HOW DOES THE ROOM'S MODELLED LEVEL OF DETAIL INFLUENCE THE CHOICE OF SCATTERING FOR AURALIZATION?

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Abstract

Architectural room models used for auralization are typically created with varying geometric levels of detail (LOD), which directly affect both the surface areas and the effective scattering behaviour, and thus introduce uncertainty into room acoustic simulations. This study quantifies the influence of geometric LOD on the choice of scattering and proposes a compensatory modelling strategy for auralization. Two auditoria are investigated as case studies: the Gasteig philharmonic hall in Munich and the chamber music hall of the Konzerthaus in Berlin. For each room, five hand-crafted 3D models with systematically reduced LOD are derived from photogrammetric meshes. Geometrical-acoustics simulations (RAVEN) are evaluated using RT30, EDT, and C80 and compared with measurements. Results show that equalizing equivalent absorption improves agreement in reverberation time, while additional geometry-driven scattering calibration yields further improvements, particularly in mid to high frequencies and more prominently in the larger hall. A combined multi-LOD approach per frequency band is proposed to obtain robust impulse responses for auralization from heterogeneous architectural models.

Keywords: *Acoustic simulation, auditoriums, auralization, architectural modelling*

1. Introduction

Surface scattering is a key mechanism in sound propagation in architectural spaces [1]. In geometrical room acoustics, scattering is usually introduced by splitting reflected energy into a specular and a diffuse component [2], [3]. The specular part obeys the geometrical law of reflection, while the diffuse part is often represented by Lambertian scattering [4]. Standardized random-incidence scattering coefficients provide angularly averaged values that mask the detailed structure of sound–surface interaction. Early reflections in room impulse responses are dominated by specular contributions, whereas higher-order reflections become increasingly diffuse due to multiple interactions with irregular surfaces [4].Pure image-source models have limited physical realism [5], [6]. Nevertheless, scattering data for building surfaces are scarce, particularly for modern, highly structured geometries, so scattering coefficients are usually estimated heuristically [2]. Changing LOD alters room volume and surface area and thus the equivalent absorption area and scattering behaviour. These interdependencies complicate calibration against measurements and introduce modeller-dependent variability. Similar work was presented by Pelzer et al. [7], [8] but they focused only on one geometry close to a shoebox. Nevertheless the results showed that geometric details small than 70 cm do not contribute to difference in the auditory perception as long as the scattering coefficients are properly chosen. We take this finding as starting point for our investigation. The aim of this paper is to quantify how LOD in hand-made architectural models influences scattering choices and resulting acoustic predictions, and to propose a compact method to compensate LOD disparities for auralization. Two case-study halls are analysed; five LODs per hall are derived from photogrammetry, absorption is calibrated and transferred, equivalent absorption areas are equalized, scattering is made geometry-dependent, and the

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impact on RT30, EDT and C80 is assessed. A simple multi-LOD impulse response combination is finally proposed.

2. Scattering background and modelling

The relation between wavelength λ and characteristic feature size l governs scattering behaviour. For a corrugated wall with spacing l (Fig. 1), three regimes can be distinguished [2], [9]:

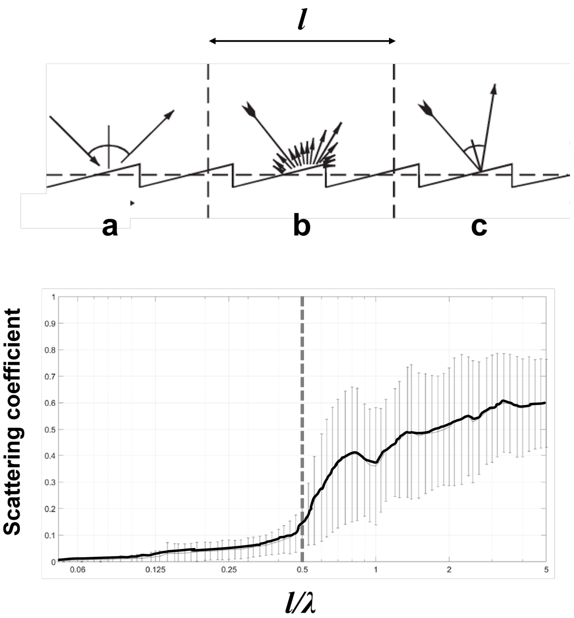

Figure 1: Reflection regimes for corrugated surfaces at low, mid and high frequencies (top), and corresponding random-incidence scattering coefficients for 1D angular shapes (bottom), adapted from Vorlander1989DrThesis,Vorlander2024ShowScatterings.

- low frequencies ($\lambda \gg l$): acoustically smooth surface, mostly specular reflection;
- mid frequencies ($\lambda \approx l$): increased scattering, mixed specular–diffuse behaviour;
- high frequencies ($\lambda \ll l$): each element acts as an independent reflector, strong angular diversification.

Rayleigh examined sinusoidal periodic structures and showed that below $l/\lambda \approx 0.5$ scattering is negligible, whereas above this ratio complex diffraction patterns appear with multiple lobes and a zero-order specular maximum [10]. This defines a critical frequency at which scattering becomes pronounced. Subsequent work extended this to various surface geometries and provided measured and simulated scattering coefficients [11]. Motivated by this theory, we suggest to model scattering coefficients as frequency-dependent sigmoid functions whose inflection points are tied to $\lambda/2 \approx l$, with l the smallest relevant geometric feature size for each LOD and surface class. Finer LODs have smaller l, hence their scattering increases at higher frequencies.

3. Materials and methods

3.1. Case studies and measurements

Two existing auditoria are investigated: the Gasteig philharmonic hall in Munich (GM) and the chamber music hall of the Konzerthaus Berlin (KB). Parts of the modelled auditoria are used by the authors in further literature [12], [13], [14]. The sound source was the ITA dodecahedral loudspeaker, a 3-way DSP-driven system optimized for omnidirectionality up to the 5-6kHz band [15]; the receiver was a Sennheiser K-4 microphone.

3.2. Photogrammetry and geometric LODs

Dense photogrammetric meshes were created for both halls from high-resolution image sets using Agisoft Metashape, following standard reconstruction, filtering and mesh-smoothing steps. These meshes serve as geometric reference. From each mesh, five manual CAD models with systematically reduced LOD were derived following an object-based approach [16], [17], [18]. Each room was decomposed into ceiling, inner walls, outer walls, hanging objects and floor. For each LOD, only features larger than a target size were kept; this target was chosen as $\lambda/2$ of a centre frequency (63, 125, 250, 500 or 1000 Hz). Thus coarser LODs represent low-frequency geometry, finer LODs support higher-frequency detail. Polygon counts decrease with coarser LODs, while average polygon size increases.

3.3. Absorption and equivalent absorption area

Frequency-dependent absorption coefficients (one-third-octave bands) were assigned to each material class using the PTB database [19]. For the least detailed model of each hall, absorption coefficients were calibrated so that simulated RT30 matched measured values across bands and source–receiver pairs. The calibrated absorption curves were then applied to all LODs. Because LOD changes room volume and surface area, the equivalent absorption area A_{eq} varies across LODs even with identical material coefficients. To compensate, A_{eq} was computed for each LOD and absorption coefficients were scaled proportionally by the same factor so that all LODs of a given hall share the same A_{eq} (referenced to the detailed model). The fitted scattering coefficients can be observed in Figure 3. This maintains relative differences between materials but enforces consistent global absorption strength.

3.4. Scattering modelling

After the theoretical background exposed in Section 2, the scattering coefficient modelling of the surfaces is applied. This follows a sigmoid function with their inflection points equal to $\lambda/2$, being λ the size of the modelled material. In Figure 3, all fitted scattering curves can be observed. It can be noted that the sigmoid inflection points vary towards higher frequencies

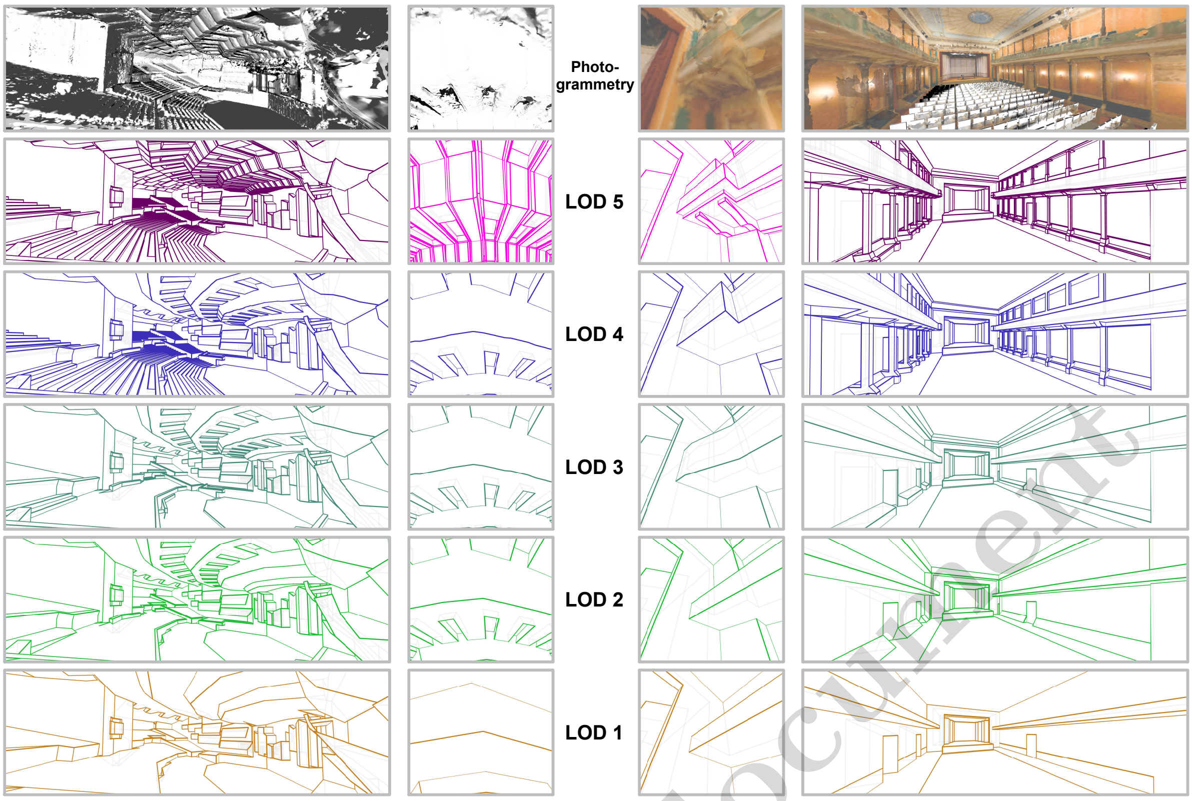

Figure 2: Comparison of the 3D models with different levels of detail (LODs). The photogrammetry is used as reference (top) for the other five models with reduced LODs: from most detailed, to the least detailed (bottom). On the left, the Gasteig München (GM) philharmonic hall study case. On the right, the Konzerthaus Berlin (KB) chamber music hall study case. Both case studies are depicted with an overview picture (outer columns) and a detailed one (central columns)

as the level of detail increases. Six different materials have been included: seating, floor, walls, windows (for hanging acoustic pannels), organ and ceiling.

3.5. Simulation framework and model variants

Geometrical-acoustics simulations were performed with RAVEN [20] using its hybrid algorithm: image sources up to second order and ray tracing with 500 000 rays in one-third-octave resolution. IRs from all LODs were simulated; for each frequency band, the IR segement from the most appropriate LOD (coarse for low, fine for high) is selected and combined into a hybrid IR. For each hall, two model variants were considered:

1. **Equivalent absorption area A_{eq} adjusted to the most detailed model**: the A_{eqLOD5} (the most detailed model) was calculated and used to readjust the absorption coefficients of each material so the resulting A_{eqLODx} equals the A_{eqLOD5}; scattering coefficients are constant 0,1 for all frequency bands and materials and LODs. The A_{eq}-adjustment was done using the Sabine equation and the reference reverberation time is the one shown in Figure 4a and b, respectively (red lines).
2. **Equivalent absorption area A_{eq} and scattering coefficients adjusted to the most detailed model**: as (1) plus the S_{LODx} was adjusted following the l/λ approach. Figure 3 shows the adjusted scattering coefficients per LOD.

From measured and simulated IRs, RT30, EDT and C80 were computed for each band and source–receiver pair. After calculating broadband IRs for each LOD model separately, one more IR is "composed" by filtering the LOD1-5 IRs regarding their target frequency band and adding them up. This results in one IR that uses different geometry for different frequencies (multi-LOD IR).

4. Results and discussion

Figure 4 illustrates, for GM and KM, the differences between measured and simulated room acoustical parameters for the measurement and for the combined multi-LOD IRs, abosorption-adjusted and scattering + absoprtion adjusted.
Three main observations emerge:
(1) Effect of equivalent absorption equalization. Equalizing A_{eq} across LODs significantly reduces discrepancies in RT30, especially in mid-frequency bands.

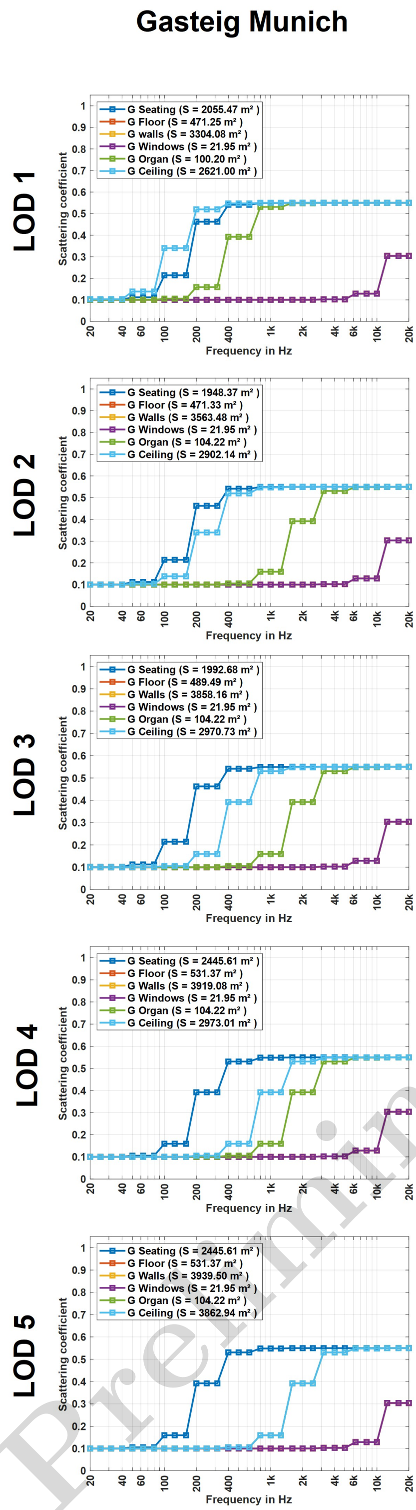

Figure 3: Adjusted scattering coefficients for the different LODs for the GM room.

In GM, differences between measured and simulated RT30 are reduced by about half in the mid-frequencies; KB shows similar but smaller improvements. This confirms that global amount of absorption strength must be made consistent across geometric simplifications to avoid LOD-induced bias in reverberation time.

(2) Effect of geometry-driven scattering. Introducing sigmoid scattering curves tied to geometric feature sizes further improves agreement, not only for RT30 but also for EDT and C80. Improvements are most pronounced in mid–high frequencies, where fine geometric details govern scattering. For GM, error reductions around 50 % are observed relative to absorption-only models; KB improvements are on the order of 30 %. This demonstrates that scattering coefficients should be linked to geometry instead of being chosen as fixed, room-independent values.

(3) Influence of room size and multi-LOD IRs. The larger GM hall shows a stronger sensitivity to the scattering choice, as longer paths and richer late reverberation emphasize the role of scattering. In both halls, the combined multi-LOD IR variant yields the smallest overall deviations across RT30, EDT and C80: coarse LODs provide stable low-frequency behaviour, while fine LODs capture high-frequency scattering and clarity. This suggests that multi-LOD impulse response synthesis is a practical and robust strategy for auralization when architectural models evolve or coexist at different levels of detail.

5. Conclusion

This paper examined the influence of geometric level of detail on scattering modelling and acoustic predictions in two concert halls. Five hand-made LOD models per hall were derived from photogrammetry; absorption was calibrated in the detailed model and transferred to all LODs; equivalent absorption areas were equalized; scattering was modelled via geometry-driven sigmoid functions; and RT30, EDT and C80 were compared with measurements.

The main conclusions are:

- Equalizing equivalent absorption area across LODs is essential to obtain consistent RT30 predictions when geometry is simplified.
- Geometry-driven scattering calibration substantially improves agreement with measurements, especially in mid–high frequencies and more strongly in larger rooms.
- Combining impulse responses from multiple LODs per frequency band yields robust auralization signals that exploit the strengths of coarse and fine geometric models.

For practical auralization workflows, we recommend using a calibrated detailed model as absorption reference, enforcing A_{eq} consistency across LODs, tying scattering coefficients to feature sizes, and employing multi-LOD impulse response combinations when architectural models exist at different levels of detail. Future work will extend the approach to psychoacoustic metrics and to automated geometry analysis in BIM or CAD environments.

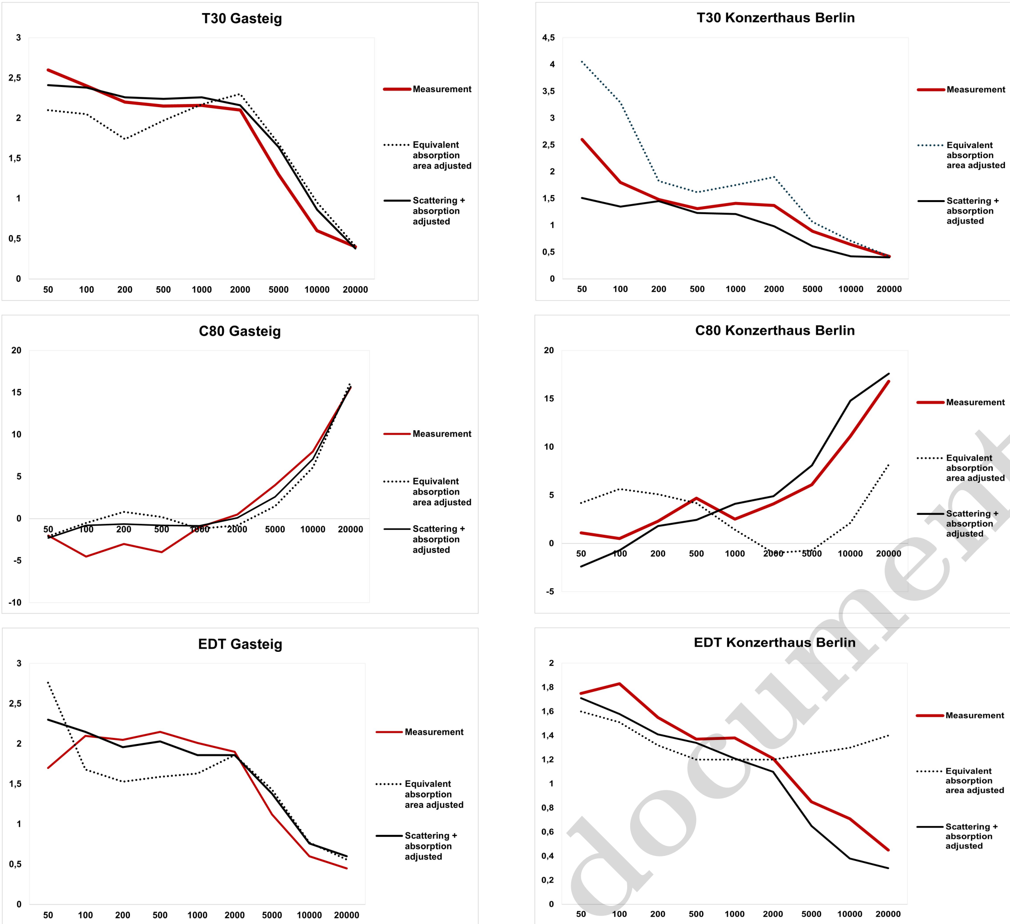

Figure 4: Room acoustical parameters comparing between measurement and the two model variants studied for GM and KM rooms.

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