



# 3D Acoustic Map Analysis of the National Theatre of Zagreb

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**Abstract:** Rapid technological advances in recent decades have led researchers to refine the accuracy of their studies. In the field of acoustics, the impact of new devices is noticeable, especially in the investigations of cultural heritage buildings. The selection of a seat in theatres and concert halls has always been a concern, since the live experience of artistic performance depends on the quality of hearing and sight view. This paper deals with the elaboration of 360° acoustic maps made in the National Theatre of Zagreb, one of the opera theatres investigated with the Sipario project. The analysis of the main acoustic parameters has been carried out, starting with site measurements describing the acoustic response at various representative points of the main hall by covering the audience area. In addition, acoustic maps have been created for some selected positions based on a 3-degree-of-freedom (3dof) technique that allows a panoramic visualization of the impulse responses (IRs). This methodology completes the determination of early and late reflections that contribute to the acoustic quality of a place. In addition to the interest of experts in acoustics, this methodology can also be adopted by music lovers who can find a reasonable explanation for seat selection when booking their tickets.

**Keywords:** soundscape; acoustic map; opera theatres; Zagreb; Croatia



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## 1. Introduction

The employment of multichannel devices for acoustic measurements has become very popular in the last decade, especially among researchers interested in developing auralization, which can be characterized also by dynamic sound sources and receivers [1]. The goal of combining a 360° video with a 3D sound field is one of the ways that enables a virtual navigation and an immersive listening experience. This technique is becoming the basis of various application areas, including gaming, cinema/entertainment, and the automotive industry, with surrounding effects that make the products more attractive and competitive in the global market [2].

In this paper, the 3D soundscape in the National Theatre of Zagreb is investigated, based on the use of a multichannel spherical array microphone capable of detecting the spatial sound waves characterized with a specific directivity. In order to understand the architectural development of this theatre, a brief description of its history is given, together with the geometric and dimensional details [3].

Some knowledge regarding the functionalities of a multichannel spherical array microphone is presented [4], as well as the principles of a beamforming process and the filtering process of virtual microphones [5]. Specifically, the elaboration of these maps does not follow any commercial package, but it has been improved at the University of Parma over the years since 2008–2010, when the outputs detected with simple circles the virtual microphones overlapped onto the panoramic photo. Based on the needs of recording artistic performances within theatres and concert halls during the pandemic, the system was implemented by representing the contour levels of the sound energy arriving at the microphone from a direct path or after the latest reflections. The detection of the directivity

over the image helps the listener to understand the sound behavior within that specific space. This tool was broadly used with the Sipario project during the pandemic, when the demand for assistance to virtual artistic performances from a remote position was significant. The Sipario project was held by the University of Parma and Bologna and was focused on virtually reconstructing both 3D audio and panoramic video of live artistic performances executed within the most historical theatres and concert halls spread all over Europe. For this occasion, both artistic experience and acoustic information of historical architecture were digitalized to provide broader access to the public, especially for those heritage buildings whose integrity is preserved by international organizations like UNESCO, therefore limiting their access. During the Sipario project, also a demo session was created to give the listener the possibility of virtually exploring the immersive experience by moving in different points across the space, as much as the measuring points were selected for the acoustic measurements within the theatre. One of the goals achieved with the Sipario project was the capturing of the acoustic characteristics of the main Italian and European opera theatres based on spherical array microphones, in order to be thereafter convolved with the anechoic signal related to music, acting, and prose.

After a general assessment of the acoustic response carried out using traditional equipment [6], an in-depth study of the interaction between sound energy and architectural elements of the main hall was carried out and identified with the evaluation of 3D acoustic maps [7]. The authors of this paper would like to persuade the researchers in acoustics to present technical data by following these two methodologies in order to achieve a complete acoustic description of performance arts spaces.

## 2. Method

### 2.1. Historical Background

The first opera theatre in Zagreb was erected as early as 1834 with the support of the nobleman K. Stankovic [8]. After the donation of private land in 1852 at the corner of St. Mark's Square and Freudenreich Street, the construction of a new theatre started under the direction of the architects Cragolini (i.e., father Cristoforo and son Antonio), who proposed a space for performing arts with a capacity of 750 seats in the Neoclassic style. The exhibitions were mostly, but not exclusive to, German and only in 1840 the heroic comedy by Ivan Kukuljevic was performed with local artists.

The design for a new theatre was created when an earthquake in 1871 caused severe damage to the structure, so Emperor Franz Joseph I supported the idea of a new public space to be located in the city center. The new project design was proposed by the architects Helmer and Fellner, who took over the construction management in 1894 and the following year [9].

After its realization, the National theatre of Zagreb experienced various restoration and consolidation works, especially in 1937 for the safety requirements related to the electrical system and again in 1967–1969 for the consolidation of the west side [3].

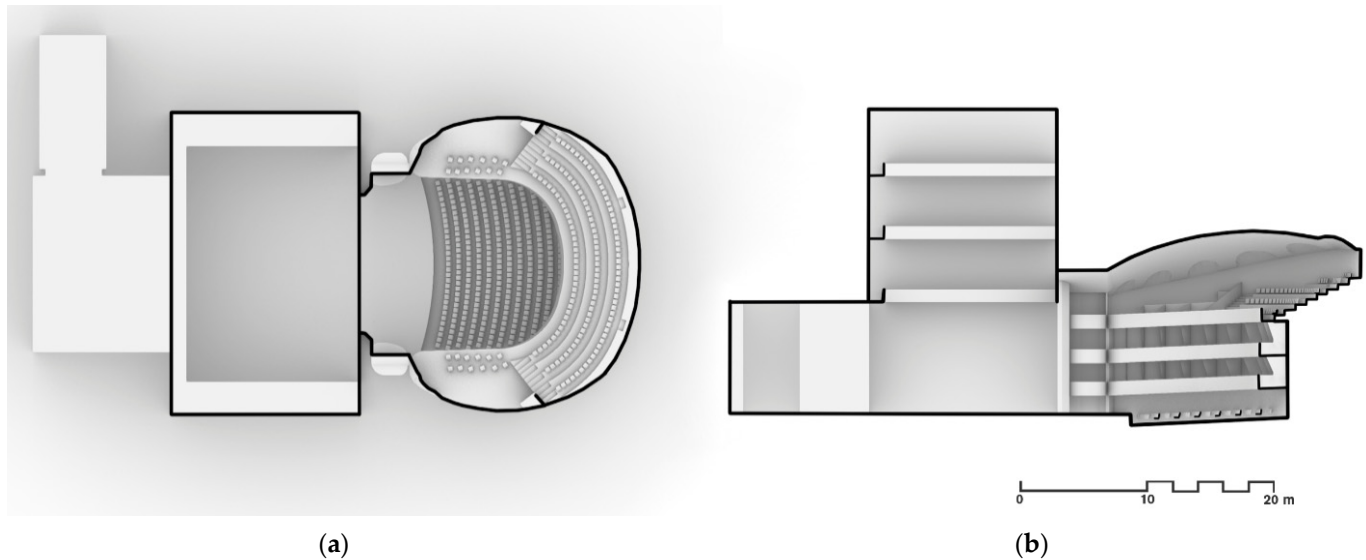
### 2.2. Geometry, Dimensions, and Organization

The National Theatre of Zagreb was designed for 765 spectators, divided into 345 seats in the stalls and 420 seats in the boxes, including the top gallery. The floor plan geometry is a U-shape inscribed in a square of 17.6 m side length [9], heading to a total volume of the main hall equal to 4760 m<sup>3</sup>.

The rectangular stage, with a length of 24.1 m and a width of 15 m, which can accommodate up to 80 musicians, is equipped with a circular platform with a radius of 8.5 m, which allows a 360° rotation in plan. Figure 1 shows the plan layout and the longitudinal section of the theatre.

The National Theatre of Zagreb has a floor plan similar to other buildings built in the same period. An example is given by the Bellini theatre of Catania (Italy), designed by the architect Carlo Sada and inaugurated in 1890. Although the total capacity is larger (i.e., 1200 seats) than the National Theatre of Zagreb, the Bellini theatre of Catania consists of four orders of balconies surmounted by a top gallery provided with a sloping floor [10],

similar to the National Theatre of Zagreb. The U-shape of the floor plan and the ornaments at the head of the partitions between the boxes remain the main analogies between these two theatres. As for the typology of the plan layout, the floor shape with parallel side walls was used during the Renaissance, when theatres were built inside royal or ducal palaces, adapting the form to the existing parallelepipedal salons [11].



**Figure 1.** Plan (a) and section (b) of the National Theatre of Zagreb.

The U-shape of the plans continued to be proposed also in the 20th century. Another example to be mentioned is the Queen's theatre of London, with a capacity slightly larger than the National Theatre of Zagreb (i.e., 1200 seats) that was opened in 1907. The floor plan is very similar to the National Theatre of Zagreb, and it is also organized into two tiers above the stalls.

### 2.3. Interior Design and Finishing Materials

The main feature of the main hall, which is particularly noticeable when visiting this performing space, is the large chandelier located in the center of the vault [9].

The architectural design of the heads of the partitions characteristic of muses is only on the first level of balconies, while floral motifs are found in the upper levels.

In terms of finishing materials, the floor of the stalls and boxes is carpeted, while the top gallery is made of wooden planks. The walls and partitions between the boxes are covered by a layer of paper. The seats are upholstered with a medium-thick pad (i.e., 40 mm). The wooden balustrades are characterized by high-relief decorations forming small angels, medallions, and shields, which all contribute to diffuse the sound in the audience area.

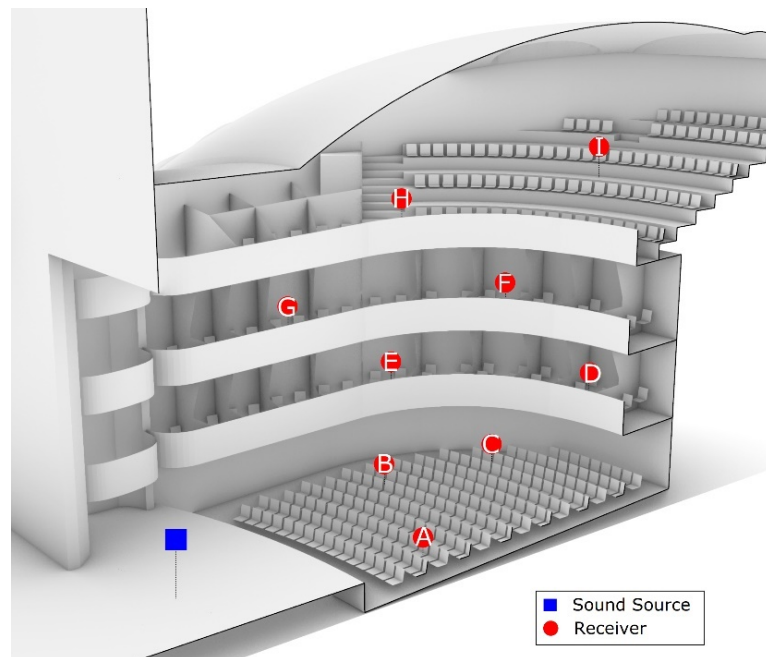
### 2.4. Acoustic Measurements

Inside the theatre, a series of acoustic measurements has been carried out based on the new generation equipment. In detail, the instrumentations used are the following:

- Equalized omnidirectional loudspeaker (Look Line);
- Binaural dummy head (Neumann KU-100);
- B-Format microphone (Sennheiser Ambeo);
- Omnidirectional microphone (B&K 4165);
- 32-channel spherical array (Mh Acoustic em32 Eigenmike®).

The sound source was placed at the height of a standing actor on the stage, while the receivers were placed on the stalls and balconies at the height of a seated listener. The sound signal used for the impulse response (IR) was an exponential sine sweep (ESS) [12] with a time duration of 15 s and a uniform sound pressure level in the frequency bands comprised between 40 Hz and 20 kHz. The sound level was set up to be at least 60 dB

above the background noise level of the main hall. Figure 2 shows the positions of the equipment during the site survey.



**Figure 2.** Schematic of source and receiver positions during the acoustic measurements. A–I identify the receiver positions across the seating area.

Figure 3 shows one of the moments in the theatre during the acoustic measurements.



**Figure 3.** View of the equipment installed in the stalls during the acoustic measurements.

The variety of equipment and the post-processing data analysis have been used for the following, different purposes:

- A summary assessment of the main acoustic parameters as described in ISO 3382-1 [6]. The research study on this subject has already been carried out together with the evaluation of the spatial distribution of the parameters in the frequency domain [13]. The IRs recorded by omnidirectional and B-format microphones with the addition of a dummy head were already used.
- Elaboration of 3D acoustic maps in different receiver positions to understand the early and late reflections of sound energy as they hit the boundaries of the room [14]. A multichannel microphone array has been employed for this purpose, as this is the goal of the research presented in this paper.

### 2.5. Acoustic Benefits on Employment of a 32-Channel Microphone

Many acoustic analyses use the outcomes from omnidirectional and/or B-format microphones up to the tetrahedral disposition of the capsules. Only a few acoustic researchers employ multichannel microphones with 32 or even 64 transducers. The methodology of the 360° acoustic maps is very diffused commercially and recently adopted by different manufacturers [15], but the first laboratory tests started in 2008–2010 at the University of Parma with a multichannel microphone composed of 32 channels [16], which was considered very advanced for the time.

This system synthesizes virtual microphones in real time based on a robust convolution processor, obtaining full control of the directivity with a small latency, with a better result than what is elaborated with by the traditional processing algorithms. The progress of this system consists mainly of the visualization part, where, at the beginning, the virtual microphones were indicated with circles, where the larger circle corresponded to a wider directivity, and the acoustic maps were represented as a pure superimposition of the colors corresponding to different microphones. This technology was developed over the years and improved for the creation of high-order ambisonic (HOA) directivity patterns, reaching up to the 7th order, while the virtual microphones are able now to reproduce the shape of soundwaves with an adjustable contour-line system (stepped by 2, 5, or 10 dB) for the scaling of the sound levels.

The improvement of the whole system was extensively adopted for real case studies during the Sipario project [17]. In detail, the software Matlab 2024a has been used to process the 32-channel impulse response, which has been convolved with the inverse exponential sine sweep at 48 kHz [18]. Then the filters obtained from laboratory calibration measurements were used for the encoding process. As a following step, the regulation of the time frame and gain are necessary to adjust the contour levels to be suitable for the recorded IRs, to be higher for the external environment as it is intended an absorbing large room, and lower for enclosed spaces given the return of sound in form of reflections [19].

### 2.6. Multichannel Microphone Array and Its Functionalities Post Processing

Among different configurations of arrays (planar, linear, etc.), the spherical type has been used for this case study and identified in the em32 Eigenmike®, which is equipped with 32 channels, uniformly distributed on the surface of a sphere. The advantage of the spherical array is that the capsules are equally sensitive to the arrival of sound waves from all direction due to their physical arrangement [20,21]. This is the methodology that different manufacturers have adopted for their production. Additionally, the number of capsules is the main characteristic that determines the synthesis of directivity; the larger the number of capsules that make up the array, the better the reconstruction of the sound field, since it covers as many angles as possible [22]. In technical language, this process is called beamforming [23].

As with any other microphone array, the beamforming can be achieved by the convolution of the numerical inversion of the IR measured in an anechoic chamber and the use of finite impulse response (FIR) filters in a time domain that synthesizes the real microphone

into a virtual microphone [24]. Specifically, each virtual microphone must sum the results of the convolution of 32 input channels with 32 FIR filters. A  $32 \times 32$  filter matrix can be used to convert the signal coming from the 32 transducers into 32 spatial PCM sampling (SPS) signals, whilst a  $32 \times 16$  filter matrix produces signals of 3rd order ambisonics (3OA) [24]. The number of directions determined for the use of the em32 Eigenmike<sup>®</sup> has been established to be 362, which is considered an adequate oversampling for the spherical array microphone used for the acoustic measurements [25].

To encode an audio signal in the time domain, pulse code modulation (PCM) can be used to convert the waveform of the analog signal into spatial pulses in a 2D plane characterized by the amplitude ( $y$ -axis) as a function of time ( $x$ -axis) [26]. Similarly, in the spherical spatial domain, the SPS decomposes the sound arriving at the microphone array into 32 virtual super-directive microphones and generates spatial pulses that homogeneously cover the sphere in a 3D space [27]. This parallelism is useful to also understand the calculation of the sum of products given in the time domain (2D) by sinusoidal oscillations through the application of FIR digital filters, while, in the spatial domain (3D), the spherical sound wave can be expressed as a sum of spherical harmonics through the pursuit of high-order ambisonics (HOA) [27].

The discrete Fourier transform (DFT) can be employed to transform the overdetermined system into the frequency domain and can easily elaborate it. After this step, the matrix can be transformed again into the time domain to obtain a temporal structure of the sound.

### 2.7. Acoustic Maps and Immersive Visualization

Once the IRs are recorded by the multichannel microphone, they can be processed to create the acoustic maps [28]. Specifically, the measured IRs are processed using convolution, which is a mathematical operation that digitally filters one signal with another. In this particular case, the convolution can be performed between the inverse filter of the sound signal and the multichannel IR recorded by the spherical array microphone [29]. The convolution is applied here for each source-receiver position combination, based on the position indicated in Figure 2.

Both audio and video have specific settings. In particular, after the convolution operations, audio parameters can be adjusted based on microphone gain, frequency passband filters (i.e., high and low passband), and weighting filters (e.g., A-weighted, linear). After adjusting the audio settings, the 32 signals extracted from the 122 highly directional virtual microphones can be elaborated [30]. The capture window of the samples, as highlighted with two blue lines, is adjusted such to cover all the soundwave, from the small amplitude to the wide curve amplitude at the peak and going down again to the small amplitude; in this way this way, all the energy levels can be represented in the color map [31]. If the capture window is too narrow and collects only 1–2 samples, the color map would be more monochromatic and would only red if focused on a spike or only blue-violet if focused on a small wave amplitude [32].

Previous research studies have already used a similar technique for regular shoebox room volume [33], but the innovation of these acoustic maps consists of the visualization of the IRs in a 360° view applied to a 19th century opera theatre with a particular volume shape [13]. On the image/video perspective, the parameter settings include the step size and frame rate, which are involved in the realization of the video flow. An additional option of horizontally tilting the 360° image allows for the alignment of the microphone front (identified with channel No. 1) with the loudspeaker to increase the accuracy of the video overlay.

Overlaying the panoramic image with the IR creates a series of contour levels. The output-rendered video is identified with a color scale ranging from red-orange, representing a high sound energy level, to blue-purple, where the sound pressure level is lower. Specifically, the color scale ranges from 75 dB (A) to 105 dB (A). The reflectograms at the bottom of each acoustic map represent the time flow of the impulse response, which is

given in the unit of millisecond (ms). The source simulated for the acoustic maps has omnidirectional directivity for all the octaves.

Combining audio and video for impulse response analysis is important for visualizing the reflections from the surfaces directed towards the receiver, with their direction of origin indicating the last surfaces implicated. Both early and late reflections can be visualized as they impinge on boundary surfaces. This is useful for acousticians when corrections are to be made in the form of installing new panels or similarly to eliminate undesirable reflections and/or flutter echoes. Accurate predictions, as can be conducted with this audio-video technique, are very useful for acousticians when mitigation solutions are very expensive; this method can be adopted to save stakeholders' money. The synthesis of arbitrary directional patterns that are available without having to move the equipment also reduces the need for several required site surveys. For non-technical people, the acoustic maps can also be used by music lovers when they reserve a seat for an artistic performance; this paper provides more information about the sound envelopment in the stalls and in the balconies and about the clear difference between the two.

### 3. Analysis of Results

#### 3.1. Acoustic Parameters by Graphic Representation

Based on the measured IRs, the main acoustic parameters have been analyzed in the frequency bandwidth between 125 Hz and 4 kHz, as shown in Figure 4. Differentiation of the average values has been performed for the measurement points located in the stalls and in the boxes. The results reflect the unoccupied condition.

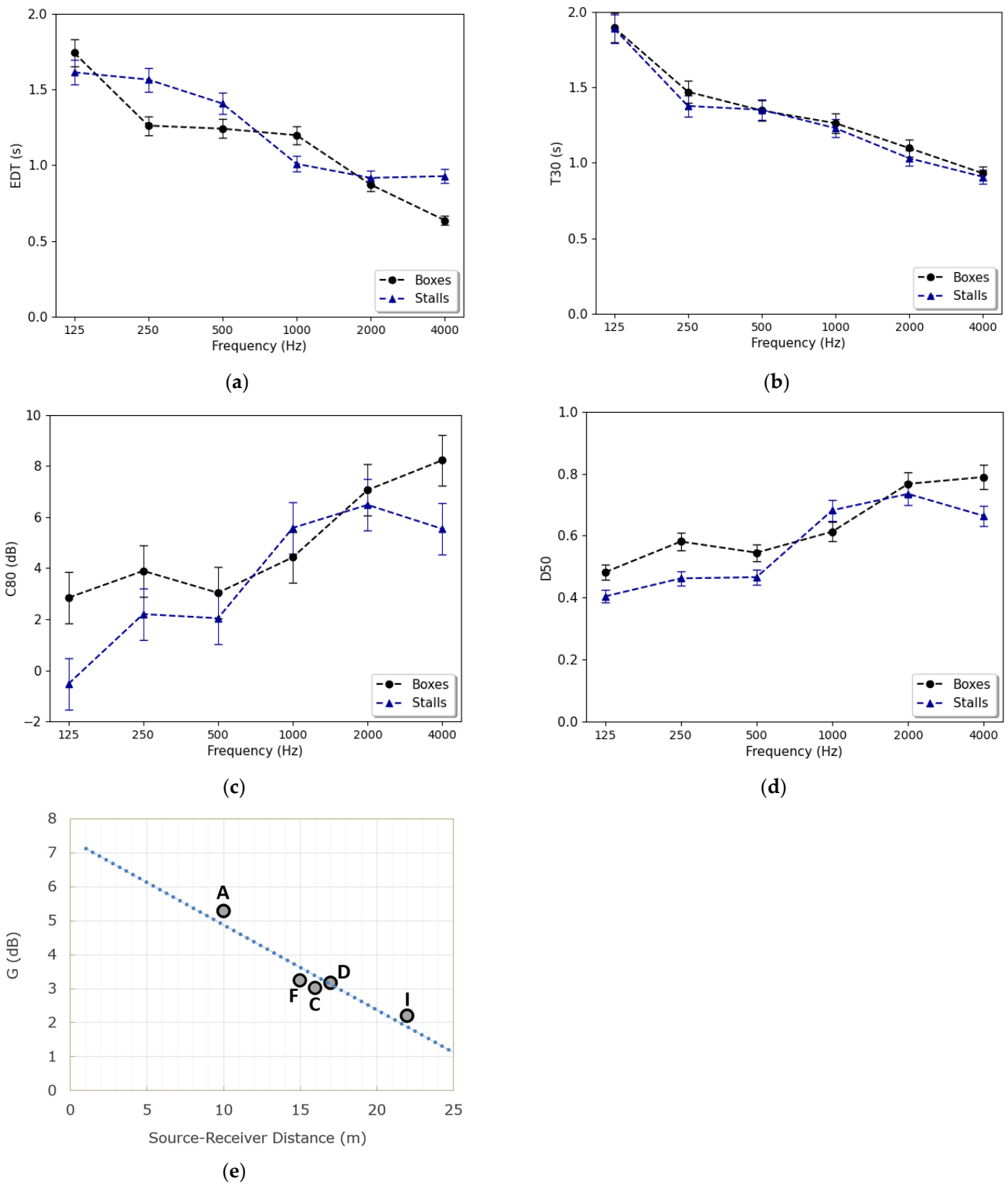
EDT values vary from 1.6 s at low frequencies to 0.7 s at 4 kHz. The difference between boxes and stalls is up to 0.5 s, being more pronounced at 250 Hz, 1 kHz, and 4 kHz, while the difference in the other octave bands can be considered negligible. These values are slightly lower than the optimal range reported in the literature [34], where the limits are set at 1.6 s and 2.6 s based on the integrated Schröder curve. However, this response is similar to other opera theatres [35]. The difference between the two curves at 250 Hz is due to the presence of surfaces closer to the microphone when located in the boxes, while in the stalls, the EDT values are similar to T30, since no close surface to the microphones are present, and therefore the reflections have the same time of arrival of a diffuse field.

As for the reverberation time (T30), the values are about 1.4 s at mid-frequencies, which is a good result for both opera and symphonic music in such a room volume [36]. Overall, the trend lines of boxes and stalls do not differ that much, which means that the T30 response is quite consistent across the sitting areas [37].

Considering that the optimal values for the clarity index C80 ranges from  $-2$  dB to  $+2$  dB [38], the measured results in the boxes are above the upper threshold, while in the stalls they are within the optimal range only at low frequencies, up to 500 Hz. This means that the sound is perceived more clearly, especially at high frequencies.

The results of the definition (D50) vary between 0.4 and 0.8, which means that the acoustic response of the National Theatre of Zagreb is suitable for both music and speech [39].

The G values are given as a function of the distance occurring between the source and the receiver, as shown in Figure 4e. Note that the location of the receiver is referenced in Figure 2. The results calculated at 1 kHz show that all G values are between 2 dB and 5.3 dB, falling within the optimal range for an opera theatre, very similar to other Italian opera theatres, whose average G value ranges between 4 dB and 8 dB. Position A, in the center of the stalls, has a G value of 5.3 dB, while position I, located in the upper gallery, has a G value of 2 dB. These results indicate a good level of sound robustness for singers during their live performance [40].

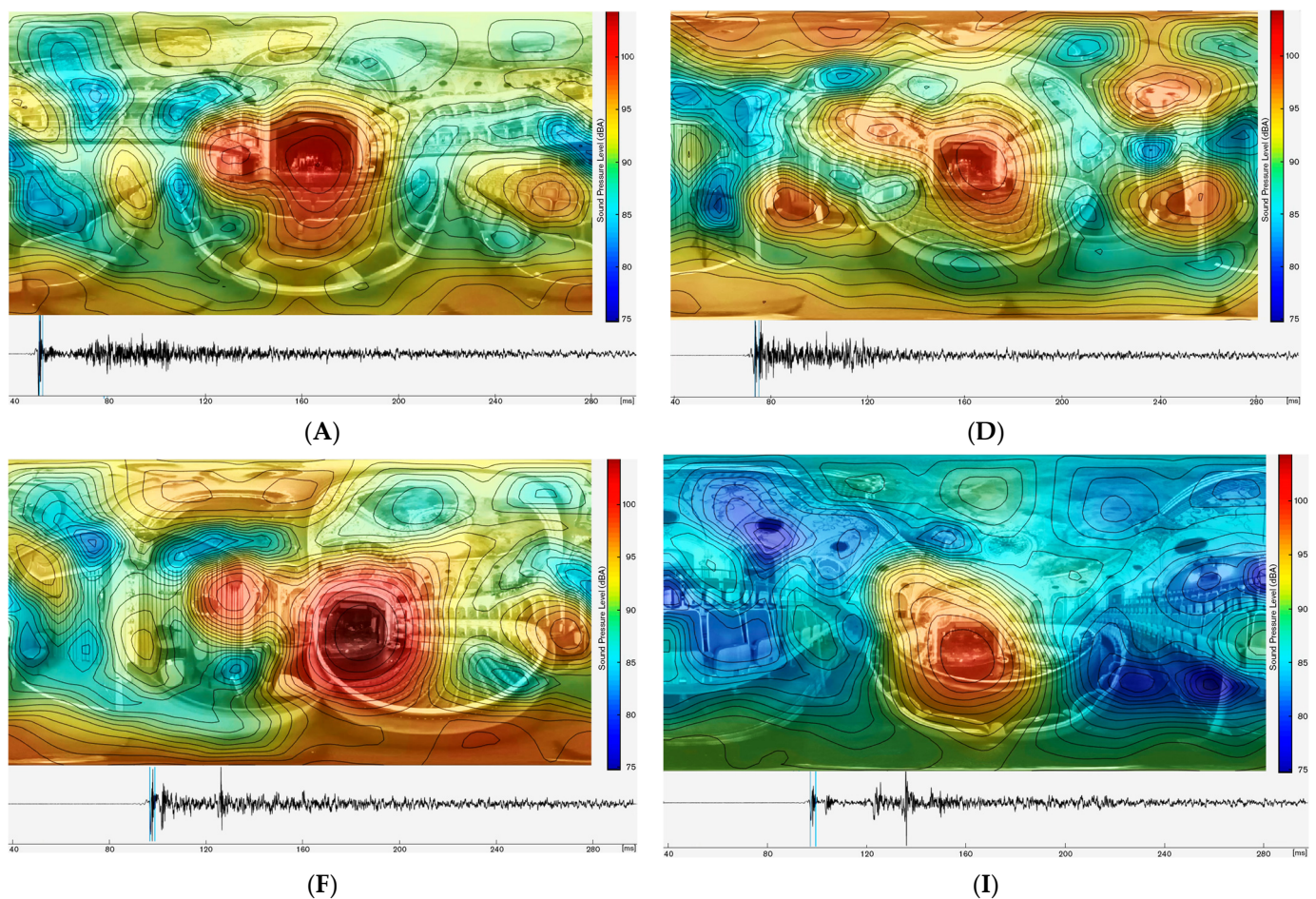


**Figure 4.** Measured results of the main acoustic parameters: EDT (a), T30 (b), C80 (c), D50 (d). In the graph related to G (e) the letters A to I stand for the positions of receiver as per the indication in Figure 2.

### 3.2. 3D Sound Maps and Volumetric Behavior of the Sound Energy Inside the National Theatre of Zagreb

Some selected positions of the multichannel spherical microphone have been considered for the realization of the acoustic maps, as indicated in Figure 2. It should be noted that the description and the technical details are already covered in Section 2 of this manuscript.

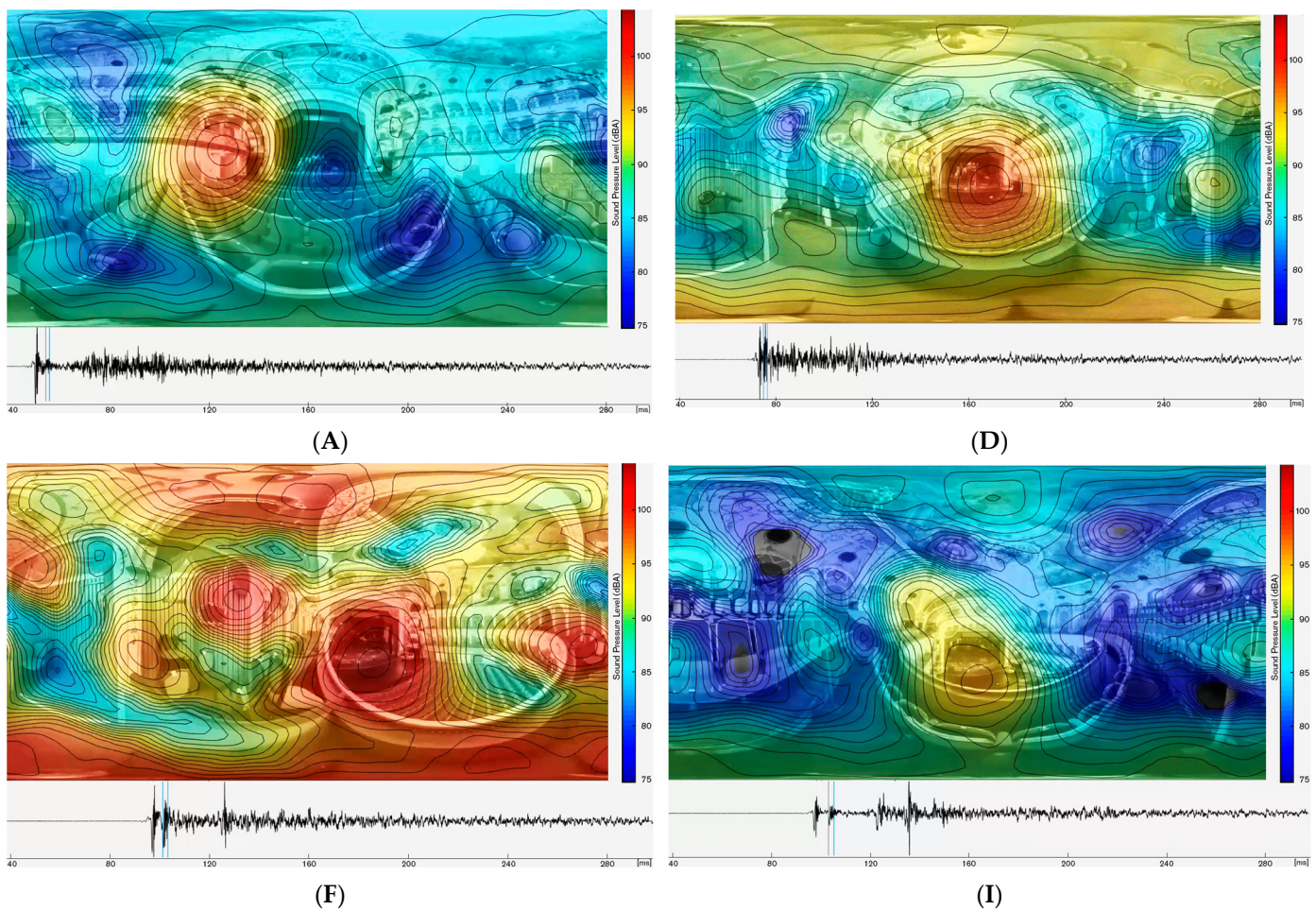
By analyzing the IRs recorded by the multichannel spherical array microphone, it is possible to detect the direct sound coming from the position of the sound source placed on the stage, followed by the early and late reflections [41]. Figure 5 shows the direct sound energy at the four representative positions across the audience where the time frame goes from 40 ms to 300 ms, as shown at the bottom of every image.



**Figure 5.** Panoramic view of the acoustic maps at the time of direct sound energy. Microphone positions in the stalls (A), first balcony (D), second balcony (F), and upper gallery (I). Time frame goes from 40 ms to 300 ms. Omnidirectional source on stage.

Based on the maps shown in Figure 5, the direct sound energy can be detected in the red color. Specifically, in the boxes of the first and second balconies, the sound energy easily hits the floor and ceiling of the boxes as well since the sound energy arrives on both surfaces simultaneously [42]. In the open spaces, such as the stalls and the upper gallery, the sound energy is more detectable, because there are no surfaces nearby other than the floor that reflects the soundwaves. The relationship between the soundwave amplitude of the time frame is visible with the color graphics; the higher the amplitude, the redder the contour levels.

Similarly, the snapshots of the early and late reflections of the overlay videos are summarized in Figure 6, where the time frame goes from 40 ms to 300 ms, as shown at the bottom of every image.

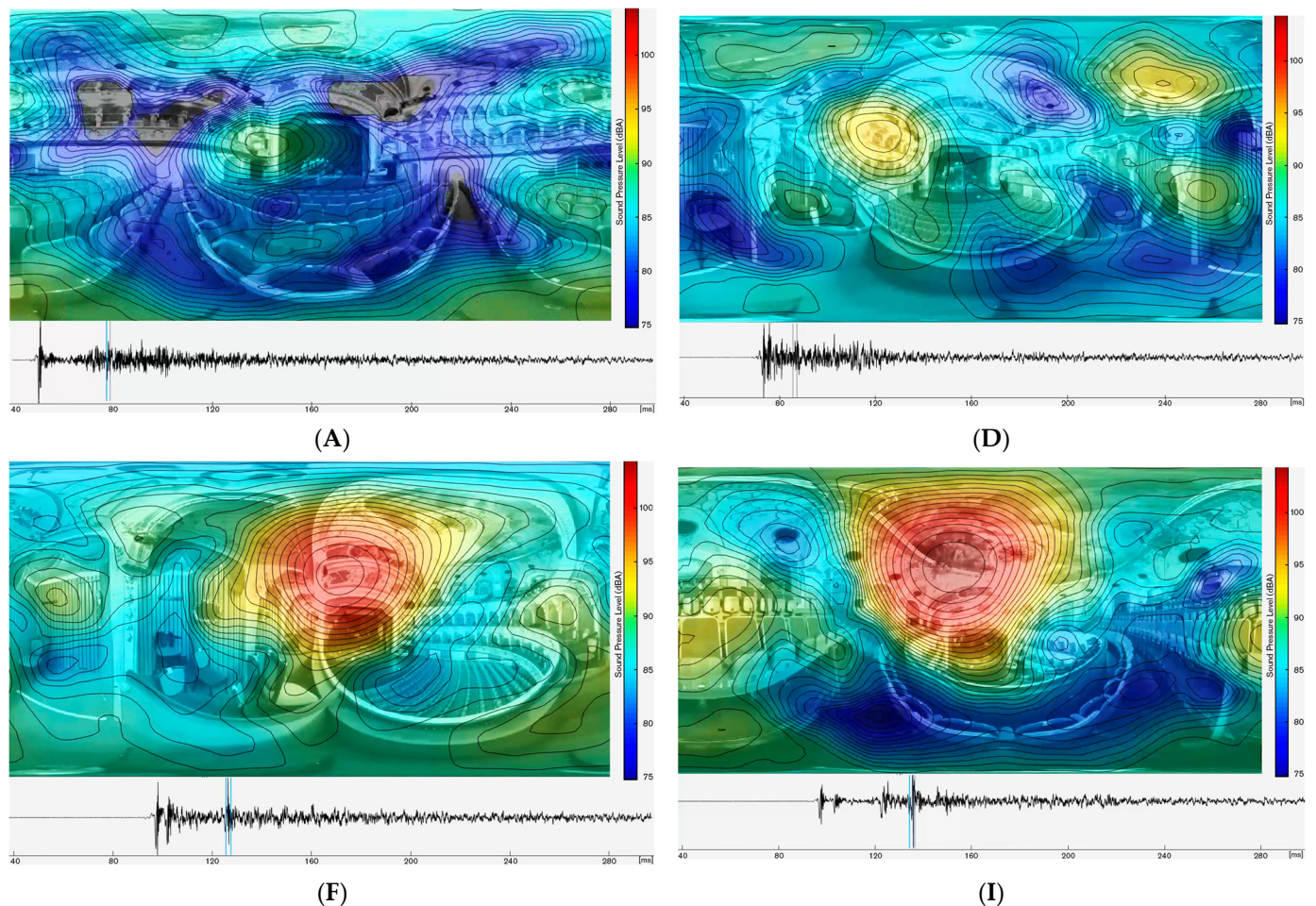


**Figure 6.** Panoramic view of the acoustic maps at the time of the early reflections. Microphone positions in the stalls (A), on the first balcony (D), on the second balcony (F), and in the upper gallery (I). Time frame goes from 40 ms to 300 ms. Omnidirectional source on stage.

Figure 6 illustrates the early reflections bouncing off towards the microphone. In particular, the two following scenarios can be observed: at position 1 and 4, the early reflections are weak, highlighted by yellow contour levels, while at position 2 and 3, corresponding to the boxes, the early reflections are stronger, highlighted by orange-red tonalities. As expected, this result can be explained by the presence of side walls and other bounding surfaces near the microphone, whereas in positions 1 and 4, the sound energy propagates throughout the open space.

It is possible to analyze the late reflections, as summarized in Figure 7, where the time frame is always included between 40 ms and 300 ms, as shown at the bottom of every image.

Figure 7 highlights the later energy reflections hitting the bounding surfaces farther from the sound source. Since the reflections are still within the 80 ms, they cannot be classified as late reflections, but they have been taken into consideration for their strong energy to be detectable from the contour levels. In position 1, the selected reflection clearly comes from the left side wall. In position 3, the detected reflection comes from the part of the ceiling closer to the proscenium arch, while in position 4 it comes from the ceiling but at a different angle. Inside the box of the first balcony, represented by position 2, strong reflections come from different directions, including the head of the right-side wall, the floor, and the ceiling of the box, as well as the architectural decoration that separates the first from the second order of balconies.



**Figure 7.** Panoramic view of the acoustic maps at the time of later reflections still with strong energy to be detectable. Microphone positions in the stalls (A), first balcony (D), second balcony (F), and upper gallery (I). Time frame from 40 ms to 300 ms. Omnidirectional source on stage.

#### 4. Conclusions

A complete study of the acoustic behavior of the National Theatre of Zagreb has been conducted using these two approaches: one closer to the standard presentation of the main acoustic parameters in the form of graphs and another considered more innovative and made possible by the employment of the latest generation of equipment during the on-site survey.

Overall, the acoustics of the National Theatre of Zagreb are suitable for both opera and symphonic music, considering that the reverberation time at mid frequencies is 1.3 s, and the definition varies around 0.5. In addition, the strength has been found to be between 2 dB and 5.3 dB, which is considered an optimal result and is in line with other European opera houses [43], including the Italian opera theatres having an average G value around 4–6 dB in many cases [44].

The alternative representation of the acoustic behavior of the main hall in the National Theatre of Zagreb is determined by the acoustic maps recorded at different positions across the sitting area. The 360° video overlay consists of an IR recording at a selected receiver position. This result allows for the visualization of the architectural components contributing to the early and late reflections, along with the visualization of the sound energy intensity at each time frame, as determined by the contour levels [45]. This more advanced methodology can be considered as a practical support for musicians and music lovers who want to find a scientific explanation for seating selection when attending live events.

Future research studies should focus on comparing these acoustic maps that are realized with a 32-channel spherical microphone array with new measurements that can

be created with a higher number of transducers (i.e., 64) composing the microphone, characterized by the same array typology. Based on predictions, the outcomes are expected to increase the directivity of the virtual microphones and reduce the solid angle between the capsules. This would mean a more accurate detection of soundwaves as they interact with the boundaries of a room before they reach the microphone probe later than the direct sound. Another refinement could involve the graphics of the time frame by highlighting the energy peaks occurring during an IR. In addition, the current system can be further implemented by correlating the contour levels to binaural acoustic parameters that are not described in this paper.

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