THE ACOUSTICAL SURVIVAL OF SAN VITALE, RAVENNA, ITALY THROUGH TWO MILLENNIA

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1 ABSTRACT

The musical heritage of Western Europe has early roots in 6th century Italy, during Ostrogothic and subsequent Byzantine rule established in 540 at Ravenna. Only a very few examples of 6th century architectural spaces are extant. Among them, the basilica of Santa Sofia in Constantinople (transformed into a mosque in the sixteenth century), and that of San Vitale in Ravenna, remain the primary representative buildings of Late Antiquity.
From at least the 6th century to the liturgical reforms of Pope Gregory the Great (c.540-604), the Christians of Ravenna practiced their own rite and chant tradition suited for the churches of the city including San Vitale. One chant (*versus*) of the Ravennate rite in particular is appropriate for this church: *Lux de luce Deus tenebris illuxit Averni*.
In order to reconstruct the original environment in San Vitale in the 6th century, after a campaign of acoustic measurements, a numerical model of the church was properly calibrated, in which the binaural and b-format impulse responses were obtained and compared with those gathered in the experiment. A photo-realistic 3D model of the church was realized with the addition of window glass and candlelight. The original Ravennate versus, *Lux de luce Deus tenebris illuxit Averni*, was recorded in the large anechoic room at the ISVR, University of Southampton, UK.
The acoustic rendering of the church, both of the 6th and 21st centuries, was obtained by means of the stereo – dipole and Ambisonics systems. The dry chant was utilized during the auralisation process, and convolved both with the numerical and experimental 3D IRs. Finally, the virtual sound reconstruction was firstly performed in the Arlecchino Ambiophonic listening room at the University of Bologna in 2008 [March, 27th].

2 INTRODUCTION

The church of San Vitale invites a person to circulate through areas partially visually obscured by columns, partially open to vistas of inner, almost tangible volumes of space. These characteristics make the acoustics of the church very sensitive to the position of sound sources and receivers. Moreover, in the sixth century, Ravennate choral music was considerably different from the Gregorian music of later centuries, and sound effects produced in the church were remarkable. The proper understanding of sound perception of choral music in the church could be retrieved considering the acoustics of the room and reproducing its effects in the “Arlecchino” listening room by means of 3D Auralisation (Ambisonics and Stereo Dipole).

3 HISTORICAL BACKGROUND

The construction of San Vitale at Ravenna was initiated by Bishop Ecclesius (526-534) and privately financed by the banker Julianus Argentarius in 526, in the final year of King Theoderic’s (493-526) life[11]. It is an important example of the cultural exchange between East and West and is at present a UNESCO World Heritage Site. The church was most likely consecrated on the first Sunday after Easter (Quasimodo Sunday), April 19, 548 by Archbishop Maximianus (546-556) when Ravenna had already been under Byzantine rule for eight years.

Figure 1: Images of San Vitale, Ravenna

Architecturally San Vitale has an octagonal double-shelled central plan with a three-story vaulted octagonal domed core surrounded on the lower two levels by an ambulatory and gallery (*matroneum*). The interior volume of the church is approximately 25800m^3. Its design is influenced both by contemporary examples of churches and baptisteries in the eastern Empire, southern Gaul and northern Italy (Figure 1). Entry is via an outdoor courtyard (*atrium*) and adjoining elongated rectangular apse-ended porch (*narthex*). The extant interior wall mosaics of the chancel apse are world famous and include vibrant representations of Biblical subjects and the processional imperial court of Justinian and Theodora (Figure 1).

From at least the sixth century to the liturgical reforms of Pope Gregory the Great (c.540-604), the Christians of Ravenna had their own rite and chant tradition suited for the churches of the city including San Vitale. One chant (*versus*) of the Ravennate rite in particular is appropriate for this church; *Lux de luce Deus tenebris illuxit Averni*[10]. While it is understood that liturgical practice had an impact upon sixth century church architecture very few available historical accounts describe contemporary musical features. Therefore an acoustic measurement campaign was carried out by means of binaural and 3D microphones and an omni-directional loudspeaker[1,2].

4 MEASUREMENTS OF ACOUSTIC QUALITY

Extensive measurements of acoustical quality were performed by positioning the loudspeakers in the stage and microphones at several points throughout the church[3,4], as shown in Figure 2.

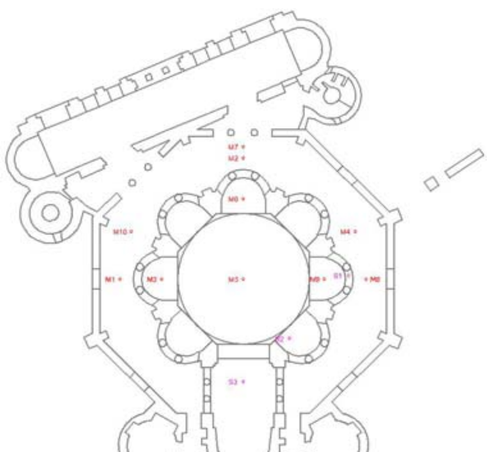

Figure 2: Positions of sound source and microphone placement within San Vitale.

The acoustic measurement campaign utilised the following instruments:
- An equalised, omni-directional, loudspeaker located in the stage, located in three positions.
- A dummy head (Neumann).
- A Soundfield microphone (MK V) was added to the dummy head.

The measurements were conducted by means of a logarithmic sine sweep, ranging between 40 Hz to 20 kHz. The signals acquired by the microphones were stored in a 20bits 96 kHz sample rate soundboard (Layla), and then post processed in the laboratory.

Figure 3: Images of the measurement instruments used within San Vitale

4.1 Analysis of measurements

The acoustical measurements were performed by positioning the sound source in 3 positions and the microphones at 10 positions within the church on the ground floor and balcony. Starting from IRs, the most important acoustical parameters (Clarity, T20, LF, IACC, STI, etc.) were calculated. An example of Impulse Responses measured in the church interior is presented in Figure 4.

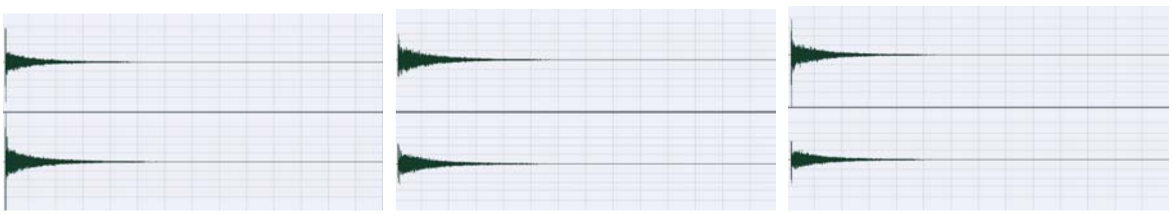

Figure 4: Acoustical measurements (WY, XZ and Binaural IRs) in San Vitale

Acoustical parameters were mainly calculated from the W channel signal of the Soundfield microphone, whilst IACC was calculated from the Neumann dummy head, and LF from the W and Y tracks of the Soundfield. Considering the values of acoustical parameters reported in Table 1, the resultant reverberation time was very long, San Vitale being a church this wasn't a completely unexpected discovery. All maps of acoustical parameters were calculated for every sound source. Considering mono-aural acoustical parameters such as C50 & C80, CT and D, the measurements underlined the low intelligibility of the church. The reverberant tail caused low values of clarity, this being in general agreement with the typical properties of a place of worship. Also at different frequency octave-bands the values of acoustical parameters remained mainly constant at each band.

The low values of clarity helped greatly to merge singing music across all the church, but a proper comprehension of the acoustic effects caused by the architecture and the original Ravennate versus could be properly understand only during the auralisation.

Freq. [Hz]	31.5	63	125	250	500	1000	2000	4000	8000	16000	A	Lin
C50 [dB]	-6.31	- 8.96	- 10.84	- 11.12	- 9.64	- 10.28	- 8.86	- 6.05	- 2.92	2.99	- 7.10	- 7.05
C80 [dB]	-4.45	- 6.05	- 8.68	- 8.53	- 7.50	- 7.56	- 6.33	- 3.65	0.07	6.92	- 4.71	- 4.70
D50 [%]	20.04	14.17	9.07	8.82	11.82	10.21	13.64	21.45	35.96	64.82	18.36	18.67
Ts [ms]	232.46	371.80	409.25	438.61	434.60	403.21	325.71	214.56	114.77	63.20	278.20	287.95
EDT [s]	4.62	4.90	4.96	5.80	5.86	5.27	4.32	2.89	1.57	0.74	3.80	3.99
T20 [s]	5.53	5.59	5.17	5.58	5.74	5.27	4.39	2.91	1.69	0.74	4.46	4.75
T30 [s]	7.02	5.80	5.02	5.60	5.77	5.35	4.44	2.95	1.78	0.11	4.70	5.00
IACC	0.99	1.00	0.96	0.74	0.39	0.35	0.35	0.23	0.14	0.25	0.25	0.26
LE	0.54	1.12	1.21	0.84	0.82	0.89	0.70	0.68	0.50	0.25	0.66	0.65
LF	0.80	1.72	1.49	1.09	1.10	1.16	0.99	0.93	0.65	0.37	0.91	0.90
LFC	0.44	0.79	0.70	0.60	0.59	0.60	0.54	0.49	0.36	0.25	0.49	0.48

Table 1: Averaged parameters measured in San Vitale

5 THE AURALISATION

The measurements of acoustical quality were necessary not only to understand the effective acoustic characteristics of the church nowadays, but also to create a numerical model of the church, calibrated on the experimental values of the reverberation time, which could be used afterwards to render the acoustics and the architecture of the original church[8,9].

In order to virtually reproduce the acoustic characteristics of San Vitale in the Arlecchino listening room[7], a dry recording of the chant *Lux de luce Deus tenebris illuxit Averni* was required. Therefore a vocal recording in the large 90 Hz anechoic chamber at the Institute of Sound and Vibration Research (ISVR) at the University of Southampton, UK, was realized (Figure 5) by means of a microphone (USB Samson CO3U).

Figure 5: Vocal recording at the ISVR, Southampton, UK

The dry recording was later used to convolve the measured and simulated impulse responses of the church during the virtual reconstruction of the internal architecture.

In order to properly simulate the sound conditions during the 6th century, the physical properties (for acoustics and lighting) of the ancient window-glass and mosaics have to be considered. For this reason a measuring campaign has started in 2008 on the original fragments of glass, actually conserved in the San Vitale Museum in Ravenna. The measured data (diffusion, diffraction) were afterwards used during the calibration and modelling of the church. An historical investigation has also occurred to reconstruct some architectural aspects of the church during the 6^{th} century, with regard especially to its original lighting. As far as the windows are concerned, some examples of stained glass windows were reconstructed and utilised throughout the church. Even though the original number and placement of the candles is not known, it may not have been dissimilar to a modern Greek Orthodox church where they are hung as chandeliers from the centre and near the gates. This solution was therefore chosen during the modelling of the church.

Figure 6: Fragments of original glasses and windows conserved at the Museo of San Vitale in Ravenna

5.1 The stereo-dipole rendering

One of the most useful procedures that could be used for the auralisation experiments is the stereo-dipole playback system. It is a two-loudspeakers based system that enables the reconstruction of the sound characteristics of any auditorium or theatre in a properly designed listening room, provided that the cross-talk paths between the two loudspeakers are avoided, and their frequency responses are flattened by means of a special set of digital inverse filters.

The calculation of the digital inverse filters requires special care. The acoustic treatment in the listening room, especially on the floor, and the position of the loudspeakers, could compromise the excellent quality of the system. Any changes in the room require a recalculation of the inverse filters.

Using the stereo-dipole system, it became easier to merge video and sound together in a movie, which could be played with a simple movie player, and displaying a perfect reproduction of architecture and sound in the listening room where the digital filters have been calculated and applied. On the other hand, the sound reconstruction requires that the loudspeakers should not be moved in any way from their original position, unless a new set of digital filters would be calculated and applied. The stereo dipole also allows a rather fair sound reproduction with normal stereo home systems. Moreover, in the listening room the stereo dipole allows a perfect sound reproduction only in a few seats.

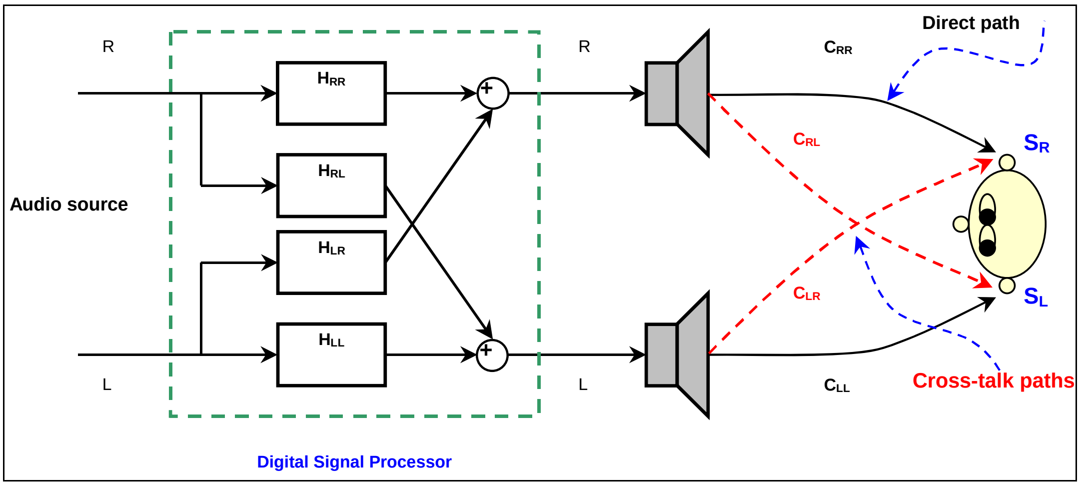

Figure 7: The stereo-dipole technique

In addition, the stereo-dipole technique allows for a perfect sound reproduction of virtual rooms. Using the aforementioned numerical model of the church, properly calibrated, it was possible to calculate the binaural impulse responses in the same positions of the measurements, but using the architectural features of the 6th Century.
The calculation of the binaural impulse responses here utilised was firstly described in 2000[5]. During the acoustic simulation in the room the early reflection in the impulse responses can be recorded. The time delay and the angles of last impact (cosine) up to 10 (and even more) early reflections are stored.
The point P represents the position of the early reflection after the last impact with the room. With reference to the azimuth and elevation angle of the receiver, the ray coming from the point P intersects a sphere in a point U, which lies inside a triangle having vertexes V_1, V_2 and V_3 These three vertexes represent the position of the Head-Related Transfer Functions (HRTFs) measured on a Kemar dummy head at MIT, Boston (MA).

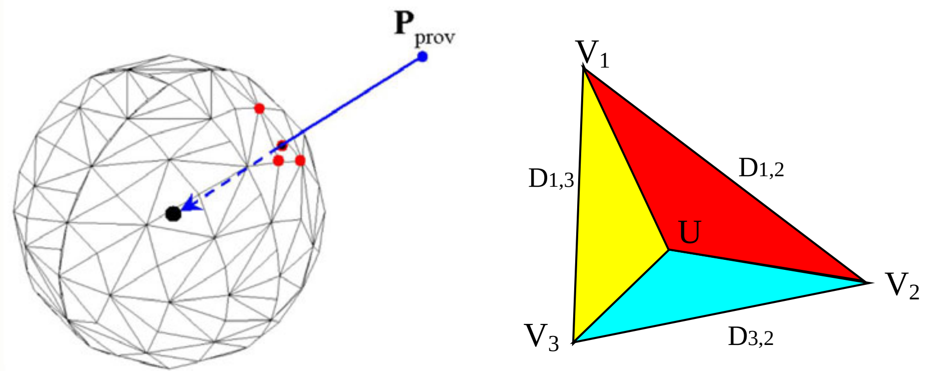

Figure 8: Calculation of the interpolation of HRTFs during the acoustic simulation.

The calculation of the HRTF for the point P is based on the interpolation between the three HRTFs corresponding to each vertex, using the three triangular surfaces as a weighting coefficient.

6 THE VIRTUAL MODEL

A further 3D model was finally realized for visual purposes[6]. The model, which was used for the visualisation of the architectural characteristics of the church in the two historical ages, thanks to the actual possibilities of computer graphics, has also allowed consideration of the lighting effects of the window-glass and candles.

Figure 8: Calculation of the interpolation of HRTFs during the acoustic simulation.

In order to calibrate the architectural vision of the church, many lighting parameters were measured in the church by means of a special probe (babuc). The model was finally completed considering the lighting properties measured in the church in relation to the physical characteristics of the original fragments of extant glass, which are stored in the Museo di San Vitale in Ravenna, Italy.

7 CONCLUSIONS

The architecture of this beautiful sixth century church afforded special acoustical effects that invited the listeners to appreciate vocal music at several positions within its complex interior space. The aural elements of liturgical ritual were materially expressed and influenced the development of ecclesiastical architecture and, conversely, architectural innovations such as the centrally planned octagonal domed church and its acoustic properties may have influenced the development of vocal music. Nowadays 3D auralisation is the only method of reproducing and restoring these Late Antique special effects.

In order to play back the original Ravennate music in the “Arlecchino” listening room, an acoustical measurement campaign in San Vitale was realized. Afterwards, a numerical model was realized and calibrated, and finally used to virtually reproduce the architectural and acoustical effects in the church. In this work the acoustical properties of the church of San Vitale and its virtual reconstruction have been presented.

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