WAVE FIELD ANALYSIS IN CONCERT HALLS USING LARGE SCALE ARRAYS

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1 INTRODUCTION

ISO 3382-1 [1] provides a well accepted and common ground for acoustical measurements in auditoria. Discussing the acoustics in auditoria using this standard has a clear focus on room acoustic parameters. This perspective is motivated by research linking room acoustic quantities like D50 [2], C80 [3], EDT [4], LF [5], LG [6] or G [7] to their perceptual counterparts of definition, clarity, reverberance, apparent source width, envelopment and strength. Through years of experience using the standard since its first publication there is a reasonable understanding about how the collected results can be interpreted to form conclusions [8, 9].

Based on studies discussing the suitability of (at the time) modern correlation techniques to measure room impulse responses [e.g. 10, 11] there is also an awareness of the standard's pitfalls and a basic understanding about the factors contributing to the uncertainty in measurements. In these studies it was investigated (among other influences) how sensitive these room acoustic quantities are relative to a small change in the receiver position. Perhaps due to investigating a relatively small range of displacements the results were not distinct enough to identify a significant issue. De Vries et al. [12], for the first time conducted acoustical array measurements in concert halls and were able to show the significant changes of LF over distances of a few cm. These findings cast some doubt on the practical measurability of ISO 3382-parameters. This conclusion, however, requires careful consideration: The association of "randomness" when discussing the spatial fluctuations of room acoustic quantities may be misleading, when, ultimately, the parameters are derived from deterministic impulse responses.

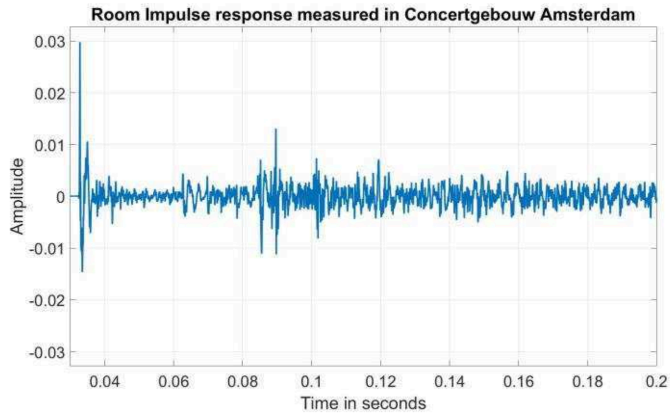

Figure 1: Measured room impulse response in Concertgebouw Amsterdam by de Vries et al. [12]

The interpretation of impulse responses in architectural acoustics seems to be one of the oldest analysis tools in design and research. Identifying prominent events in the impulse response and discussing the associated time delay is a helpful strategy for determining wall reflections (see Figure 1). With simple room geometries and "tidy" impulse responses, it is easy to identify reflections and recognize the responses deterministic character. This strategy, however, becomes considerably more difficult for the signal components of lower amplitudes, e.g. between the direct sound and the first protruding reflection in Figure 1. The noise-like appearance and the multitude of possible causes – which can no longer be clearly worked out – raise the question of whether these signal parts may actually be of random nature.

Of course, this hypothesis can be easily refuted by performing repeated measurements or applying methods to improve the signal-to-noise ratio – such as arithmetic averages or using longer excitation signals [13]. Nevertheless, the question remains whether these low-amplitude events in impulse responses can be related to their deterministic cause.

This problem can be addressed using array technology. In addition to the information coded over the running time of the impulse response the measurement location can also be evaluated in the case of microphone arrays. Since the solution of the wave equation links an oscillation in time to a propagating sound wave in space, acoustical measurements with a number of microphones at different locations makes it possible to identify the origin of the respective sound waves, and hence, determine the cause for the different reflections.

2 ARRAY MEASUREMENTS IN ARCHITECTURAL ACOUSTICS

Sampling the sound field in auditoria or rooms is a strategy that regularly applied. The investigation by de Vries et al. [12] was initially targeted to collect a data set that can be used to decompose the sound field into plane waves. It was the first time a large line array was used in auditorium acoustics.

The strategy to measure the acoustic conditions at an auditorium at a number of seats has been brought to its extreme by Akama et al. [14] through their measurements at every single seat (up to 1900 positions) in a number of auditoria. Their goal was to investigate the statistical distribution of room acoustic quantities and determine how much the sample size can be reduced while still maintaining the properties of the underlying population.

From measurements in different concert halls [15], that are quite similar to the strategy in [14], the authors have learned that acoustic measurements are very labour-intensive. Despite theses efforts, the exact coordinates of the measurement positions usually cannot be determined, even with floor plans or sectional drawings available. The dimensions of common reference objects (i.e. seats) are generally too large and the position accuracy is too low to consider such measurements as array measurements in its original sense.

These considerations nurse the wish to perform automated measurements in true scale with a high resolution that cover a sufficiently large area that is comparable to the dimensions of auditoria. This measurement device should be used to survey the sound fields in different auditoria. The analysis should focus on a visualizing sound propagation that makes it possible to interpret subtle parts of room impulse responses.

3 METHODOLOGY

3.1 Measurement setup to sample the sound field over an extended surface

Using the setup described by Witew et al. [16] and as shown in Figure 2, a device has been constructed that is capable to automatically sample the sound field over a surface of 5.3 m x 8.0 m. The setup consists of a frame made from aluminium trusses that is supported by four pillars, one in each corner. The central truss (running along the hall’s front-rear dimension) holds a motorized carriage that can travel along a rail over the full length of 5.3 m. The carriage in turn holds a carbon truss (running along the hall’s left-right dimension). At its’ both ends the carbon truss is supported by the aluminum frame through a roller- and slide bearing. This mounting allows the carbon truss to move freely as the carriage moves along the front-rear-axis. At the same time, a second motor in the carriage permits moving the carbon truss from left to right over a distance of approximately 0.25 m. The carbon truss carries 32 Sennheiser KE-4 type electret microphones that are held in place through fixtures every 0.25 m. The fixtures consist of thin carbon tubes so that the microphones can be lowered to the sampling area (normally about 1.2 m above the floor). With the microphones being aligned linearly in fixed steps of 0.25 m and as the entire microphone setup can be moved freely over a surface of 0.25 m x 5.3 m this composes a coherent sampling area of

5.3 m x 8.0 m. In a recent modification the pillars have been equipped with wheels, making it possible to manually move the entire structure on a plane surface.

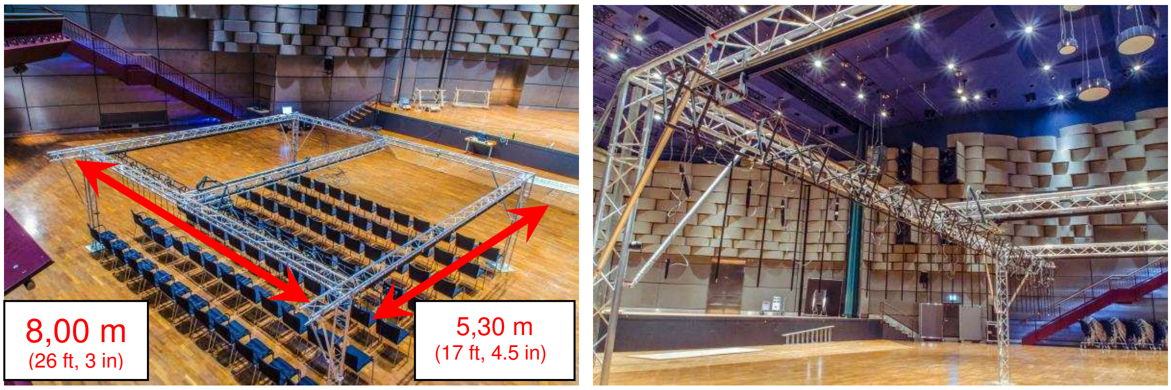

Figure 2: Measurement device to sample the sound field in auditoria.

Following the methodology similar to the measurements of de Vries et al. [12] and according to the spatial Nyquist-Shannon sampling theorem, a sampling grid with one sampling position every 5 cm is adequate for frequency bands including the 2000 Hz octave band. This corresponds to a 2D sampling area of 106 x 160 = 16960 impulse responses for each complete set of measurements. The propagation of sound over space can be illustrated using two dimensional images with each of the 106 x 160 pixels representing the acoustic conditions at the array's respective microphone positions. The propagation over time can be shown using the impulse responses at each of the pixels as input data. Animations can be prepared showing the running time as a sequence of images. In these images the amplitude of the impulse response is shown through the colour. Here blue colours are used to show low amplitudes in logarithmic scale where the highest amplitudes are shown in red.

3.2 Case studies to investigate the sound propagation in auditoria

In a first experiment the influence of chairs on the propagation of sound in auditoria is investigated. For this purpose the array was set up in the large hall of Eurogress Aachen. Eurogress Aachen is a fan-shaped multi-purpose auditorium with a reverse splay at the halls rear balcony. It is used for amplified speech reproduction during conference events as well as unamplified symphonic orchestral performances. In order to accommodate different seating arrangements stackable chairs with lean upholstery are used. In two subsequent sets of measurements the sound field was sampled with the hall completely empty in the first set of measurement and stackable chairs placed directly underneath the array (see Figure 2) during the second set of measurements. Otherwise the hall was left completely unchanged.

The second auditorium that was surveyed was a large lecture hall at RWTH Aachen University. In this case study a number of aspects are to be explored. First objective in this series of measurements was to investigate whether repeated sets of measurements at different locations in the hall can be used to extend the sampling area of the measurement device. Acoustically it was investigated how sound propagating over classroom style seating behaves differently compared to traditional stage seating. A third focus is placed on the reflection and scattering of sound at the halls side surfaces. The left image in Figure 3 shows the left side wall is an undecorated large plane surface. The right wall is divided into two parts, namely hot water radiators behind a vertical duckboard at ear level with glass windows above.

The third auditorium that was investigated is the large hall at Concertgebouw Amsterdam (Figure 3, right). The acoustics of this hall are sometimes discussed to be among the top three worldwide for symphonic music [17]. Since the proportions of this hall differ significantly from other renowned auditoria it is well worth while to study the sound field.

Figure 3: Acoustical Measurements in different Auditoria. Aula 2 at RWTH Aachen University (left) and Concertgebouw Amsterdam (right).

4 RESULTS AND DISCUSSION

4.1 Influence of chairs - Case Study in Eurogress Aachen

The results of the first experiment can be best shown in Figure 4 where the propagation of the first wavefront through the empty auditorium (left) and the auditorium with chairs (right) is illustrated. The differences in both measurement scenarios are particularly evident immediately behind the direct sound. In the left image (without chairs) three wavefronts travelling downward (away from the stage) can be seen. Due to the low-pass filtering the sharp impulse is expanded to a bimodal oscillation. The first (down-most) wavefront is the direct sound. It is followed immediately by a second wave of almost the same amplitude. This marks the reflection from the ground floor. The third wave that propagates last through the array has a significantly lower amplitude. It is difficult to determine the origin of this wave beyond doubt. Due to the direction of propagation and the delay to the direct sound it is suggested that this is the scattered sound from the edge of the stage. Amplitudes behind these three waves are relatively low in the empty hall.

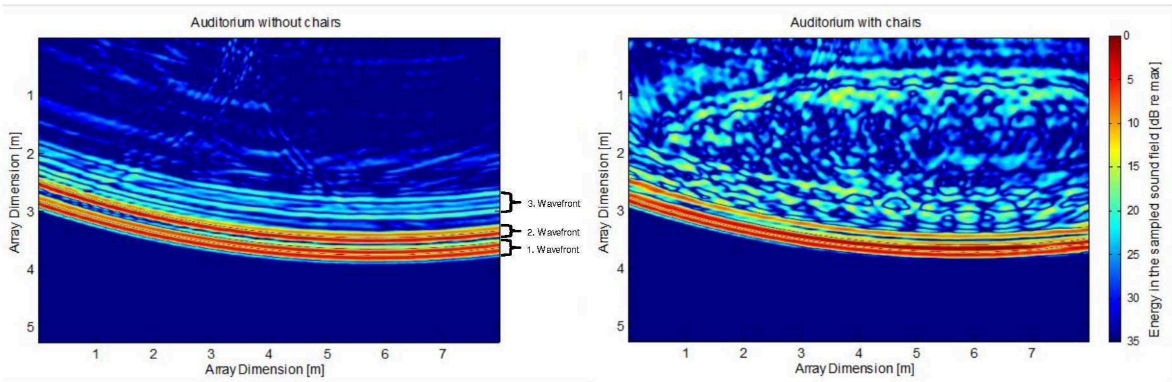

Figure 4: First wavefront propagating over an empty wooden floor (left) and rows of seating (right) 11 ms after entering the sampling area.

In contrast, the right image (with chairs) shows how the chairs influence sound propagation. The major difference compared to the empty hall is the additional wave pattern that can be seen in the upper part of the right image. This is the sound that is scattered back from the chairs. It is also noticeable that the wave scattered at the edge of the stage and the wave reflected at the floor are impaired in their propagation. This constellation becomes especially relevant when the source emits music or speech signals with non-zero coherence lengths. Significant frequency-dependent interferences such as the seat-dip effect may occur. The scattered wavefront, propagating back to the top of Figure 4 (right), shows the two parts of the direct sound and the floor reflection. For room impulse responses measured in auditoria these results show that the time directly following the direct sound is dominated by surfaces very close to the path of the direct sound. Despite their relatively low amplitude these reflections are also deterministic and have a spatial relationship.

4.2 Scattering surfaces - Case Study in a large lecture hall

The results from the measurements in a large lecture room are shown in Figure 5. Due to the fact that the entire measurement setup is mounted on rollers, the sampling area was extended to more than 10 m x 15 m through four repeated sets of measurements. Upon close inspection it can be seen that the tiles from the individual sets do not fit together seamlessly. Two main reasons can be considered: Firstly, the coordinate systems during the different measurements may have been rotated against each other and secondly, the meteological conditions may have changed so that the speed of sound may not have been constant over the duration of the entire measurement.

In this experiment the sound propagation over seats was investigated as well. As it can be seen in Figure 3 (left) the lecture room has a classroom style seating, i.e. the sound propagates over rows of chairs and tables. The left image in Figure 5 shows the first wavefront as it propagates through the auditorium. Similar to the case discussed before secondary waves can be seen that are scattered back to the stage. At this point it is interesting to discuss the counterpart of the floor reflection from the example of the empty room. In the lecture hall a “blurred” reflection which follows behind the direct sound is visible as well. In contrast to the previous situation, however, this reflection is interrupted or weaker at regular intervals. Since these transitions coincide with the position where the scattered waves from the chairs touch the “broken” reflection it seems evident that the disturbed reflection is from the tables in the auditorium.

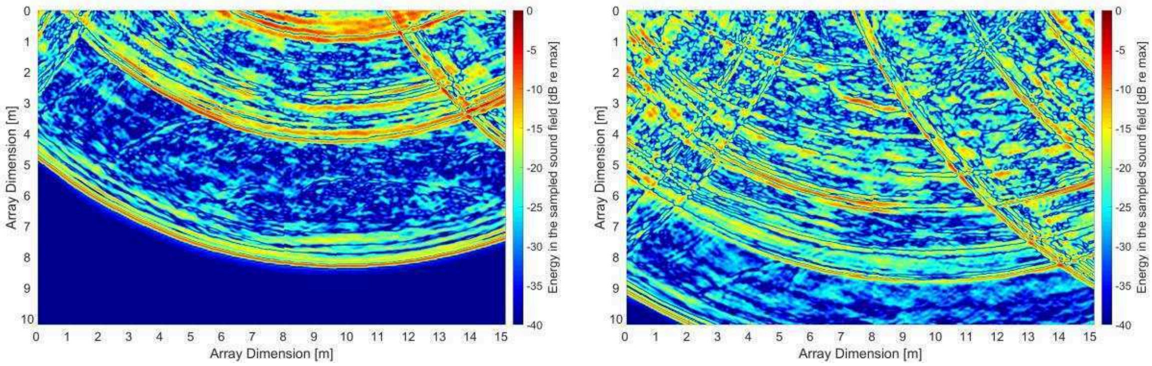

Figure 5: Sound field in a large lecture room. Direct sound and ceiling reflection (left) 25 ms after entering the sampling area. Scattered and reflected sound from the side walls (right) 35 ms after the direct sound entering the sampling area.

In Figure 5 (left) there are two other prominent reflections that are concentric to the direct sound. These are the first order reflection from the ceiling and the second order reflection from the stage floor and the ceiling of the hall. This is supported by comparison of the left and the right image in Figure 5 which show that the distances between these reflections are not constant over space. This is an indication that at least two of the wavefronts are travelling askew to the sampling area which is characteristic to waves approaching the array from above or below.

Three very distinct reflections that enter the sampling area from the right are shown in Figure 5 (right). It seems clear that the first of these is the first order reflection from the plane wooden surface shown in Figure 3 (left). This trio of reflections follows a similar path compared to the reflections concentric with the direct sound. The second reflection from the right is returned to the seating area due to the two-planar retroreflector consisting of the ceiling and the side wall. The third reflection follows almost the same propagation path, except, that it was additionally reflected from the stage floor.

Although the shape of the hall is almost symmetric the reflection from the halls left boundary behaves differently. At ear level the side wall is fragmented by heating radiators hidden behind vertical panels comparable to a duckboards. Figure 5 (right) shows that the reflection from this surface is not quite as distinct compared to the reflection from the opposite wall. Sound hitting the left wall of the auditorium is less reflected but scattered back into the hall. The higher-order reflections from this side wall are less pronounced as well. The cause is not immediately obvious, as the reflection from the flat glass surface should also lead to a sharp and isolated event. Instead, it seems the window panel is not build with a mass sufficient to reflect the sound at low frequencies.

4.3 Concert hall acoustics - Case Study in Concertgebouw Amsterdam

Similar to the discussion in the previous cases, Figure 6 (left) shows how the direct sound is scattered from the rows of seating. As the array extends beyond the block of seating, it can also be seen that the scattered waves do not reach all the way to the left and right of the sampling area as there is the aisle without chairs. Direct comparison to the reflections immediately following the direct sound in Eurogress Aachen shows some differences: The reflection from the floor is only visible at the very right of Figure 6 (left) where the sound is reflected from the floor of the aisle. Since there is no comparison to the “empty” hall in this measurement, and since the stage in Amsterdam is very high, it is difficult to identify scattered sound that can be assigned to the edge of the stage in good conscience.

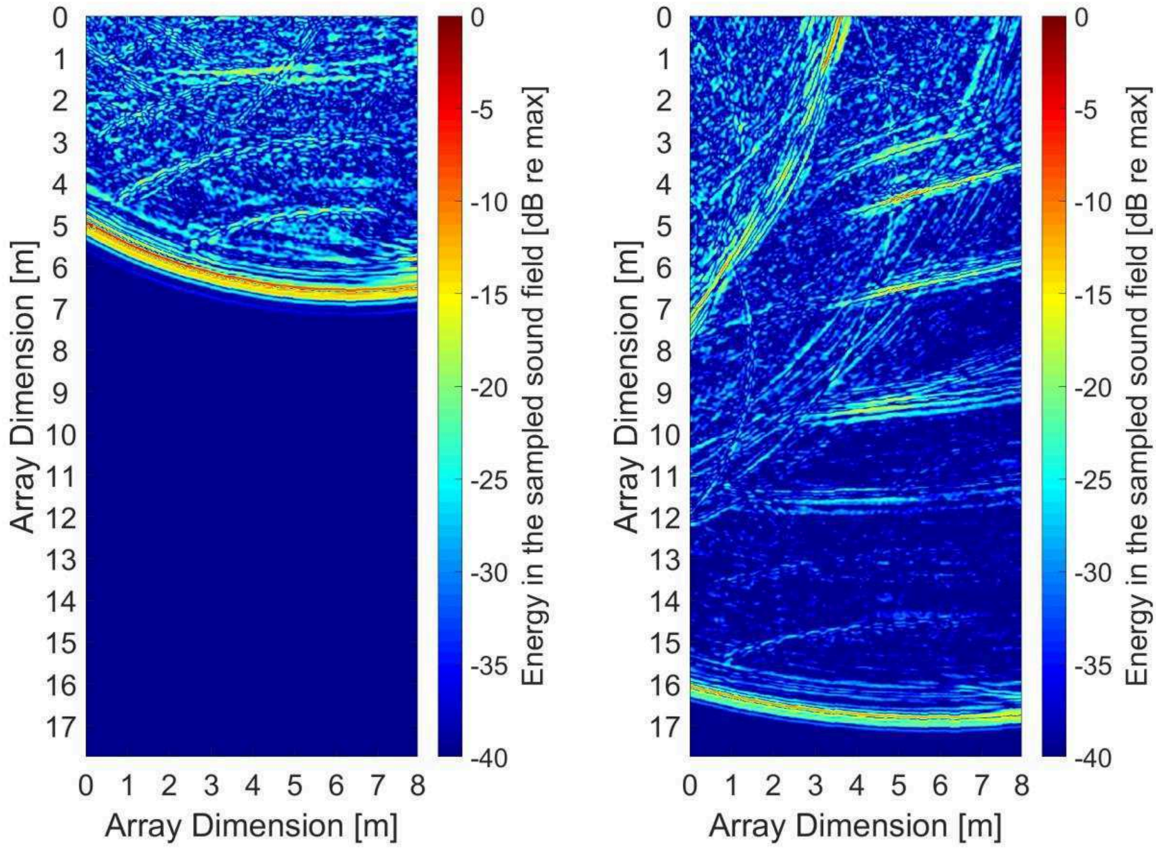

Figure 6: Sound field in Concertgebouw Amsterdam as the direct sound propagates through the hall – 25 ms (left) and 55 ms (right) after the direct sound entered the sampling area.

In the right tile of Figure 6 the direct sound has worked its way to rear rows of the concert hall. Compared to the direct sound in the left tile, the direct sound on the right has a significantly lower amplitude. Entering from the left there are three types of reflections visible. The most distinct one is at the top left corner of the tile – the reflection from the side wall. A little less pronounced, in front of the side reflection, is the scattering from the balcony’s façade. Upon close inspection there are two circular waves entering the sampling area from the left. These are scattered waves from the pillars supporting the balcony. At this particular moment in time the scattered sound from all the pillars the direct sound has already passed intersects at the left side of the tile at about 12 m.

Particularly noticeable are five regions of relatively high energy levels at the center of the right tile in Figure 6 at 12 m, 10 m, 7 m, 5 m and 4 m. These reflections wouldn't exist in a normal concert as these are focal points from the concentric steps of the orchestra platform. During concerts, when there are chairs, stands and musicians on stage sound cannot propagate as freely on stage, hence, preventing these focal points to develop. Comparing Figure 6 (right) to Figure 7 (left) it can be seen that the focal points travel through the concert hall and form their maximum amplitudes at different positions at different times.

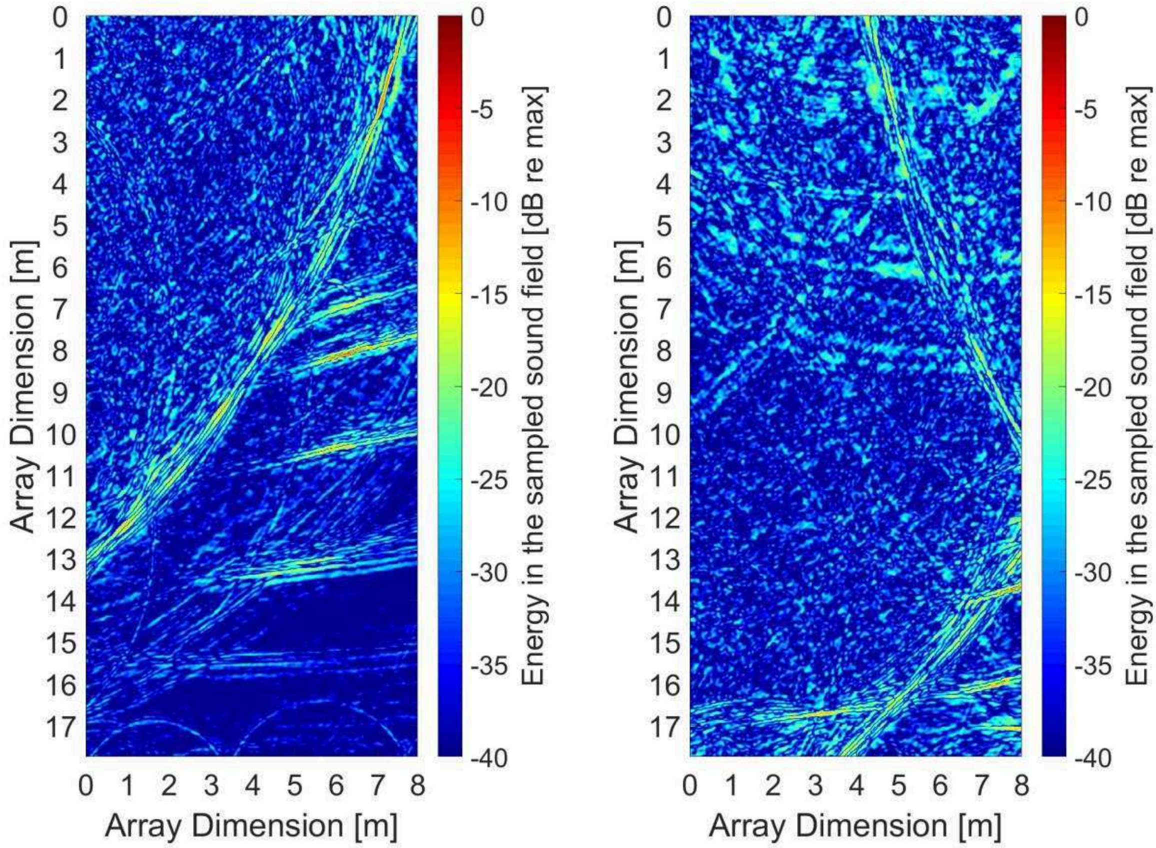

Figure 7: Higher order reflections in Concertgebouw Amsterdam – 70 ms (left) and 85 ms (right) after the direct sound entered the sampling area.

The left image in Figure 7 shows the sound field in Concertgebouw Amsterdam just after the direct sound has left the sampling area. The reflection from the side wall almost spreads through the entire tile. Interestingly the side reflection is interrupted. It should be considered that this may be due to the fact that the side wall is fragmented by protrusions and that the columns of the balcony may cause frequency dependent shading. In addition, it is striking that the scattered sound from the balustrade is not concentric to the side reflection despite both surfaces running in parallel. Major difference, however, between both wavefronts is, that the scattered front is approaching the array from above, hence, the retardation of the two waves is not the same at all positions.

In Figure 7 (right) the sound field is shown as the first order reflection from the rear wall enters the sampling surface. Also, the reflection from the right side wall and the right balcony can be seen. Here, the distance to the reflecting and scattering surfaces is much larger, which is why both waves (almost) run concentrically.

The main feature of the upper part of this tile is the arrival of the reflections from the ceiling of the hall. Through the significant coffering of the ceiling the reflection is not very isolated but widespread over time and space. A special feature in Amsterdam also seems to be the arrangement of a large and sloped audience area behind the orchestra. This is the reason why no particularly pronounced reflection from the "choir"-wall of the concert hall is detectable. The second order reflection from the front wall and the ceiling can be seen at the very top of Figure 7 (right). Just like the first order ceiling reflection this reflection is also blurred significantly.

5 CONCLUDING REMARKS

In this contribution a measurement device was presented that performs automated measurements in auditoria in a high resolution. Three case studies have been presented. Through acoustic array measurements the sound field was recorded and visualized. The illustrations give an account how sound propagates in the different auditoria. From the examples studied, it is shown how low energy signal components can be associated to a unique source or a unique cause.

The presented data shows that impulse responses can be measured with a very high accuracy. The potential difficulty in interpreting individual impulse responses may be due to a lack of information regarding the direction of sound incidence and detailed information about the source and receiver position. From the spatial information of the array microphones the directional information of the room impulse response has been analyzed.

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