The Acoustics of the 'Teatro all'Antica', Sabbioneta, Italy

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***Abstract*—Music, sound, and architectural acoustics are internationally recognized as key elements of the Intangible Cultural Heritage. Therefore, acoustic measurements should be encouraged to preserve the acoustic information concerning ancient theatres. The "Teatro all'Antica", located in Sabbioneta, Italy, was the first example of a permanent, free-standing, purpose-built theatre in Europe. This paper describes the results of the acoustic measurements and the 3D Sound Characterisation performed in the theatre. In addition to the traditional methods, a cylindrical microphone array made it possible to obtain 3D multichannel Impulse Response, providing an excellent spatial resolution and the possibility of creating a visual map with detailed information about the spatial distribution of sound.**

***Keywords*—Room Impulse Response, theatre, acoustical parameters, spatial PCM sampling, beam forming, room acoustics, concert hall**

I. Introduction

Preserving the acoustics of significant historic buildings is essential for several reasons: first of all, the need to store the acoustic parameters in the unlikely event that the building can be destroyed or damaged due to accidents or natural disasters; moreover, the creation of acoustic models of the buildings could be used in post-production location or listening rooms, providing the possibility to benefit elsewhere from the acoustics of places such as theaters, opera houses, churches and cathedrals [1].

A real-world example of the latter is the Sipario project, in which measurements of Impulse Responses (IR) in theatres allow understanding the acoustics of these important venues and thus the realization of 3D auralization (e.g., virtual reproduction of sound distribution in rooms) in specific listening rooms (or with headphones), preserving this information for posterity [2].

Gerzon, in 1975, was the first who made proposals "for recording the acoustic itself (in a way independent of the music) for the purpose of studying architectural and musical acoustics" [3]. In subsequent years, also due to the fires that destroyed two theaters in Italy, Teatro Petruzzelli in Bari and Teatro La Fenice in Venezia [4], many attempts were made to standardize the acoustics measurements in historic buildings [5, 6]. However, only a few aimed to analyzing, in addition to the position, also the type of sound source, test signals, and microphones [7].

Thanks to this research, there is now a greater awareness that these details are “crucial when measured Impulse Responses (IRs) are employed for performing 3D auralisation of the room” and that “the full spatial sonic behaviour of a theatre, which includes information about energy, intensity and location of early reflections in the room, is required to determine and solve some acoustic problems that could not be resolved by only considering mono or 2-channel Irs” [8].

This paper aims to present the results of the acoustic measurements and the 3D Sound Characterisation performed in the Teatro all'Antica, located in Sabbioneta, Italy, a perfect example of acoustics to be preserved.

II. The Teatro all’Antica

A. *Historical information*

Built between 1588 and 1590, the "Teatro all'Antica" in Sabbioneta was the first permanent, free-standing, purpose-built theatre in Europe: the first theatre of the Modern Era. Commissioned by Vespasiano I Gonzaga, Duke of Sabbioneta, it was constructed by the Vicentine architect Vincenzo Scamozzi, celebrated 16th-century architect, who had previously taken over the construction of the Olympic theater in Vicenza after the death of the original designer, Palladio. In the second half of the eighteenth century, the original fixed scene was removed and destroyed to make modern sets and moving scenes. In 1994, thanks to the Roman architects Francesco Montuori and Anna Di Noto, through an European funding of the Raphael Program, the original Scamozzi's scene, which represents the ideal city of Sabbioneta, was reconstructed and inaugurated in 1996 [9]. Today it is a venue for early music concerts, cultural events, and conferences [10].

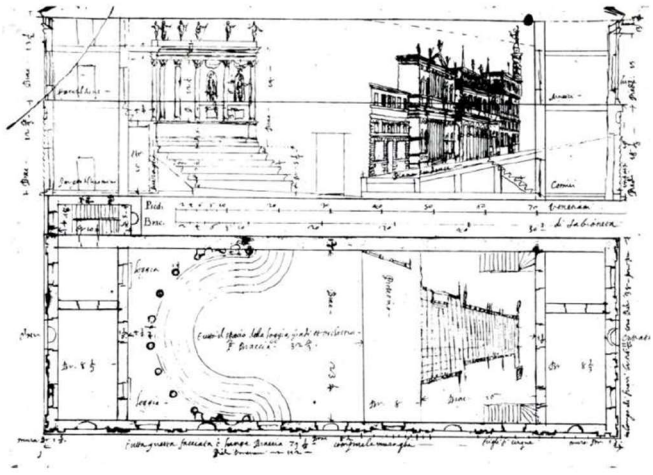


Fig. 1. Project of the Teatro all'Antica by Vincenzo Scamozzi

B. *Interior architecture and design*

The main rectangular room is divided into two squares separated by the short rectangle of the orchestra: one occupied by the semicircular cavea and the other by the stage. On the raised stage, it was located the fixed scene designed by Scamozzi, by which he wanted to recreate the illusion of real space around the actor's physical action (Fig. 2 shows the new, reconstructed scene). In addition, a sense of depth was accentuated by the inclination of the stage, and the false ceiling tilted itself above the stage. The frescoes on the side walls of the stage were part of the scene (Fig. 2), a fixed single vision perspective with a square, a street central flanked by noble and bourgeois buildings and side streets. Floor, steps, stage, false ceiling, and roof are interventions of the last centuries. The original loggia is made up of twelve Corinthian columns that adorn the façade of the ducal loggia on which statues of the gods of Olympus surmount a rich curved cornice (Fig. 3). Furthermore, four busts of Roman emperors are present.

It should also be noted that the foyer, dressing rooms, and separate artists' entrance built in this theatre were important innovations.

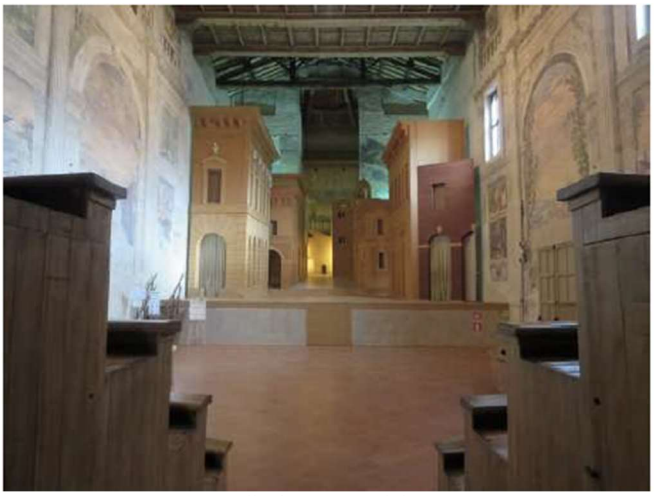


Fig. 2. Stalls, frescoes, and theatre scene.

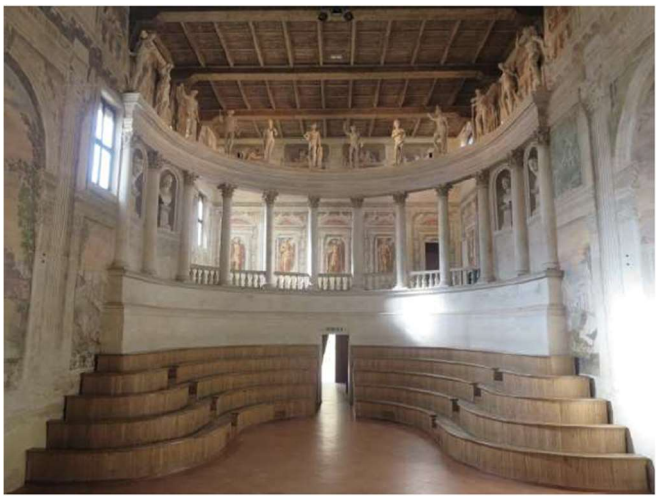


Fig. 3. Cavea and loggia

III. TECHNICAL SPECIFICATIONS

In this work, measurements were performed using a sound source and a set of microphones placed inside the theatre, using an Exponential Sine-Sweep (ESS), in accordance with ISO 3382. For a more in-depth analysis, a cylindrical array was used to obtain a 3D multichannel IR, providing an excellent spatial resolution and the possibility of creating a visual map with detailed information about the spatial distribution of sound. The measurements were performed twice for each point.

A. *Equipment*

Omnidirectional sound source:

- dodecahedron, with 12 speakers, on stage

Microphones:

- B-Format (Soundfield SPS422B)
- Binaural Dummy Head (Neumann KU-100)
- Omnidirectional (Behringer ECM8000)
- Cylindrical microphone array (custom made with 32 capsules, based on mhAcoustics Eigenmike em32 hardware)

Audio interface:

- Motu Traveler mk3

DAW:

- Adobe Audition
- Aurora plugin suite (Sine Sweep generator, convolution, deconvolution, calculation of acoustic parameters)

Audio quality:

- WAVs, 24bit 96kHz

B. *Traditional parameters*

- Reverberation Time (T20, T30, EDT, Tuser)
- Clarity Indexes (C50, C80)
- Definition index (D50)
- Barycentric Time (Ts)

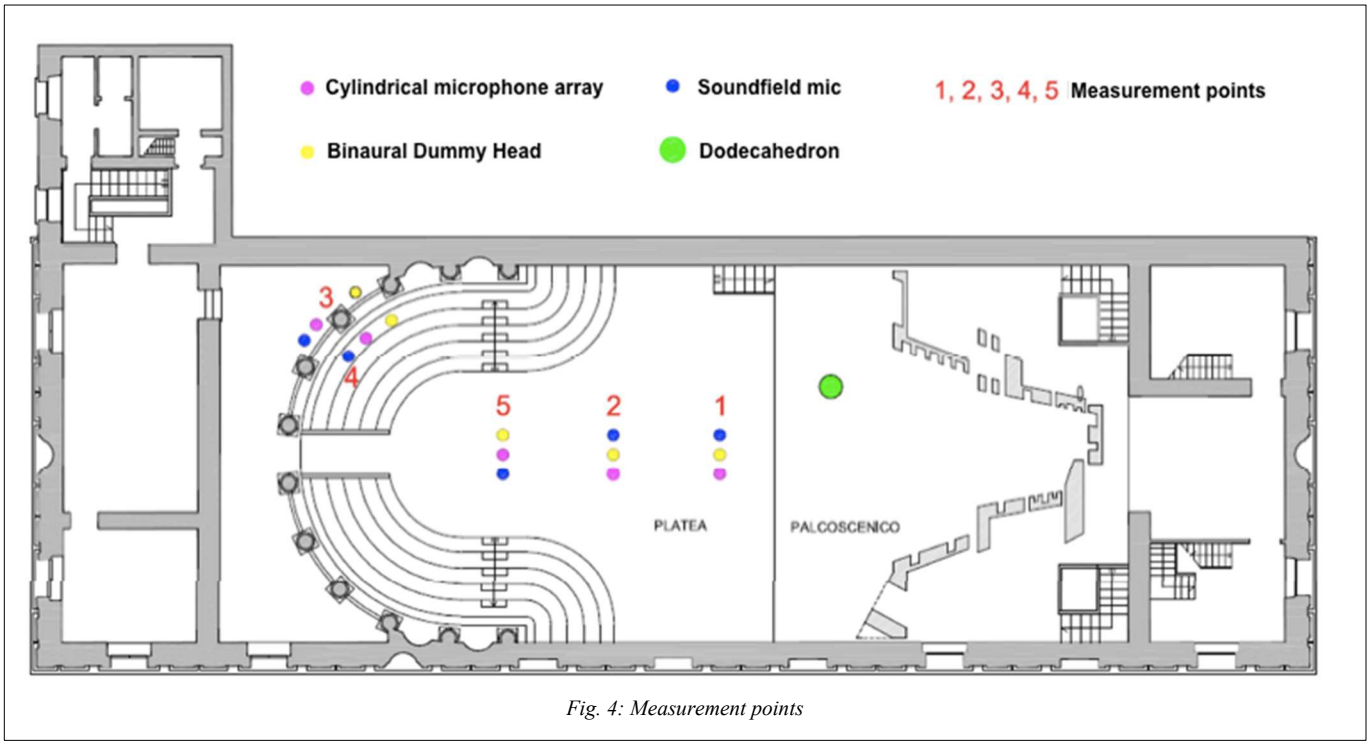


Fig. 4: Measurement points

- Strenght (G)
- Speech intelligibility, with STI (Speech trasmission index) and RASTI (Rapid speech trasmission index)
- Spatial parameters Jlf, Jlfc, IACC

C. *Spatial analysis with 3DVMS Method*

In addition to the traditional parameters (ISO 3382), a cylindrical microphone array made it possible to obtain a 3D multichannel IR, providing an excellent spatial resolution and the possibility of creating a visual map with detailed information about the spatial distribution of sound. This method (Three-Dimensional Virtual Microphone System 3DVMW) has been developed by the University of Parma and has been originally created for a spherical microphone array [11]. However, it can be extended to any microphone array. The data obtained is subsequently plotted on a panoramic photograph of the inside of the theater, or an animated video, to illustrate the directions of arrival and the intensity of the reflections [8]. Furthermore, this data set will make it possible to recreate the sound field of this theatre in a purpose-built immersive room [2].

IV. Analysis of the Results

As it can be seen in Fig. 4, five measurement points have been chosen, three in the pit, at various distances from the stage, and two on the steps, much far away and higher than the others. Due to a small size of the theatre, the sound source (dodecahedron) was placed in a single position, on the left side of the stage.

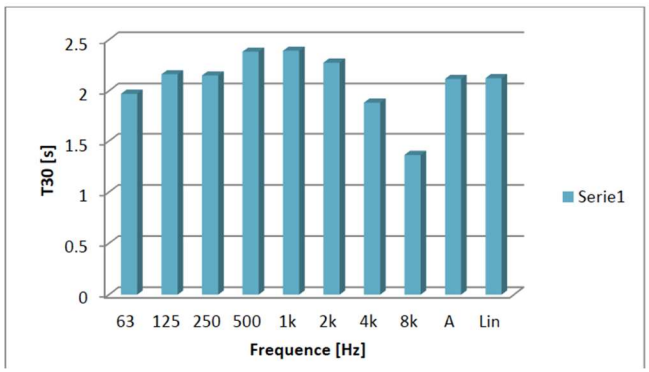


Fig. 5: Average T30 values

A. *Traditional parameters*

In order to give a complete panorama of the acoustics performance of the Sabbioneta's theatre, all the main objective acoustical parameters have been calculated (T20, D50, C50, C80, Tbar) plus the so-called spatial parameters (IACC, Jlf, Jlfc, Lj); the average results of the five sample points have been reported in Table 1, where it appears immediately clear why this theatre is appreciated for ancient music concerts: the T30 values seems a bit high if compared to the standard values for chamber music, especially at the mid-low frequencies, but the C80 values show a good perception and intelligibility of music in every listening point. The sound strenGth is very good, given the small room; also, the spatial indices evidence an appreciable intrinsic surround effect due to the short lateral reflection paths.

TABLE I: AVERAGE RESULTS OF THE FIVE MEASUREMENT POINTS

Acoustical parameters									
Freq. [Hz]	***125***	***250***	***500***	***1k***	***2k***	***4k***	***8k***	***A***	***Lin***
G[dB]	1,54	5,81	8,54	10,81	14,65	18,36	15,1	12,01	13,88
C50[dB]	-4,14	-4,82	-3,72	-4,24	-4,69	-2,34	1,25	5,35	-2,21
C80[dB]	-1,57	-1,69	-1,41	-1,68	-2,26	0,13	3,95	0,14	0,42
D50[%]	30,50	25,61	30,16	27,46	25,48	37,39	56,8	37,87	39,17
Ts[ms]	265,2	208,2	190,5	178,1	171,7	123,6	70,4	124,0	120,5
EDT[s]	1,83	2,08	2,40	2,34	2,24	1,82	1,18	1,92	1,88
T20[s]	1,93	2,12	2,36	2,38	2,26	1,86	1,31	2,06	2,06
T30[s]	2,16	2,15	2,38	2,39	2,28	1,88	1,36	2,12	2,12
IACC	0,53	0,32	0,16	0,13	0,11	0,15	0,15	0,14	0,14
Jlf	0,38	0,27	0,28	0,23	0,19	0,10	0,08	0,10	0,09
Jlfc	0,54	0,38	0,40	0,32	0,26	0,14	0,11	0,14	0,13

Since the theatre is currently used also for conferences, it is useful also the computation of the Speech Transmission Index (STI) that, substantially, confirms the fair results of the C50, as shown in Table II: as is the Teatro all'Antica has good musical performances and decent speech intelligibility.

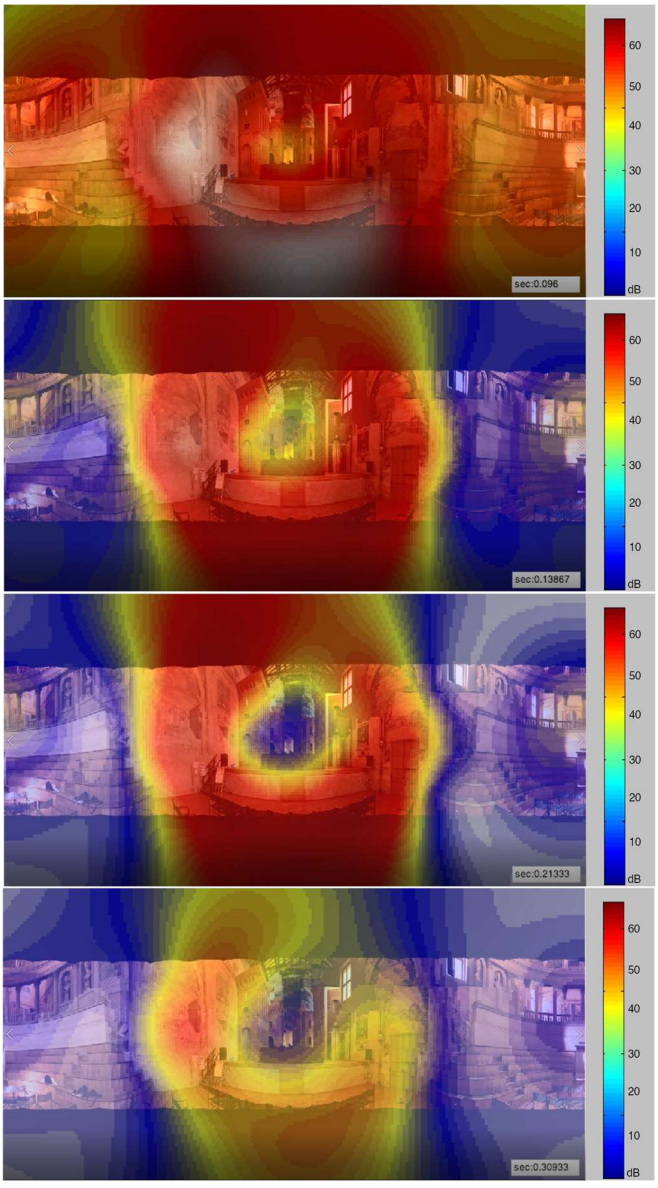
TABLE II: STI

Speech Transmission Index (STI)						
Meas. point	**1**	**2**	**3**	**4**	**5**	**Average**
STI Male	0,47	0,46	0,42	0,45	0,43	0,44
STI Female	0,48	0,47	0,42	0,46	0,44	0,45
RASTI	0,43	0,41	0,38	0,43	0,37	0,41

B. *Acoustic analysis of 3D sound maps*

In Fig. 6 to 15, some frames of the sound energy animation have been reported: these colored maps have been obtained from the measurements recorded with the cylindrical array and give an effective visual analysis of how the sound propagates across the room, in particular for receiver 1 the reflections on the left wall and on the floor are clearly visible after the direct wave; for the receiver 3, on the top of the steps, it is also clear the energy drop after about 40 ms.

Fig. 6-10: Frames of the sound energy animation of measurement point 1 (pit)



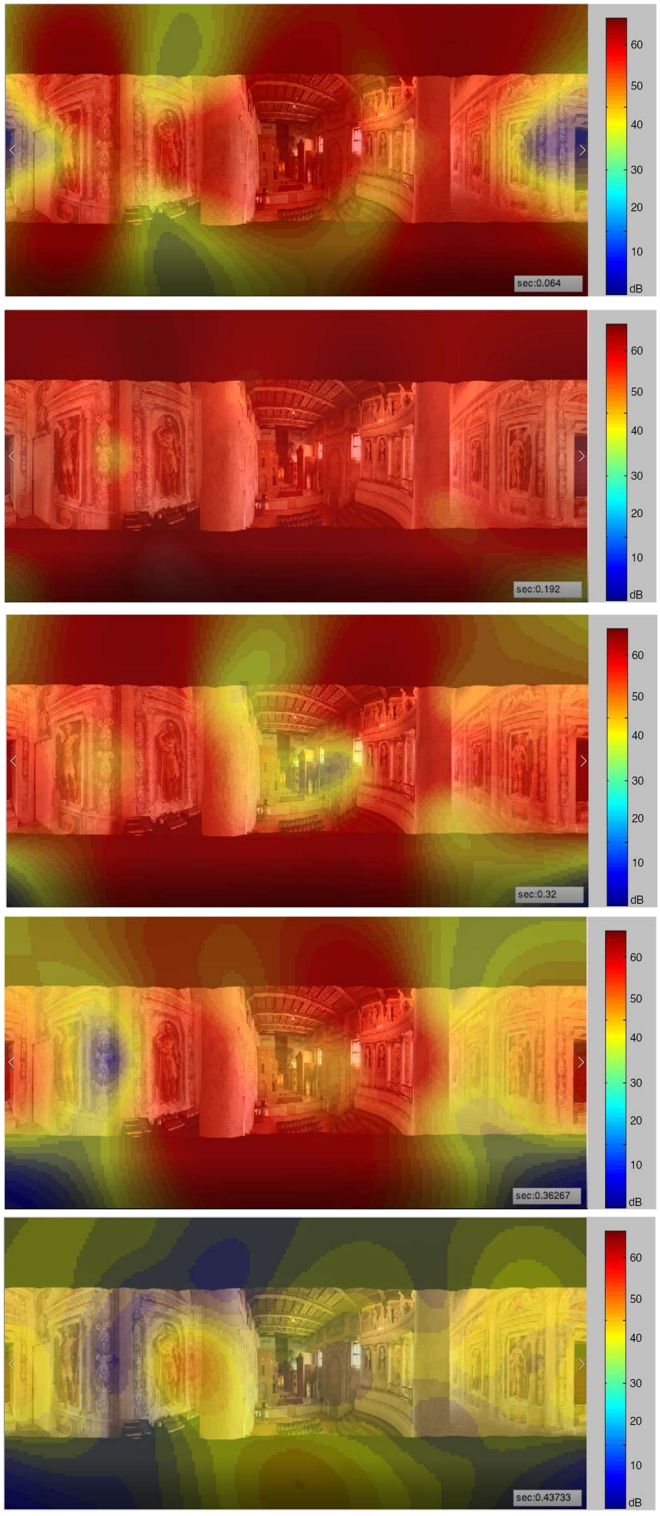


Fig. 7-15: Frames of the sound energy animtion of measurement point 3 (steps)

The technique used for maps generation is substantially the SPS (Spatial PCM Sampling) developed by prof. Angelo Farina [12]: 32 ultradirective virtual microphones have been generated from a filtered sum of the real 32 cylindrical array signals; the filter comes from a full set of anechoic impulse response measurements covering the whole spherical surface of the cylindrical array, combined with the target directivity of the virtual microphone. Then a Matlab script was prepared to capture the SPL of every virtual microphone over time and generate a set of colored maps of the SPL, one for every sampled time slot, which was used, overlapped to the theatre 360-picture, to obtain the animation frames [13].

The SPLs so computed are not absolute values because a reliable calibration method for the cylindrical array has not been set up yet; hence the values represented in the maps are relative.

V. Conclusion

The "Teatro all'Antica" of Sabbioneta is a very special example of baroque theatre, and the reconstruction of the ancient scenographic system gave us back what was one of the main targets of the baroque artists: to impress the audience, in this case – like the Teatro Olimpico of Vicenza – with a theatrical *trompe-l'œeil*. Thanks to the small size, the room also has a good acoustic behaviour, witnessed not only by the parametric analysis but especially by the three-dimensional visual analysis, capable of highlight critical issues simply by a glance. The SPS confirmed itself as perfectly suitable for this kind of analysis.

Acknowledgment

The authors would like to thank Serena Montecchio for having put together the results and made all the photographic materials, and, especially, remember the work but above all the person of Alberto Amendola who left us too soon.

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