DOI: 10.61782/fa.2025.0388

FORUM ACUSTICUM EURONOISE 2025

EXPLORING SIMPLE METHODS FOR ROOM ABSORPTION ESTIMATION IN EARLY REFLECTIONS FOR BINAURAL AUDIO RENDERING

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ABSTRACT

Accurately estimating room absorption coefficients is a key step in many binaural audio rendering approaches, as it directly impacts the realism and perceptual quality of virtual acoustic environments. This work explores fast and simple methodologies for deriving absorption profiles from room impulse responses (RIRs), focusing on their application in modelling early reflections within a room. We examine theoretical models and an iterative computational technique as potential tools for estimating absorption profiles, based on the assumption of a single material for the entire room. These methods use acoustic properties from real RIR measurements to quickly provide absorption coefficients for simulating the early reflections, setting a basis for further exploration across different acoustic applications.

Keywords: *absorption coefficient, binaural, early reflections, room impulse response.*

1. INTRODUCTION

Binaural sound provides spatialised listening with 3D positioning and a sense of volume, usually reproduced through headphones [1]. It is used to create immersive experiences, especially for Virtual and Augmented Reality, where the sense of space and immersion is improved by audio cues [2]. The reverberation of the space surrounding the listener becomes then an important factor, offering relevant information about the environment. This reverberation is influenced by the dimensions of the space and the materials present, whose acoustic properties, such as absorption and scattering coefficients, shape the reverberation of the place [3].

In geometrical room acoustic modelling [4], the value of absorption coefficients can be incorporated by means of pre-existing tables that provide standardised data on the materials' characteristics. However, due to the uncertainty and variability between these data and reality, a calibration process is usually necessary when simulating a real environment [5]. Various studies have addressed this calibration task using different methods and for various applications. A common approach for calibrating acoustic models is manual adjustment through iterative steps [6,7], though this process can be time-consuming. Automated methods with varying computational costs have also been proposed, including a machine learning genetic algorithm [8], a heuristic algorithm for optimization [9], considering integration with a statistical database [10], and using the gradient descent algorithm [11].

The acoustic impulse response (IR) of a room can be addressed psychoacoustically by considering at least two main parts: early and late reflections. The late reverberation or reverberant tail consists of reflections of high temporal density, which are generally diffuse, and thus do

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not contribute to the directional perception of the sound source, but instead enhance the listener's sense of envelopment [12]. In contrast, early reflections have a strong influence on sound source localisation, the perception of apparent source width and sound level [13], and on the perception of timbre [14], supporting speech intelligibility [15].

In view of the above considerations, a simple method is presented here to obtain an estimate of the absorption coefficients of the materials in a room, specifically from the first reflections of an IR, and is evaluated considering its application with binaural auralisation.

2. METHOD FOR ESTIMATION OF ABSORPTION COEFFICIENTS

The method we propose uses a given Room Impulse Response (RIR), together with the corresponding room dimensions, to estimate the absorption coefficients of the materials. The functional core of the method is an iterative process based on the calculation of an acoustic parameter relevant to early reflections. For example, let us define the total energy of early reflections (EE_t) as:

$$EE_t = \int_0^t h_k(u)^2 du \quad (1)$$

where h is the given IR and k denotes the different frequency bands that can be considered.

To estimate early reflections, the iterative process uses the Image Source Method (ISM) [16], widely employed in geometric acoustics simulations [17]. The acoustic parameter is then calculated both from the simulated ISM early reflections and from the early part of the target RIR that is intended to be modelled, assuming for simplicity that all walls are made of the same material. By comparing these values, the algorithm obtains an estimation error that informs the iterative optimization process. Our approach, which follows the secant optimization method, adjusts the absorption coefficients by reducing this error, resulting in the iterative calculation in Equation (2):

$$\alpha_k^n = \alpha_k^{n-1} - P_k(\alpha_k^{n-1}) \cdot \frac{\alpha_k^{n-1} - \alpha_k^{n-2}}{P_k(\alpha_k^{n-1}) - P_k(\alpha_k^{n-2})} \quad (2)$$

with α_k^n being the absorption coefficient of band k used at iteration n, and $P_k(\alpha_k^n)$ the acoustic parameter to be adjusted. The obtained α_k^n in each iteration is truncated to either 1 or 0 when values beyond those limits are reached.

Notice that the secant method needs two points to start. For the first one, a value of $\alpha_k^1 = 0.5$ is used. Then, in order to have a second point, α_k has to be increased or decreased (depending on the value of P_k) an arbitrary amount for the second iteration. In our implementation this is set to 10%. Furthermore, as all α_k are updated in each iteration, the overlapping among bands is included in the loop.

In our implementation of the estimation method we have used nine cascaded second-order-section IIR filters, the first and last being shelving filters and the rest peak-notch one-octave filters, covering the entire audible band from centre frequencies of 62.5 Hz to 16 kHz [18].

Figure 1 illustrates the iterative process. In each iteration, the optimization recalculates all frequency bands considered simultaneously to account for cross-band influence, an advantage of using a cascaded filter bank to simulate the wall absorption.

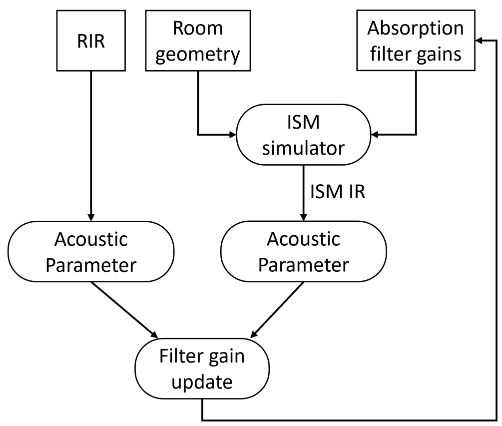

Figure 1. Absorption coefficients estimation method algorithm.

This simple iterative framework offers considerable flexibility, allowing the model to be adjusted to match other acoustic parameters (e.g. C_{80} or EDT). This can produce an absorption profile that best represents the room characteristics according to the chosen metric. Also, if the absorption coefficients of certain walls are known, they can be fixed while optimizing only the remaining surfaces. Alternatively, a predefined ratio between the absorption coefficients of different walls can be set, leading to a more constrained and realistic representation of the room's acoustic profile.

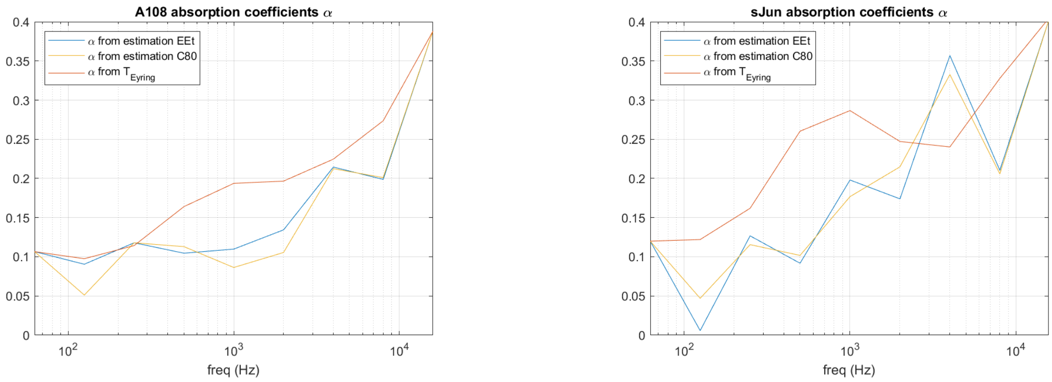

Figure 2. Absorption coefficients obtained for the two real rooms.

3. EVALUATION

We test the practical feasibility of the estimation method by simulating a binaural reverberation. The simulation of the first reflections is made using ISM (in the same way as in the estimation method of the absorption coefficients), and as reverberation tail we keep the one of the given RIR.

Acoustic measurements were carried out in two rooms ($V_1 = 580m^3$, $V_2 = 370m^3$) to be used as input for our method and also for evaluation tests of the estimated absorption coefficients. Eight combinations of different listener positions (L1 to L5) and source positions (S1 to S4) were measured with an omnidirectional microphone and a Neumann KU100 binaural head [19]. The binaural synthesis of the early reflections was also performed taking into account HRTF measurements of the KU100, obtained from the Sadie II database [20].

The evaluation consists of a comparison of the generated impulse responses using different approaches to estimate the wall acoustic profiles. The effect on various acoustic parameters of the rooms was examined, as well as its perceptual impression when simulating a different auralisation position than the one used for the estimation.

3.1 Calculation of the α coefficients

We compare the adjustment of absorption coefficients using our estimation method with two acoustic parameters (EE_t defined in Equation 1, and the clarity index C_{80}) and also with the coefficients obtained from applying Eyring's analytical formula for reverberation time, see Equation 3. For simplicity and comparison with Eyring, in the estimation with our method all walls have been considered equal, i.e. assuming diffusivity conditions for the sound field in the room.

$$T_{Eyring} = \frac{0.161V}{-Sln(1-\alpha)} \quad (3)$$

The omnidirectional measurement of the L1-S1 position (L at the center of the room, S two metres in front) was taken as the input to estimate the absorption coefficients of each room with our method. For both estimating the absorption coefficients and generating the evaluation impulse responses with the hybrid model, a very long transition time between early and late reflections of 100 ms was used. This is to ensure the audibility of the effect of the absorption coefficients in the early reflections.

Figure 2 presents the absorption coefficients α for the two real rooms used in the evaluation. The iterative method, applied with different acoustic parameters (EE_t and C_{80}), produces similar results, while the coefficients derived from the T_{Eyring} formula show some variation.

3.2 Acoustic parameters

The acoustic parameters T_{20}, EDT and C_{80} were calculated with omnidirectional RIRs. According to the ISO3382-1-2009 standard [21], the average of the eight listener-source combinations (positions) was computed for each room, for the actual measured RIRs (reference) as well as for the RIRs obtained with the different absorption coefficient estimations. Figure 3 illustrates how the α estimates obtained through the iterative method produce similar RIRs, whereas those obtained with the T_{Eyring} equation show slightly different results. In addition, the RIRs obtained with the iterative method estimations are closer to the values of the actual measured RIRs.

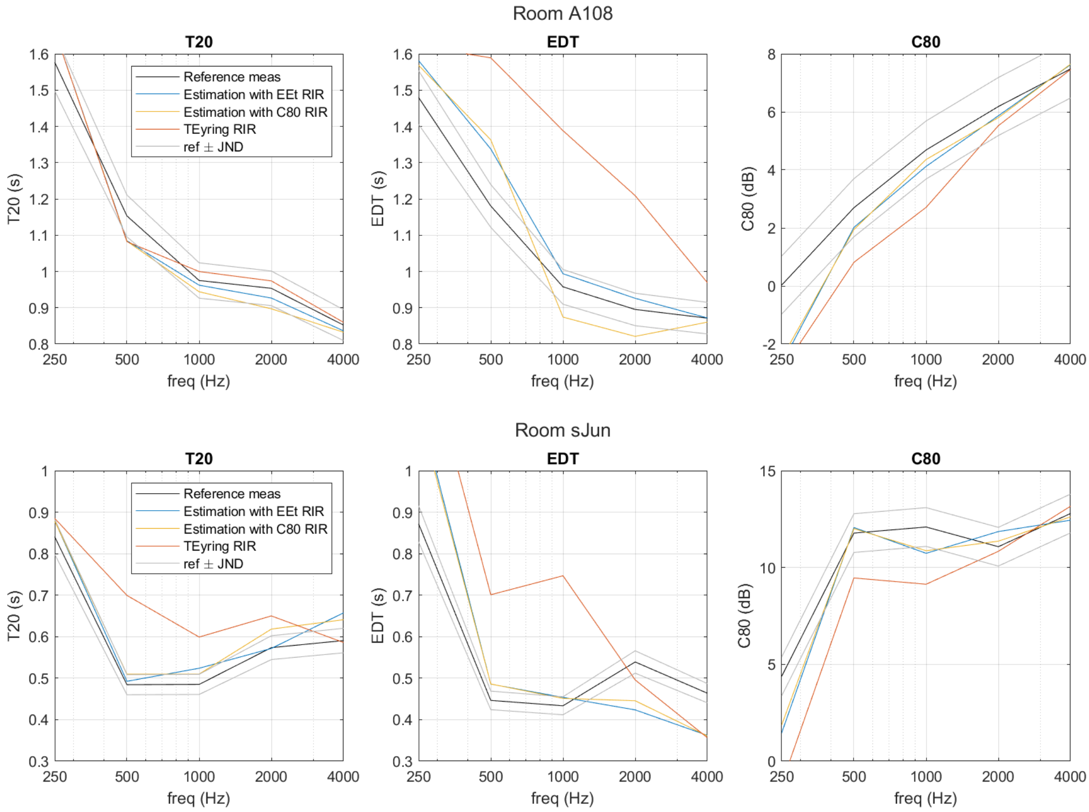

Figure 3. Average values of acoustic parameters for the two real rooms.

3.3 MUSHRA test

A MUSHRA-type perceptual test was designed following the ITU-RBS.1534-3 standard [22]. In this test, 10 participants evaluated the locatedness similarity between two sound stimuli —a female voice and pink noise— both convolved with BRIRs generated from the different absorption coefficients conditions (C1: Alpha estimation with EE_t, C2: Alpha estimation with C_{80}, C3: Alpha with T_{Eyring}). The stimuli were compared against reference versions obtained from the actual measured BRIR at the specific L5-S2 position (Reference). Additionally, three anchor signals were included: a low-pass filtered version of the reference at 7 kHz (A1), a mono version of the reference (A2), and another measured BRIR from a different position, L1-S1 (A3).

All three absorption coefficient conditions are rated much higher than the anchors A2 (mono version) and A3 (measurement in different position). The results show little differences between the three absorption coefficient conditions, except for the female voice case. Here, the α values obtained using the proposed estimation method resulted in higher scores and less dispersion in responses compared to the C3 condition (α with T_{Eyring}) (see Figure 4).

4. CONCLUSIONS AND FUTURE WORK

An iterative method for adjusting absorption coefficients based on a RIR and the room dimensions has been presented. The approach compares the RIR early reflections and their simulation by ISM calculating a selectable acoustic parameter. Its performance was tested under the assumption that all room materials were identical, and the results were compared with those obtained using the T_{Eyring} analytical equation. Both the comparison of different acoustic parameters and a perceptual test indicate that the iterative adjustment method provides better re-

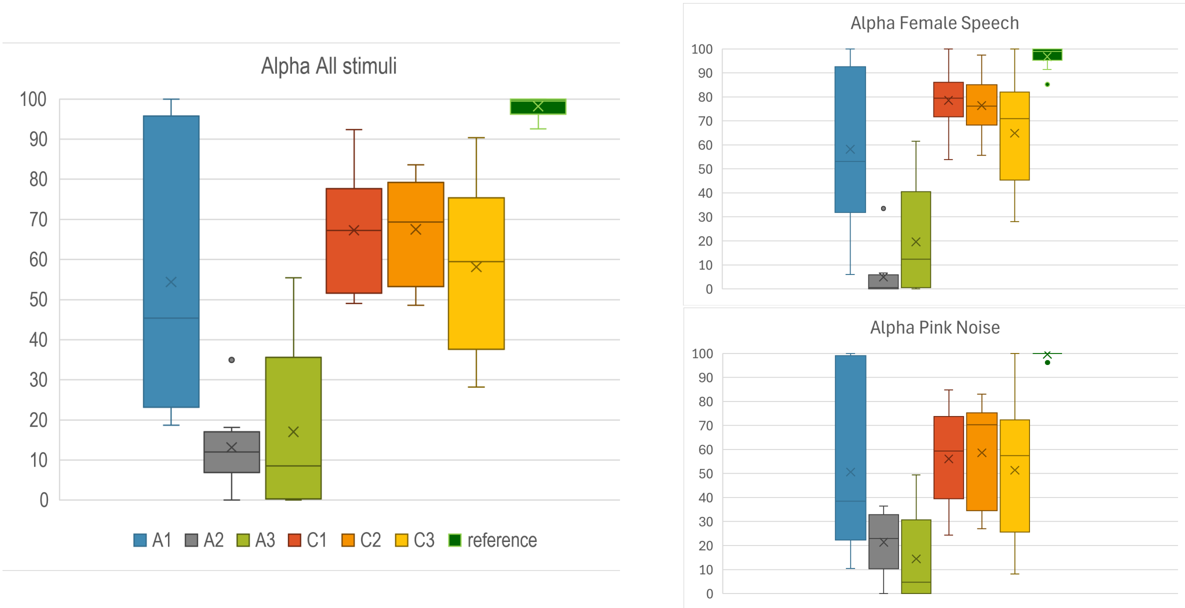

Figure 4. MUSHRA test results.

A1:	Reference LowPassFiltered 7kHz
A2:	Reference Mono
A3:	Measure position L1-S1
C1:	Alpha estimation with EE_t
C2:	Alpha estimation with C_{80}
C3:	Alpha with T_{Eyring}
Reference:	Measure position L5-S2

sults than T_{Eyring}, particularly when applied to a voice stimulus. This improvement may be related to better performance in mid-frequency ranges.

The results should be confirmed with more data analysis and additional participants in perceptual tests. Since this method relies on early reflections, it could be useful in hybrid reverberation models, which remains an area for future research. Future work could also explore its effectiveness with different acoustic parameters as adjustment criteria or by predefining the absorption profile of specific walls.

5. ACKNOWLEDGMENTS

This work was carried out in the context of the SONICOM project (`www.sonicom.eu`) that has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 101017743, and the Spanish National Project SONIX (PID2023-152547NB-I00). Also supported with the postdoctoral program APOSTD (grant number CIAPOS/2021/132) financed by the Generalitat Valenciana and the European Social Fund.

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