Comparison of strategies to model spatial fluctuations of room acoustic single number quantities

Ingo B. Witew (Ingo.Witew@akustik.rwth-aachen.de)
Pascal Dietrich (pdi@akustik.rwth-aachen.de)
Sönke Pelzer (spe@akustik.rwth-aachen.de)
Michael Vorländer (mvo@akustik.rwth-aachen.de)

Institute of Technical Acoustics
RWTH Aachen University
Templergraben 55
52056 Aachen, Germany

ABSTRACT

In a number of independent empiric studies it was shown that room acoustic single number parameters vary severely with small changes of the source and microphone position. Presently there is no evidence that these spatial fluctuations can be modelled using simulated impulse responses. As a result there is limited knowledge about the origin and the contributing influence factors of this variance over space. In this contribution the results of simulations using wave based as well as ray tracing simulations are compared to each other. It will be discussed if these simulations are able to predict the fluctuations that were found in measurement series taken in a number of different auditoria.

1 INTRODUCTION

One of the key factors of measurements is the question of validity, i.e. how meaningful the measurement results are. Previously as part of the preparations of the evolving ISO 3382 standard many empiric studies were conducted to shed light on this aspect. One of the detailed investigations is the work published by Pelorson et al. in which it was investigated how much acoustic sound field predictors (e.g. reverberation time, clarity $C_{80}$, etc.) varied at different measurement positions. More recent work in this aspect is the measurement series conducted by de Vries et al. in the Concertgebouw, Amsterdam, NL. In a sequence of measurements roughly 520 room impulse responses (RIRs) were measured in the auditorium. In between the measurements the microphone was moved in steps of 5 cm along a line parallel to a seating row. Based on these measurements the lateral energy fraction LF and the interaural cross correlation coefficient IACC were calculated. It was shown that already small changes in the receiver position suffice to change the measured predictor substantially. This raises the question of the validity of room acoustic single number quantities again.

In the discussion of these findings two contributing factors were considered. First it is argued that narrow band filtering of the RIR will increase the spatial fluctuations. Second it is discussed whether the sharp time windowing of the RIR, which is part of the algorithm to calculate many predictors such as $C_{80}$ or LF, will enhance the fluctuations.
Although de Vries et al. shows an example in which a smoothly fading time window reduces the fluctuations, there is reason to believe that other influences potentially contribute to this phenomenon. This aspect can be illustrated when the 522 RIRs of the Concertgebouw measurement data are reanalysed and both $C_{80}$ and “center time” are calculated. The results are shown in figure 1.

![Clarity $C_{80}$ at 1000 Hz measured along an one dimensional array](image1)

![Center Time $t_c$ at 1000 Hz measured along an one dimensional array](image2)

**Figure 1:** Clarity (top) and center time (below) at 1 kHz calculated from impulse responses measured in the Amsterdam Concertgebouw\(^2\). Although the algorithm for center time does not rely on sharp time windowing spatial fluctuations of significant extend are evident.

Both sound field parameters shown in figure 1 are accepted predictors for the perceived clarity of sound. In contrast to clarity, “center time” doesn’t rely on sharp time windows. Still the spatial characteristics of both parameters show measurable fluctuations. In both cases the fluctuations exceed the values for the just noticeable differences (for $C_{80}=1$ dB and $t_c=0.01$ s) published in ISO 3382\(^1\). Therefore the significance of other influence factors for the spatial fluctuations needs to be considered.

1.1 **Spatial fluctuations in a measurement uncertainty context**

Knowledge of influence factors is important to determine the measurement uncertainty of an aspect of interest. Strategies in this domain have the goal to determine the relation between a change of these (influence) factors and the final measurement result. This possibly multidimensional link is regularly referred to as the model function.

In regard to room acoustics: the function showing how the sound field changes over distance, can be used to determine the measurement uncertainty for two central questions. Often the position of the source or the receiver is only determined inaccurately, perhaps as the seat where the microphone was placed (accuracy ±25 cm) or as the row at which the receiver was positioned (accuracy ± 2-3 m or more). As the sound field changes over this range in space the measured result has to be stated with an uncertainty. In another viewing angle a singular measurement (with the previously described uncertainty) will eventually be used to quantify the acoustic condition of larger audience areas. This is a related, but inverse problem.
While the mathematical background to treat these two questions has already been discussed\textsuperscript{4, 5}, both applications require a well founded knowledge how the sound field changes spatially. This knowledge can be acquired either through extensive measurement series to collect a sufficient empiric data basis or through modelling in which a relationship between relevant input quantities and the sought after spatial change of the sound field can be determined. Modelling strategies have the advantage that an understanding of the physical interrelations that lead to this phenomenon will be obtained along the way and hence it will be possible to understand what factors contribute to the magnitude of the effect. So far no attempts of this kind have been undertaken and hence there is little knowledge on the physical properties governing this effect.

2 SIMULATION STRATEGIES

For room acoustic applications generally two approaches are used to simulate the acoustic conditions. For small rooms or low frequencies wave based simulations are used and for higher frequencies or larger rooms ray tracing algorithms are generally preferred for efficiency reasons.

2.1 Wave based simulations

The analytic model used in this work is based on the wave equation and its closed solution. Details are provided by Kuttruff\textsuperscript{6} or Mechel\textsuperscript{7}. The used approach is valid for rectangular enclosures with rigid boundary conditions. The model considers the position of the source and the receiver in the room and obtains the complex frequency response by modal superposition. The modal damping coefficients are calculated based on provided mean reverberation times. The impulse responses are calculated by inverse Fourier transform. Details on the implementation are published by Pollow et al.\textsuperscript{8}.

2.2 Geometric acoustic simulations

Geometric acoustic simulations also model the propagation of sound physically correct as long as a focus is placed on medium to high frequencies. Strategies regularly include hybrid methods in which image source algorithms are used to determine the early reflections. The later parts of the impulse response are determined through ray tracing approaches. Advantage of these strategies compared to analytic solutions is the possibility to calculate the sound field in complex geometries. The implementation used for this study is the development at the Institute of Technical Acoustics: RAVEN\textsuperscript{9}.

3 COMPARISON OF THE SIMULATION STRATEGIES

3.1 Simulated scenario

Starting point of the comparison is a very simple model of a rectangular room. The dimensions of this room are chosen on the basis of architectural drawings (figure 2) of the Concertgebouw in Amsterdam to approximate the size of the auditorium. In detail the length of the model room is 43.21 m, the width 27.53 m and the height 17.60 m. There is no doubt that this simple rectangular room is merely a first order approximation of the original auditorium. Any “details” such as the stage, the balconies, the coffering of the side walls and the ceiling or other aspects cannot be modelled in this simple way. Based on a photo (figure 2) taken during the measurements by de Vries and the origin placed at the front-lower-left corner of the room, the position of the source was determined to (17.13 m, -13.83 m, 2.75 m). The array appears to be placed in row 16 and hence the receiver array was modelled at (29.13 m, -1:00.05:25.55 m, 1.2 m). The Y-range reflects that 512 source-receiver combinations are modelled with the
receivers spanning a line from left to right starting at 1 m away from the left side wall. Likewise to the measurements, each receiver has a distance of 5 cm to its two nearest neighbours. All surfaces have equal acoustic properties. Based on Sabine’s reverberation formula the walls’ absorption of the model was calculated to match the mean reverberation time of the empty auditorium at 1 kHz of 2.62 s. In the comparison a focus is placed solely on the 1 kHz octave band. The acoustic properties of the model at other frequency bands were identical to the properties at the 1 kHz band.

Figure 2: Floor plan of the Concertgebouw in Amsterdam, NL. The red circle marks the source position and the blue circles symbolise the receiver array that was used during the measurements. Floor plan: courtesy of “Het Concertgebouw Amsterdam”; Photo: Diemer de Vries

3.2 Simulation results – solution of the wave equation

Initial results of the simulations are the impulse responses of the 512 source-receiver combinations. The RIRs were calculated to a frequency of 1818 Hz to make sure the 1 kHz octave band plus a “safety margin” are included. The results are shown in figure 3. In a next step the RIRs are used to calculate $C_{80}$ at the 1000 Hz octave band. This result is shown in figure 4. From the measurement uncertainty point of view the average change of $C_{80}$ as a function of distance between two microphones is of interest. The last step of signal processing therefore compares $C_{80}$ for every two pairs of receivers. Figure 5 shows the average change in $C_{80}$ (absolute value) for any two receivers that are the same distance apart from each other.
Figure 3: Impulse responses calculated for different source receiver combinations in a rectangular room. The x-axis shows the position of the receiver. The y-axis marks the time of the RIR.

Figure 4: Clarity $C_{50}$ calculated for different source receiver combinations in a rectangular room. The x-axis shows the position of the receiver. Strong fluctuations can be seen.

Figure 5: Average change of Clarity $C_{50}$ as a function of distance between two receivers. Already small distances between receivers yield a significant change in clarity.
3.3 Simulation results – Ray tracing simulations

3.3.1 Simulation settings and the implications on simulation uncertainty

The comparison of the two simulation strategies is made complex with the different settings a simulation can be run with. In order to maintain a clear view on how the different settings affect the simulation result, the comparison between the wave based method and the ray tracing simulation is delayed in favour of the comparison of ray tracing simulations with different parameters. This is done with the goal to determine the simulation uncertainty.

For reasons of completeness it is noted that there are helpful formulas available to predict the uncertainty of ray tracing simulations. It needs to be recognised, however, that many dialects and different implementations exist to model the different aspects of sound propagation. These formulas are valid for specific cases and it is therefore essential to have a decent understanding of the simulation process to be sure the formulas are applicable. Alternatively proper strategies to determine the simulation uncertainty can be applied. This approach might be especially useful where detailed information on the algorithm is not available. The easiest and in some cases unfortunately also the most time consuming method is conducting repeated simulations and comparing the spread of results. Generally in this study simulations were conducted with the settings shown in table 1.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value / Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation Type</td>
<td>Hybrid: image source and ray tracing</td>
</tr>
<tr>
<td>Image source order</td>
<td>9</td>
</tr>
<tr>
<td>Number of sound particles</td>
<td>5'000'000</td>
</tr>
<tr>
<td>Ray tracing time interval</td>
<td>1 ms</td>
</tr>
<tr>
<td>Radius of detection sphere</td>
<td>0.05 m : 0.2 m : 1.05 m</td>
</tr>
<tr>
<td>Air absorption</td>
<td>Disabled</td>
</tr>
<tr>
<td>Scattering</td>
<td>Disabled</td>
</tr>
</tbody>
</table>

The uncertainty of the simulations was determined on the grounds of 100 repeated simulations of two arbitrarily chosen source receiver combinations. The influence of the detection sphere radius on the uncertainty can be determined through the presented (figure 6) standard deviation and the mean value of $C_{80}$. Especially the results of the first position deserve a detailed discussion. Given that the result for the smallest detection sphere is significantly higher than the converging results of the larger detection spheres it has to be recognised that the results for the small spheres appear to be wrong. This is especially remarkable as the standard deviation of $C_{80}$ results for both positions and the 5 cm sphere are quite low (4% of the JND). This
divergence emphasises that the uncertainty of simulations should be an aspect that needs to be discussed with great diligence in order not to come to faulty conclusions.

![Graph showing uncertainty of clarity based on 100 repeated simulations.](image)

**Figure 6:** Uncertainty of ray tracing simulations with different sizes of detection spheres. For very small spheres (5 cm) it can be recognised that the uncertainty is highest. For small detectors there is also the danger of calculating erroneous results. This aspect can be seen in the large difference in C80 at Position I.

### 3.3.2 Radius of the detection sphere

Analysis of the simulated RIRs is done as discussed previously (see section 3.2). Based on the simulated RIRs C80 is calculated and presented as a function of position in figure 7. In order to consider the uncertainty aspects discussed in the previous section 3.3.1, the result for the small 5 cm detection sphere (blue line) is shown with its uncertainty (dashed red line). The results of the larger detection spheres (25 cm to 105 cm) are very similar and are shown in green. This confirms that the results of the small sphere are potentially unreliable compared to the results of larger spheres.

![Graph showing spatial fluctuation of clarity at 1000 Hz.](image)

**Figure 7:** Spatial fluctuation of C80 as it is calculated with geometric simulation approaches. The results are shown for a small detection sphere of 5 cm in blue and for spheres ranging from 25 cm to 105 cm in green. The red dashed lines mark the uncertainty interval of the simulation with the small sphere.
In a next step the average change in clarity as a function of receiver distance is determined. These results are shown in figure 8. The larger uncertainty and the simulation error yield higher spatial fluctuations compared to the results based on simulations with larger spheres.

![Figure 8](image-url)

**Figure 8:** Average change of Cₘₐₓ as it is calculated with geometric simulation approaches for different detection spheres. The larger simulation uncertainty and the simulation error yields higher spatial fluctuations for the small detection sphere (5 cm – blue line) compared to the fluctuations simulated for the larger spheres in green.

### 3.3.3 Reciprocity principle

Although the larger detection spheres yield results that have a lower uncertainty and are less likely to be prone to errors the special focus of this study raises the question whether detection spheres with radii larger than the stepwise displacement may be used without making mistakes. Possible reasons for these mistakes could be the overlapping between two adjacent spheres. If the principle of using detection spheres implies calculating the average sound field of the volume contained within the sphere the comparison between two adjacent spheres would be based on differences in the sound field in the volume where the two spheres do not overlap. This is of course a different situation compared to the wave based simulations and the measurements as well. The influence of this divergence is difficult to predict theoretically.

An alternative could be the application of the reciprocity principle in which the receiver would be placed stationary at the former source’s position and instead the source is moved. Although this approach avoids the problem of overlapping spheres the averaging is now done for an entire different volume which raises the question if the reciprocity principle is valid for ray tracing approaches at all. To test this factor the previous simulations were repeated with the source and the receiver exchanged. After the different steps of analysis the average change of Cₘₐₓ is compared of the two reciprocal simulations. The result can be seen in figure 8. The original results are shown in blue and green – the respective reciprocal results are shown in the dashed red lines. The general trend of the two simulations is evident as well but in detail there are small differences that can be found in the comparison of the two reciprocal simulations.
Figure 9: Average change of $C_{80}$ for reciprocal simulation sets. The original simulations are shown in blue and green. The reciprocal results are shown in the overlapping dashed red line. While the results are similar small differences are evident.

3.4 Wave equation vs. geometric simulation and reference to measurements

The results of the two simulation approaches that were presented earlier are jointly shown in figure 10. The special fluctuation as it is predicted by the solution of the wave equation is shown in cyan and is significantly higher compared to the results achieved by any of the ray tracing simulations. Despite these differences it can be seen that the detailed progression of the two curves shows some visible similarities. For reasons of completeness the reference to the original de Vries-measurements is given through the cyan line. It is noted, however, that these measurements contain all influences of measurement uncertainty that cannot be removed from the measured results.

Figure 10: Average change of $C_{80}$ for wave based (cyan) and ray tracing simulations (blue, green, red). The special fluctuations of the ray tracing simulations are significantly lower compared to the fluctuations predicted by the solution of the wave equation. The special fluctuations of the measurements are shown in magenta.
4 CONCLUSIONS

Based on the presented simulation results it can be seen that the different simulation approaches generally yield similar results. Especially the average raw $C_{80}$ results as they are shown in figures 4 and 7 only differ in the fourth significant digit. In detail, however, the results differ slightly from each other. The special fluctuations of $C_{80}$ are modelled significantly different. The origin of this difference cannot be identified on the grounds of the available results and needs further investigation.

The results clearly show that the parameters governing the properties of the simulation need to be chosen with great care. Results must thoroughly be checked for credibility; otherwise results might appear to have a low uncertainty but have an error at the same time. A special focus on specific details might require additional precision of the results.

Application of the reciprocity principle did not change the results significantly using geometric simulation approaches.

Larger detection spheres yield lower fluctuations for clarity. The data is not conclusive to show if this reflects an actual relationship or if this is a result of erroneous simulations.

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