

# On the influence of different scattering implementations on the sound level distribution and reverberation time within sound particle simulations

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## Introduction

Real surfaces are neither ideally smooth nor infinite. Both, scattering by roughness and edge diffraction cause impinging sound waves to reflect not only specular but to deflect some energy in other directions, too. This is referred to as diffuse reflections. Modelling diffuse reflections plays an important role in geometric, energetic room acoustic (GERA) computer simulations, as reverberation times may drastically depend on it. It has been shown that reverberation time predictions show better agreements with measurements when algorithms are used that account for diffuse reflections.

While the reflection pattern of an object may be arbitrary complex, depending on its shape, the impinging wave front and its frequency, the exact pattern is usually unknown and as has been shown in [1] not of interest within GERA simulations. Instead, diffuse reflection is simply modelled by Lambert's law. The scattering coefficient  $s$  is defined in ISO 17947-1 as ratio of diffusely reflected energy to totally reflected energy. In simulation praxis it is used to somehow interpolate between specular and completely diffuse reflections, see next section.

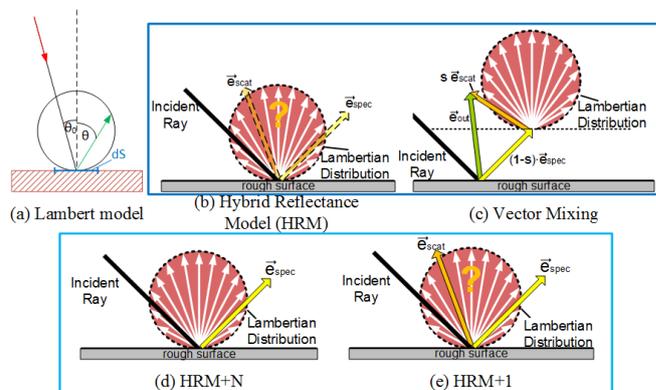
In general, GERA software models sound propagation by rays or sound particles in order to compute echograms or sound levels directly. Echograms are then used to calculate acoustical descriptors like intensity level, reverberation time or clarity. Several ways to implement Lambert's law in an algorithm have been proposed over the years. Dalenbäck gives an overview in [2]. While all these implementations treat scattering according to Lambert's law the choice of implementation has an influence on the results, as already shown by [3].

Here two principal methods to distribute the energy are compared: Hybrid Reflectance Model (HRM) and Vector Mixing (VM). Moreover two extensions of HRM are introduced and discussed, both of them using sound particle split up. First HRM+N as introduced by [4] is discussed and then HRM+1 is introduced here for the first time. It is a combination of classical HRM and HRM+N.

## Scattering within GERA

Lambert's cosine law is a simplified physical model to treat diffuse reflections, neglecting specific reflection patterns. The emergent particle direction  $\theta$  is independent of the incident angle. Instead the probability density per solid angle of the emergent direction follows a cosine law, see Abb.1a):

$$p' = \frac{dp}{d\Omega} = \frac{\cos(\theta)}{\pi} \quad (1)$$



**Abbildung 1:** a) Basic principle of Lambert's cosine law for scattering. Red: Impinging sound wave, green: diffuse reflected sound wave. b) Hybrid Reflectance Model (HRM): c) Vector Mixing d) HRM with N-fold split up (HRM+N) e) HRM with onefold split up (HRM+1). Dark blue box marks single particle methods, light blue box marks split up methods.

## Hybrid Reflectance Model (HRM)

The Hybrid Reflectance Model is the most straightforward approach, strictly obeying the ISO. Specular and diffuse parts are strictly separated, see Abb.1b). The decision whether specular or diffuse reflection occurs is made by comparing the scattering coefficient  $s$  to a uniformly distributed random number  $z$ : For  $z > s$  specular and for  $z < s$  diffuse reflection occurs. The direction of the scattered particle is chosen by drawing two random numbers obeying Lambert distribution.

## Vector Mixing (VM)

In Vector Mixing [5] specular and diffuse reflections are directly combined by vector addition, see Abb.1c). The scattering direction  $\vec{e}_{scat}$ , chosen as before, is weighted and added to the weighted specular direction  $\vec{e}_{spec}$ .

$$\vec{e}_{out} = (1 - s) \cdot \vec{e}_{spec} + s \cdot \vec{e}_{scat} \quad (2)$$

In the methods described so far, the particle's path but not its energy is influenced by the scattering coefficient. Hence only monofrequent simulations are feasible and the particles' paths and hence results vary upon repetition. In [3] these two methods were already examined analytically and in 2D.

## HRM with N-fold split up (HRM+N)

This method is similar to HRM, however instead of switching between specular and diffuse reflection depending on  $s$ , both parts are realised with adjusted energies. A

particle hitting a scattering surface is mirrored and split up into  $N$  (additional) secondary sound particles, representing the diffuse part, see Abb.1d). While their direction is uniformly distributed on a hemisphere their individual energy is weighted according to Lambert's law and the solid angle it represents, for more details see [4]. Here Lambert's law has no influence on the particles' paths as always all paths are realized. As a consequence multifrequent simulation becomes feasible as sp may carry many frequency bands simultaneously. Moreover simulations are deterministic upon repetition. Scattering is modelled more reliable and more detailed at a constant particle number per surface.

This method is believed to be most reliable and realistic and thus used as a reference within this paper, whenever possible. However the exponential growth of particles makes this method only practicle in scenarios with only one scattering surface. The gain of particles increases with  $N^k$ ,  $k$  being the number of diffuse reflections. In this contribution  $N = 2000$  by choice.

### HRM with onefold split up (HRM+1)

HRM+1 only uses one instead of  $N$  secondary scattered sound particles. The scattered particle's direction is calculated like with HRM/VM, see Abb.1e) and the energy is multiplied with  $s$ . So direction and the energy is changed. Thus multifrequent simulations remain feasible, yet variations upon repetition are introduced again.

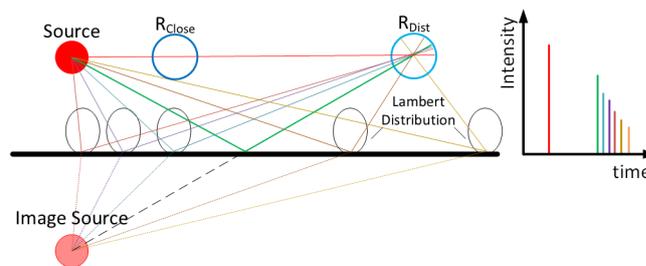
There is still an exponential growth of particle numbers, however only with  $2^k$ . While computation time rises, simulation of arbitrary scenarios is possible. All methods are the identical for  $s = 0$  and (except HRM+N)  $s = 1$ .

### Sound scattering and its influence on the sound field

Sound scattering has two effects on the sound field: a spatial and a temporal one. First, it causes energy to be deflected from specular paths, thus 'mixing' the energy in a room. It is especially important to consider in GERA as it might affect predicted reverberation times drastically. A typical practical application of this feature is to avoid flutter echoes. Second it delays energy arrival times for a given receiver. According to Fermat's principle specular paths are always shortest and therefore any diffuse reflected energy will arrive later and thus 'smear out' reflections in an echogram. This effect is shown in Abb.2.

### Numerical Studies

In order to judge the quality of scattering implementations it is examined how they achieve these effects. This is done in two studies: First examining the energy-spread away from specular direction: A single square scattering surface in free field. Second the effect on echograms and derived room acoustic descriptors is examined in two more realistic scenarios.



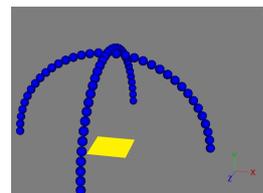
**Abbildung 2:** Sketch to visualise the influence of scattering on temporal structure of an echogram: As scattered particles travel longer distances than the specular path (green) their arrival time is later, thus spreading the energy of a single event compared to a mirror event. Note that with statistic methods close receivers are more likely to detect scattered particles due to the highest probability at directions normal to surface. For HRM+N every receiver detects some energy from every scattering point.

### Spatial diversification at single surface

In this study the spatial diversification is examined on two orthogonal arcs above a square surface in free field condition. Two side lengths are examined:  $4\lambda$  and  $16\lambda$ , with wavelength  $\lambda$ .

#### Set up

35 adjoined spherical receivers are placed on each arc with  $r_{rec} = 10\lambda$  in the x-y- and z-y-plane, yielding  $5^\circ$  steps. An omnidirectional source is placed at  $45^\circ$  in  $20\lambda$  distance in the x-y-plane, see Abb. 3. Two numbers of sound particles, yielding ca. 3200 and 200 particles hitting the surface are chosen. Experiments are done for  $s = 10\%$ ,  $20\%$  and  $50\%$ .

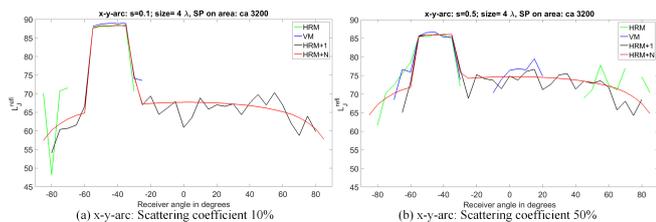


**Abbildung 3:** 3D rendering of set up for the study to examine the spatial diversification: 70 spherical receivers are placed on a x-y- and z-y-arc above a square scattering surface in free field. Side length shown here:  $4\lambda$ .

#### Results

Examined are the sound intensity levels of the reflection  $L_J^{refl}$ . This is achieved by subtracting the direct sound from the echogram. Abb.4 shows the results on the x-y-arc with 3200 particles and  $4\lambda$  for all four scattering methods and  $s = 10\%$  and  $s = 50\%$ .

HRM (red curve) yields a smooth result in agreement with [3] over the whole angular sector and can be regarded as reference here. For  $s = 10\%$  HRM and VM (green and blue lines) deliver hardly any energy outside the specular section. Within specular section all four methods show agreement. This shows typical problems of non-split up methods where for low  $s$ -values hardly



**Abbildung 4:** Sound intensity levels of x-y-arc over receiver angle for all four methods. Scattering surface size:  $4\lambda \times 4\lambda$ , source at  $45^\circ$ , ca. 3200 particles on the surface. Left:  $s=10\%$ ; right:  $s=50\%$ .

any particles are scattered. In contrast HRM+1 covers the whole sector (angle range). However some errors are introduced due to fewer detected particles. For  $s = 50\%$  the non-split up methods still show problems to cover the whole sector. However HRM covers at least the most likely scattering angular sector (around  $0^\circ$ ). Once again HRM+1 results are in good agreement with HRM+N but with a much shorter computation time (HRM, VM, HRM+1: 30 s; HRM+N: 145 s).

For the  $16\lambda$  scenario similar results were found, in accordance with [3]. All methods but HRM+N showed poor results with ca. 200 particles. This proves that non-split up methods achieve their scattering diversification only by ‘averaging’ over a number of sound particles hitting the scattering surface. Hence a certain minimum number hitting a scattering surface is required.

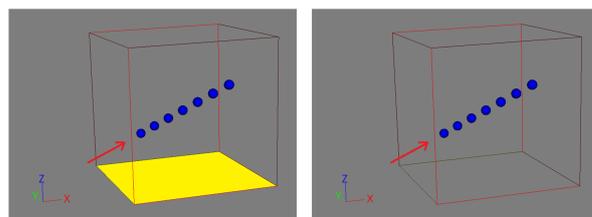
## Effect on acoustic descriptors

After all, GERA software is used to predict acoustical descriptors, like  $L_J$ ,  $RT_{30}$  and  $C_{50}$  in rooms during planing. Therefore it is important to examine the effect different scattering implementations have on those quantities.

### Set up

In a first scenario, called *scattering floor*, only one square scattering floor with  $(50m)^2$  is examined in free field, see Abb.5a). In a second scenario, called *scattering walls*, all surfaces of a cubic room with  $(50m)^3$  are equally scattering, see Abb.5b). Each scenario is simulated with scattering coefficients of  $s = 25\%$ ,  $50\%$  and  $s = 75\%$ ,  $\alpha = 0.5$ . An omnidirectional source emitting 250k sound particles is positioned in the room (see arrows in Abb.5) together with seven sphere receivers ( $r = 1.66m$ ), arranged on a line across the room, such that no symmetry occurs.

As particle paths and hence results depend on chance for all methods but HRM+N, all simulations were done 5 times. For each run  $L_J$ ,  $RT_{30}$  and  $C_{50}$  were computed. Then mean values over repetition and their standard deviation  $\sigma$  were calculated. The standard deviation can be seen as a quality measure, as it estimates how reliable a single simulation in similar conditions would have been. HRM+N can not be applied to the *scattering walls*-scenario due to high computation times.



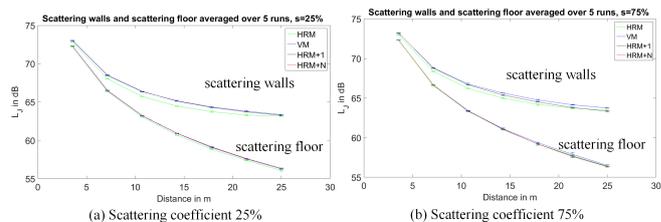
(a) Scattering floor set up

(b) Scattering walls set up

**Abbildung 5:** 3D rendering of the scenarios. Arrow pointing to the source which can't be seen in this scale. a) is the *scattering floor*-scenario: scattering floor in an otherwise free field b) shows *scattering wall*-scenario, where all walls are equal and scattering.

## Results

Abb.6 shows  $L_J$  over distance for  $s = 25\%$  (a) and  $s = 75\%$  (b). Standard deviations are small ( $\approx 0.05$  dB) so levels are invariant towards path fluctuations. Moreover all methods show good agreement (within  $\sigma$ ), therefore levels are virtually independent of scattering method choice. Only for *scattering walls* HRM shows significant but small discrepancies ( $\leq 0.5$  dB).

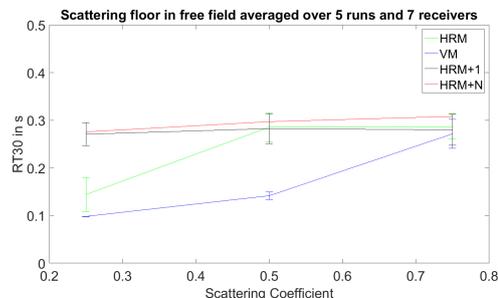


(a) Scattering coefficient 25%

(b) Scattering coefficient 75%

**Abbildung 6:** Sound intensity levels  $L_J$  over distance for all four methods and both scenarios (*scattering floor* and *scattering surfaces*). Mean values and standard deviations averaged over 5 simulations (except HRM+N) are given. Left side shows  $s=25\%$ , right side  $s=75\%$ .

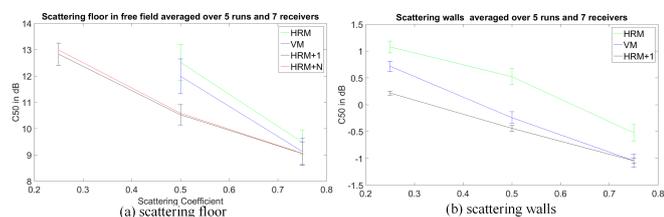
Abb.7 shows  $RT_{30}$  for *scattering floor* averaged over all receivers as a function of scattering coefficient. While results converge for medium and larger  $s$ -values there are significant differences for lower values. HRM+1 match HRM+N results within margin of error. HRM converges faster than VM. For *scattering walls*  $RT_{30} = (1.8 \pm 0.2)$  s showed fair agreement with Eyring: 1.92 s.



**Abbildung 7:** Reverberation time  $RT_{30}$  averaged over 5 runs and all receivers as function of scattering coefficient  $s$  for all methods.

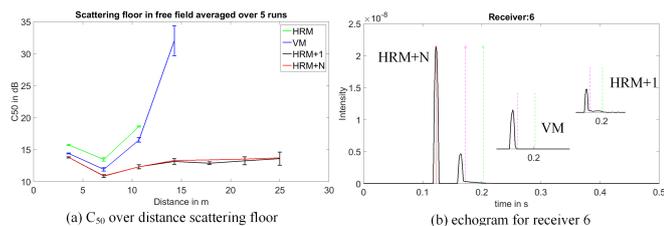
In Abb.8 the definition averaged over 5 runs and all receivers is depicted for both scenarios. As expected the de-

finition decreases with increasing scattering coefficient, as more energy gets smeared to later times. While the development is equal for *scattering floor* (parallel plots) VM shows smaller values, suggesting it to be the more efficient scattering method.



**Abbildung 8:** Definition  $C_{50}$  averaged over 5 runs and all receivers as function of scattering coefficient  $s$  for all methods. As expected definition decreases with scattering coefficient as more energy gets smeared to later times. Non-split up methods have difficulties at low  $s$ -values

It is noticeable, that for low  $s$ -values VM and HRM gain no mean value. Here non-split up methods fail for distant receivers as there are hardly any scattered particles detected. This can be seen in Abb.9a) where the averaged  $C_{50}$ -values are shown over the distance. For increasing distance  $C_{50}$  increases and vanishes.



**Abbildung 9:** a) Definition  $C_{50}$  over distance averaged over 5 runs for *scattering floor* b) Echogram for receiver 6 with time of direct sound (red) and 50 ms and 80 ms thresholds (pink and green) for HRM+N. Details show reflection detail for VM and HRM+1 respectively.

It is worth to go into detail, as it gives insight into how the scattering methods differ: For non-split up methods that change particles' paths, distant receivers are less likely to be hit by scattered particles, as most particles are mirrored or are most likely scattered normal to the surface. Thus close receivers detect more scattered energy than distant ones (compare  $R_{Close}$  to  $R_{Dist}$  in Abb.2). Therefore the energy is not smeared out sufficiently, resulting in fewer energy past the 50 ms threshold, see VM case in Abb.9b) where the threshold is shown pink. For HRM+N receivers detect (even if little) scattered energy from every point on the floor hit by a particle. Hence the smearing takes place (HRM+N case). Even HRM+1 manages to smear energy sufficiently. Once again HRM+1 shows similar good results as HRM+N (see Abb.9a)) at much lower computational expense.

For *scattering walls* VM still performs better than HRM and, considering standard deviation, approaches HRM+1 results for  $s \geq 0.5$  (Abb.8b)). In general scattering methods show less influence with increasing number of scattering surfaces, as the effects get 'spatial averaged'.

## Conclusion

Upon examining the spatial diversification above a square scattering surface, it was shown that at limited finite (detected) particle numbers non-split up methods have difficulties spreading energy over the whole angular sector, although results might be due to the specific set up. Especially for low scattering coefficients deficits occur. However HRM+1 was found to be in good agreement with HRM+N at much lower computational expense. HRM+1 computation times are basically the same as for non-split up methods for a single scattering surface. Within the specular sector all methods show the same results.

Examining the effects of different scattering implementations on acoustic descriptors revealed a more complex situation: While the choice of scattering method has virtually no influence on sound intensity levels other descriptors are more sensitive. For descriptors where energetic and temporal features are important differences can be seen for different scattering methods.

For instance HRM and VM failed for  $C_{50}$  calculations at distant receivers at low  $s$ -values and showed discrepancies for close receivers while HRM+1 performed as good as HRM+N. Only for high  $s$ -values HRM and VM converge towards HRM+N results. It is worth noting that VM converges faster and shows less deviation, suggesting it to be the more efficient scattering method.

HRM+1 showed results in good agreement with HRM+N results for all descriptors at much lower computational expense than HRM+N and full feasibility. For scenarios with low  $s$ -values and only few scattering surfaces, where HRM/VM showed problems HRM+1 is worthwhile, especially as computation times are almost equal in these cases. It could be shown that the influence of scattering implementation becomes less important the more scattering surfaces there are and the larger the scattering coefficient is, as individual diffuse reflections lose significance. In such scenarios also HRM and VM supply sufficient mixing and thus good results.

## Literatur

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