that of the Roman Church. This ceremonial independence was highly prized by the Venetian Republic, which resisted papal efforts to impose the Roman liturgy in Venice.

During the Renaissance many distinguished composers, such as Willaert (1527-1562) and Monteverdi (1613-1643), occupied the post of maestro di cappella at San Marco, writing new music for the chapel and conducting the choir. In this same period Andrea and Giovanni Gabrieli served as the church’s chief organists and composed works for the choir as well. During Willaert’s 35 year tenure, the split-choir, or coro spezzato, style for which San Marco would become famous, was introduced. The Doge had previously occupied the hexagonal pulpit, known as the bigonzo (location A,1 in Fig. 7) outside the chancel. Doge Andrea Gritti became so overweight that he could no longer climb the stairs into the bigonzo and so moved his location to a throne in the chancel [15], to location 2 in Fig. 7.

Moretti proposed that during Willaert’s tenure the split choirs occupied the twin singing galleries known as pergoli within the chancel [16]. Willaert’s student, and subsequently maestro di capello at San Marco, Gioseffo Zarlino, asserted that the split choirs were ‘placed rather far apart’ [1]. Jacopo Sansovino, appointed as chief architect, or proto, of San Marco two years after Willaert’s arrival, erected the two pergoli in the chancel following Gritti’s relocation of the Doge’s position. The first was built to replace a previous pergolo, but at a significantly higher level because the ground level was now fully occupied by stalls for the Doge’s retinue. Moretti suggested that the second pergolo, added about five years later, was constructed for the performance of coro spezzato on either side of the Doge’s new position. The south, or right, pergolo is labelled C in Fig. 7 and there is a corresponding north, or left, pergolo on the opposite side of the chancel.

The CAMERA experiments found that performances from the pergolo had excellent clarity and low EDT at the Doge’s position and throughout the chancel [1,3] but these values were considerably inferior in the nave where the congregation was located. As in the case of the Redentore, it was anticipated that the acoustics would be significantly improved on the great festal occasions. The church was therefore modelled in Odeon® with the goal of reconstructing the performance of complex polyphonic music as it would have been heard during Willaert’s lifetime.

5.2. Modelling the Current Church

The church of San Marco has a Greek-cross plan, complicated by vast series of arches and apertures beneath its five mosaic domes. The structure of the church was traced as an extrusion model, and the many

Figure 7. A plan of the church of San Marco showing: red squares - positions of audience members; blue triangle - location of acoustic measurement source, identified by letters; green circle - position of acoustic measurement microphone, identified by numbers. Positions A and 1 are in the bigonzo, slightly raised, position C is in the right pergolo in the chancel and position D is the organ gallery, high above the left side of the chapel.
The only surfaces with unknown acoustic properties in San Marco were the gilded glass mosaics that cover large portions of the walls and ceiling. The mosaics were intentionally not laid smoothly, to give the church a golden glittering appearance. Using measured values of the acoustic parameters, we worked backwards as in the case of the walls of the Ospedaletto and the Redentore. The mosaics were found to have average absorption coefficients of up to 0.1, depending on frequency band. These surfaces were assigned a mid-frequency scattering coefficient of 0.2, corresponding to a surface roughness depth of about 10 mm. The CAMERA data used four source and five receiver positions (Fig. 7), but the present analysis focused mainly on sources at A (in the bigonzo) and C (in the south pergolo).

The model was able to reproduce correctly the variation of $T_{30}$ with frequency in the nave (receiver position 5) from sources at A and C. In addition, the model correctly simulated the high measured values for EDT in the nave, a simple exponential decay.

The Doge’s position in the chancel (position 2) proved to be more complex acoustically than had been expected from the CAMERA measurements. With the source located centrally in the south pergolo and the receiver at the Doge’s position (C2), the model resulted in poor agreement with the measured values of EDT, $T_{30}$ and $C_{80}$. As with measurements in the friars’ choir at the Redentore, the $T_{30}$ simulations deviated from measured values, but in San Marco the simulated values were too high rather than too low (Fig. 9(a)). When the source was moved one metre forward to the front centre of the pergola, agreement with the measured values of EDT, $T_{30}$ and $C_{80}$ was recovered (Fig. 9(b)). The origin of the relative clarity of the sound at the Doge’s position is the direct line of sight to the choir in the pergola [17].

The reason for this is illustrated by the decay curve for C2 (Fig. 10), which shows a remarkable double-slope decay...
 decay: the first 4-5 dB was nearly instantaneous, followed by the longer decay profile of the larger acoustic volume of the church as a whole. Although double-slope decay usually results in the $T_{30}$ prediction being shorter than the actual reverberation time, in this case, since the estimate of $T_{30}$ begins at -5 dB, the $T_{30}$ value represents the longer decay time for the nave and thus overestimates the actual time for an extrapolated 60 dB decay for $T_{30}$ at the Doge’s position. While most double-slope decays are the result of a smaller acoustic volume coupled to a much large volume of the church as a whole, the modelling of the chancel of San Marco illustrates a more extreme type of behaviour. Because of the cavernous nature of the acoustic volume, the chancel exhibits almost complete ‘open-window’ absorption as the sound escapes into the larger volume of the church.

The clarity experienced at the Doge’s position depended critically upon the location of the sound source within the south pergolo. During the modelling process, it was found that moving the choir’s position by as little as 1 metre towards the back of the south pergolo drastically changed the simulated impulse response at the Doge’s position: the earliest sound path to reach the Doge was changed the simulated impulse response at the Doge’s position. While most double-slope decays are the result of a smaller acoustic volume coupled to a much large volume of the church as a whole, the modelling of the chancel of San Marco illustrates a more extreme type of behaviour. Because of the cavernous nature of the acoustic volume, the chancel exhibits almost complete ‘open-window’ absorption as the sound escapes into the larger volume of the church.

Sansovino’s elevated, slightly projecting pergolo resulted in a direct line of sight to the Doge and his entourage in the chancel, ensuring much higher musical clarity than that experienced by the rest of the congregation.

5.3. Modelling Festive Occasions

Like the Redentore, San Marco was filled with the people of Venice, tapestries and extra seating on the numerous great festal occasions, which were a very important part of the Venetian calendar. An anonymous painting from the 17th century entitled Consignment of the Sword to Doge Francesco Morosini by Pope Alexander VIII in San Marco in 1690, now in the Museo Correr, Venice, shows in great detail the stalls and tapestries in the chancel on one such occasion. The virtual chancel was altered to reflect the absorbent materials shown in this painting and the nave was filled by a large congregation and hangings were placed on the columns and walls. Virtual images of the festal San Marco from the Odeon® simulations are available on line [14].

These changes had a modest impact at low frequencies but resulted in much more substantial differences at mid frequencies because of absorption by the audience members. For combination A5, from the bigonzo to the centre of the nave, $T_{30}$ (Fig. 12(a)) and the EDT decreased by up to 3.5 seconds in the middle frequency bands, while $C_{50}$ (Fig. 12(b)) increased by up to 5 dB in that same range. This increase in clarity came at the expense of average loudness, which was nearly 6 dB lower in the festal church. A comparison of auralisations using anechoic input signals for the combination A5 in the empty and festal churches confirmed that the festal church sounded very much clearer but significantly quieter in intensity.

For source C in the south pergolo and receiver 2 in the Doge’s position, the changes were also significant. $T_{30}$ decreased by up to 4 seconds relative to the empty

![Figure 10](attachment:image.png)

*Figure 10.* Model decay curves by frequency band for source-receiver combinations C2 in San Marco in dB-SPL for a source with sound power level $L_p = 0$ dB. Note the very rapid decrease in intensity in the first 50 milliseconds.
church (Fig. 13(a)), while the chancel's EDT was only shortened by about 2 seconds in the middle frequency bands. $C_{80}$ increased by 2-3 dB (Fig. 13(b)). The average loudness for the combination C2 only decreased about 2.5 dB, remaining louder in the festal chancel than in the empty nave. Because of the problems of estimating $T_{30}$ for decay curves such as that in Fig. 10, the differences between the empty and festal churches are regarded as indicative rather than absolute figures.

6. CONCLUSIONS

Most modern measurement campaigns of historic churches focus on their suitability for performance today. Geometric acoustical modelling is also an important tool for analysing historically significant performance spaces. In conjunction with quantitative acoustic measurements for existing buildings, it provides many ways of understanding the acoustics of complex volumes such as the churches in this study. When the accuracy of the models can be calibrated using such data, the models provide insights into past soundscapes of acoustic volumes for which architectural features and/or the acoustic properties of the materials of the building have changed significantly over time.

Acoustical modelling of the highly-reverberant Redentore has clarified how the added absorption would improve the acoustics, both by showing how sound propagates within the space and by quantifying how much difference a reasonable amount of absorbent material could have made. The sound diffuses so effectively those additional
absorptive materials reduced significantly the space’s very long reverberation time - $T_{30}$ could be decreased at mid-frequencies by half or more [17]. Even if the audience was smaller than our estimates, each person’s body would gain more equivalent absorption as the audience density decreased. As a result, the church’s reverberation time would still have been significantly reduced at mid and high frequencies, and possibly reduced somewhat at low frequencies as well. For a cappella choral music, which has little energy in low frequency bands, the clarity would have significantly improved, although the overall loudness would have decreased. We can only speculate as to how Palladio’s experience may have informed his intentions for the acoustics of the Redentore, but it is clear that it would have sounded best on the single day of the year, the annual Festa del Redentore, for which it was built.

The virtual model of the church of San Marco shows that, because of the drastic double slope decay in the chancel, a direct line of sight from the choir to the listeners would have been essential to achieve the favourable acoustics found in the CAMERA measurements. Whether Sansovino built the first pergoli to ensure a direct sound path is unknown - it had to be added because the earlier gallery on the ground floor had been concealed by the wooden stalls for the Doge’s entourage. Sansovino’s higher projecting galleries would have allowed direct sound from the choir to reach the entire chancel. Moretti’s hypothesis that the pergoli were built to improve the clarity of complex polyphonic music and coro spezzato seems entirely plausible. The reconstruction of the festal interior demonstrated a significant drop in $T_{30}$ and an increase in clarity, mostly at mid frequencies and mostly due to the presence of the large virtual audience.

The historical connection between architecture and music is a complex topic, spanning multiple disciplines and posing difficult questions [1]. Though computer modelling cannot establish definite proof of any particular historical hypothesis, it can provide valuable qualitative evidence to inform the historical discussion and also answers to specific questions about soundscapes that no longer exist.

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