The number of necessary rays in geometrically based simulations using the diffuse rain technique

Sönke Pelzer, Dirk Schröder, Michael Vorländer
Institute of Technical Acoustics, RWTH Aachen University, 52066 Aachen, Germany
E-Mail:spe@akustik.rwth-aachen.de

Introduction

Today's state-of-the-art geometrical acoustics simulation tools use hybrid algorithms that combine a deterministic model, such as Image Sources (ISM), to calculate precise early specular reflections in an impulse response (IR) with a stochastic approach such as ray tracing (RT) or radiosity to calculate the late diffuse exponential sound decay. Diffuse reflections form the energetically dominant part of an IR already as from the third surface reflection of a sound wave in a room, so that the reproduction of scattering effects becomes a major task.

In RT, the overall performance is mostly dominated by the number of rays that are used in the simulation. This number also influences the accuracy and reproducibility of the resulting decay curves. A formula that allows the estimation of the number of rays was already deducted and is well known in literature. However, more advanced RT algorithms feature the diffuse rain technique, which is a radiosity derivate, and which allows an effective reduction of the number of necessary rays to achieve similar results as of simulations with higher ray numbers.

In the present paper we deduce an appropriate number of rays as a function of parameters such as detector size and reverberation time, so that the statistical error of the energetic envelope of the impulse response remains below a certain threshold. The evaluation is carried out using Monte Carlo simulations with and without the diffuse rain technique and statistical error analysis.

Simulation of room acoustics

The performance of RT is majorly (and linearly) dependent on the number of launched rays. As for the results, there are no 'too many' rays. But if the calculation is a time-critical process, such as in a virtual reality system with real-time acoustics rendering, it is necessary to keep the computation load as low as possible. But with too few rays, the results fluctuate heavily and become inaccurate.

The question is how many rays have to be spent to ensure consistent results and errors/fluctuations that are small enough to be ignored. In simple cases, this minimum number of rays can be specified analytically by statistical error analysis, e.g. as proposed by Vorländer:

$$\sigma_L = 4.34\sqrt{\frac{A}{8\pi N r_d^{\,2}}} \quad \text{[dB]} \qquad (1)$$

The error of the total energy of the impulse response σ_L (in dB) is estimated by the equivalent absorption area *A*, the number of rays *N* and the detection sphere radius r_d. Despite from error propagation analysis, the minimum ray number can still be detected in listening tests or by analyzing the reproducibility of actual simulations.

Diffuse Rain

An enhanced method which combines principles of RT and Radiosity is called 'Diffuse Rain' [2]. For rays that are identified as a scattered reflection after the collision on a surface, a secondary energy is radiated into the room and detected by all visible receivers (e.g. counting spheres). This radiation is distributed according to Lambert's Law and the received energy is deterministically calculated and not traced any further than the receivers, unlike the initial ray.

Although the radiation can be interpreted as an infinite number of rays that are spread into the half space and reunited into one ray again after crossing the receivers, the number of rays does not change and the overall computation load is very low. The energy that is detected by a receiver is calculated by integrating the Lambert's probability density over the room angle from the collision point to the receiver. For this integration some approximations can be done, yielding simple formulas that can be evaluated very fast but still accurate e.g. for spherical receivers.

Thus, the algorithm allows for an effective reduction of the necessary number of rays, as each receiver is able to detect considerably more scattered energy at the same number of rays, without a noticeable increase of the computation time. This method has already been validated in [2].

Detecting the minimum number of rays

The final number of rays that has to be applied in a simulation depends on several factors, such as the room model itself with volume, shape, absorption, scattering and reverberation time as well as the parameters of the simulation, such as detector size, time resolution and order of reflections up to which the ISM is used. All those parameters are in relation to each other, with correlations e.g. between absorption, volume and reverberation time or also volume, detector size and time resolution.

Monte-Carlo Simulations

By measuring the reproducibility of several simulations in two shoebox-shaped rooms (500m³ and 10000m³) with exact same parameterization and followed by varying the number of rays, a threshold can be detected for which the fluctuation of the energetic envelope of the impulse response remains below the just noticeable difference of 1dB, as defined in DIN/ISO 3382.

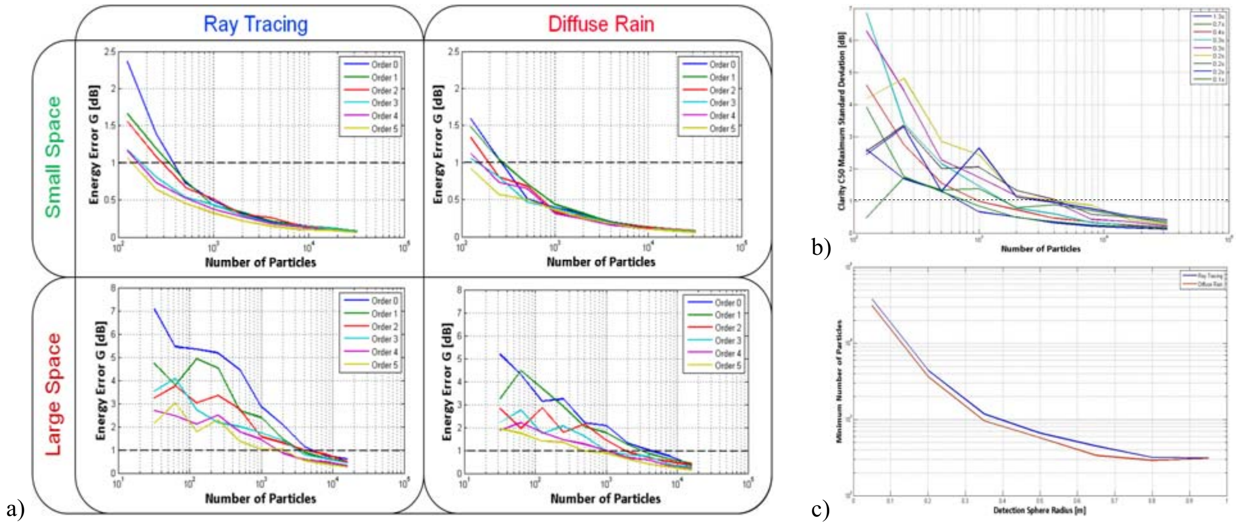

Figure 1: **a)** Two rooms were analyzed (500m³ and 10000m³) using Monte-Carlo-Simulations with and without Diffuse Rain. **b)** Comparison of the error in Clarity C50 vs. the number of rays between different reverberation times (through volume variation). The dashed line marks the JND of 1dB. Ca. 4000 Rays are necessary for keeping the error inaudible. **c)** Detected minimum number of rays for different detection sphere radiuses to keep errors below the JND of 1dB for a small space (500m³ RT ~0.5s).

The criterion is derived from the standard deviation of the energy of the impulse response, which is represented by the Strength G. In total 6 different parameters (such as reverberation time, scattering coefficients etc.) are varied in up to 10 steps. Each setup is then run 20 times in series before increasing the number of rays. To make sure that the maximum occurring error is detected, each simulation comprises an array of 10 receivers spread across the room as well as single simulations for 10 octaves from 31Hz up to 16kHz. This sums up to 1.2 Million simulations in total.

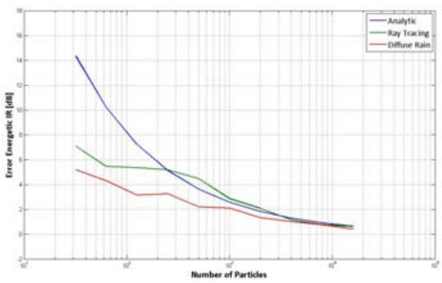

Figure 2: Comparison of the energetic error of an impulse response between theory [1], pure RT and Diffuse Rain.

The results of this method compare well to the results of the theoretical error analysis, at least for pure RT without Diffuse Rain, as shown in Figure 2. Deviations in the range with less than 200 rays are to be expected due to the stochastic premise of the formula.

Results

When including the Diffuse Rain technique, the overall number of rays that were necessary to keep the fluctuation of the energetic envelope of the IR below the JND could be reduced clearly. The detection of audible fluctuations was carried out using JNDs as proposed in DIN/ISO 3382 and parameters Strength G, Clarity C50 and Early Decay Time EDT. The EDT showed much less sensitivity for deviations, so the results mostly base on G and C50.

The ray number reduction is dependent on the actual room model as well as on the model properties and simulation parameterization. When many rays are already needed, e.g. >55000 rays for a small counting sphere (<0.1m), big volume (>10000m³) and long reverberation time (>3s), the improvement achieved by including Diffuse Rain is around 18% less rays. Especially for cases with only few rays, the improvement raises up to 50% ray savings. Then, for the small volume, even with usual simulation parameters, cases were detected where only 250 rays were sufficient. On average 29% fewer rays were necessary to keep the error below the JNDs for Diffuse Rain simulations compared to pure RT.

Conclusion

Diffuse Rain is an effective extension for RT. It allows reducing the number of rays, without negative effect on the accuracy of the results. Thus the computation time is reduced, while important scattering effects are fully covered. An analytically derived formula for the estimation of the number of necessary rays for pure RT could be verified and compared to the results of RT with Diffuse Rain. Clarity has shown a high sensitivity as an indicator for errors in the energetic envelope of the impulse response. Dependent on parameters such as receiver size, reverberation time and ISM order, a minimum number of rays has been detected for exemplary rooms. The results compare well to listening tests that have been conducted in the past. Further results will be published in the near future.

References

[1] Vorländer, M.: Auralization. Springer, Berlin, 2007

[2] Schröder, D.: Physically based real-time auralization of interactive virtual environments. PhD thesis, RWTH Aachen University, 2011