DOI: 10.61782/fa.2025.0843

FORUM ACUSTICUM EURONOISE 2025

SWEEPING ECHOES MANAGEMENT IN IMAGE-METHOD BASED OPEN-SOURCE SOFTWARE

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ABSTRACT

Sweeping echoes are an acoustical phenomenon present in impulse responses of shoebox-shaped rooms generated using either wave-based or geometrical room acoustics modelling software. This phenomenon occurs due to the concurrence of the arrival time of multiple specular sound reflections and is perceived as a distinctive pitch increase. Due to their imperfections, it is seldom experienced in real rooms. In the randomised image method-based approaches, a simple strategy of image sources' positions randomisation within a small cube- or sphere-shaped volume has proved to be sufficient for the removal of sweeping echoes, whilst introducing only minor changes to the room modal response. This study provides an overview of the current state of open-source software for image method-based room acoustics modelling in terms of the presence and implementation details of a module for image sources' positions randomisation. Furthermore, a novel tool designed as an aid to the existing open-source software is presented, enabling fast assessment of sweeping echoes intensity across 2D room slices, as well as estimation of a suitable value for the maximum displacement of image sources.

Keywords: *sweeping echo, image-source method, open-source software, room acoustics modelling, shoebox room.*

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1. INTRODUCTION

The acoustical phenomenon of sweeping echoes was first described by Kiyohara [1]. They are perceived as a distinctive increase in pitch when a sound file is convolved with simulated room impulse responses (RIRs) of shoebox-shaped (i.e. rectangular cuboid) rooms generated using either wave-based or geometrical room acoustics modelling software [2]. In [2], a theoretical analysis based on the rigid walls image-source model (ISM) solution of the wave equation developed by Allen and Berkley [3] revealed that sweeping echoes are caused by a progressive and monotonic convergence of the time delays of specular sound reflections. Moreover, it was shown that room setups with a higher degree of regularity lead to stronger sweeping echoes.

Since, due to geometrical imperfections present in real rooms, this phenomenon is seldom experienced by human listeners, a modification to Allen and Berkley's well-established algorithm [3] was proposed in [2] - named the randomised image method (RIM), in which the positions of image sources are randomised within a small cube-shaped volume. The simulation results have shown that the sweeping echoes phenomenon can successfully be removed while introducing only minor changes to the room modal response [2]. Hence, due to its ability to successfully reduce the gap between simulated and measured RIRs, this modification has been implemented in the Pyroomacoustics, a popular open-source Python package for audio signal processing for enclosed environments [4].

According to the results of the research recently undertaken by Hornikx et al. on the state of open research software for room acoustics [5], this package has gained significant traction in terms of usage, collaboration and citations. In addition to Pyroomacoustics, Hornikx et al. have identified 53 other software packages that allow the use, modification and redistribution of the code under an open-source licence, that have been developed for the purpose of studying the room physics, psychoacoustics or optimisation of room acoustics, and with which either a room impulse response or a room transfer function can be computed.

Given this large number of open-source software packages identified in [5] available to both the research and wider communities without any charge, a question of whether these packages take into account the sweeping echoes phenomenon and manage it, naturally presented itself. To answer this question, in this study, we provide an analysis of the code used for image sources' positions randomisation in the open-source software, in case it exists. We focus on the ISM-based open-source software specifically due to ISM being one of the most widely used methods for an accurate geometrical acoustics-based [6] calculation of:

- a room impulse response in its entirety, commonly for the reverberation time duration (for example in [7] and [8]), or
- early specular reflections in hybrid approaches (for example in [9] and [10]).

In addition to the aforementioned analysis, we present a novel tool that enables fast assessment of sweeping echoes intensity across 2D slices in shoebox-shaped rooms, as well as estimation of a suitable value for the maximum displacement of image sources based on the G-RIM method [11] – a recent RIM modification in which the image sources are displaced randomly within a volume enclosed by a small sphere, which in turn enables for the spherical angles of their displacement direction to be both uniformly distributed.

The remainder of the paper is structured as follows. In Section 2, the identified strategies utilised for sweeping echoes management in ISM-based open-source software are presented, whereas a novel tool for the assessment of their intensity across 2D room slices is presented in Section 3. Finally, Section 4 provides a conclusion to the research findings and discusses future work.

2. OPEN-SOURCE SOFTWARE

Among the 54 software packages listed in [12], accompanying the study by Hornikx et al. [5], after setting the following three criteria:

- an ISM-based method or a hybrid ISM + another geometrical or wave-based method,
- main programming language: Matlab, Python, C, C++ or C#,
- an active GitHub or SourceForge repository,

a total of 17 software packages were selected for further analysis of their source code and the accompanying published paper (if present). The identified distribution of main programming languages used across the software packages is as follows:

- Matlab: 5 (29 %)
- Python: 8 (47 %)
- C/C++/C#: 4 (24 %)

whereas the median year of software creation/upload to online repositories is 2017.

The analysis of source code has revealed that, besides the RIM-based randomisation of the positions of image sources within a small cube-shaped volume as a proven approach for sweeping echoes management [2], a second approach was also relatively successful in reducing their intensity for some room setups – that of utilizing the negative values of reflection coefficients, as described in [13] and first proposed by [14], using which the non-physical tail decay present in RIRs occurring when generated with positive coefficient values can be avoided.

The first approach was implemented in 3 (18 %) open-source software packages, whereas 5 (29 %) packages implemented ISM with the negative values of reflection coefficients. The remaining 9 (53 %) packages had no image sources' positions randomisation strategy or another form of sweeping echoes management implemented in the source code. From the aforementioned 9 packages, 6 were created/uploaded to online repositories after 2015 – the year in which de Sena et al. presented their mathematical analysis explaining the underlying causes of the sweeping echoes phenomenon in shoebox-shaped rooms and proposed a randomisation method for its removal [2].

In Figure 1 we present the spectrograms of RIRs generated with the original Allen and Berkley's method (left column), modified Allen and Berkley's method with reflection coefficients set to negative values (middle column), and RIM method (right column) with the random distance parameter (i.e. one half of the edge length of the cube-shaped volume used for image sources randomisation) set to 0.08 m. Room setup was as follows: room dimensions set to [4, 4, 4] m, frequency and angle-independent reflection coefficients of room boundaries set to 0.93, an omnidirectional source positioned at [1, 2, 2] m, and an omnidirectional microphone placed at 4 different positions (Table 1) selected from the set of 15 microphone positions in [2], named 'regular' due to the high level of regularity occurring in room parameters and, thus, introducing strong sweeping echoes. Simulation parameters for all three methods were as follows: RIR length set to 1 s, sampling frequency f_s to 22050 Hz, fractional delay filter length set to $40/f_s$ and its cut-off frequency to $0.9f_s/2$.

The spectrograms in the left column of Figure 1 show the sweeping echoes – straight lines of high intensity passing through the spectrogram origin, whereas the spectrograms in the right column reveal that the RIM method successfully removed the echoes, with only a small residue close to the origin present in panels b) and c), which could be removed with a larger value of the random distance parameter. On the other hand, with the negative reflection coefficients approach, mixed results were obtained: in panels a) and c) the sweeping echoes have been suppressed to a large degree, whereas in the remaining two panels the echoes have become even more pronounced and occur at different slopes than in the original method.

An informal listening test was performed by the first author (normal hearing and ten years of formal music education). Short clean speech utterances taken from [15] were convolved with the 12 generated RIRs, and listened via Sennheiser HD 595 headphones. The results of the listening test are summarized in Table 1, indicating that the RIM method provides, in addition to the objective, also superior subjective removal of the sweeping echoes phenomenon. Interestingly, it was observed that for cases b) and c), even though the echoes are only faintly present in the spectrograms obtained for the RIM method, the echoes are slightly audible since they are concentrated near their respective spectrogram origins. On the other hand, the faint lines present in the spectrograms in panels a) and c) for the modified ISM method did not create a perception of echoes since their energy was not concentrated near the origin, but instead spread out more evenly.

Table 1. Microphone positions and audibility of sweeping echoes when convolved with clean speech – very audible (VA), slightly audible (SA), inaudible (IA).

Fig. 1 panel	Microphone position [m]	Original ISM (+beta)	Modified ISM (-beta)	RIM
a)	[1, 1.75, 1]	VA	IA	IA
b)	[2, 1, 1]	VA	VA	SA
c)	[2.5, 1, 1]	VA	IA	SA
d)	[3, 1, 1]	VA	VA	IA

3. SWEEPING ECHOES INTENSITY

Even though the randomisation of the image sources' positions proposed in [2] and [11] introduces only minor changes to the room modal response, they are present, nonetheless. By acknowledging that the intensity of sweeping echoes in a simulated RIR, for a fixed room geometry and source position, is dependent on the receiver position, it can be concluded that, in some use cases, it may not be necessary to randomise the positions of image sources. Notable examples of this are training of machine learning-based speech or speaker recognition systems, sound source localisation systems, or speech source separation, speech enhancement and speech dereverberation algorithms [13], [16], where one can select, in advance, the receiver positions with weak or inaudible sweeping echoes.

To this end, a novel tool designed as an aid to the existing ISM-based open-source software was developed, that enables:

- fast visual assessment of sweeping echoes intensity (SEI) across 2D slices of constant receiver height in shoebox-shaped rooms, enabling informed, i.e. active sweeping echoes avoidance,
- estimation of a suitable value for the maximum displacement of image sources within a sphere-shaped volume implemented in the G-RIM method, that is to be employed in specific use cases where sweeping echoes need to be removed,
- generation of room impulse responses, spectrogram visualisation, and export of the generated FIR coefficients to a text file. Room impulse responses can be generated:
    - with or without the image source position randomisation, and
    - with frequency and angle-independent reflection coefficients of the room boundaries set to either positive or negative values.

While creating this graphical user interface (GUI)-based tool, the recent trends in programming languages use where Python dominates in popularity [5] were taken into account – similarly as in Roomsim [17], one of the first freely available programs for simulation of acoustics of shoebox-shaped rooms, this tool was developed in Matlab, and has been compiled into a standalone executable file to facilitate its use within the research community. Its main component – visualisation of the SEI of 2D room slices, is based on an approximation of the rigid walls image solution developed by Allen and Berkley, in which the temporal

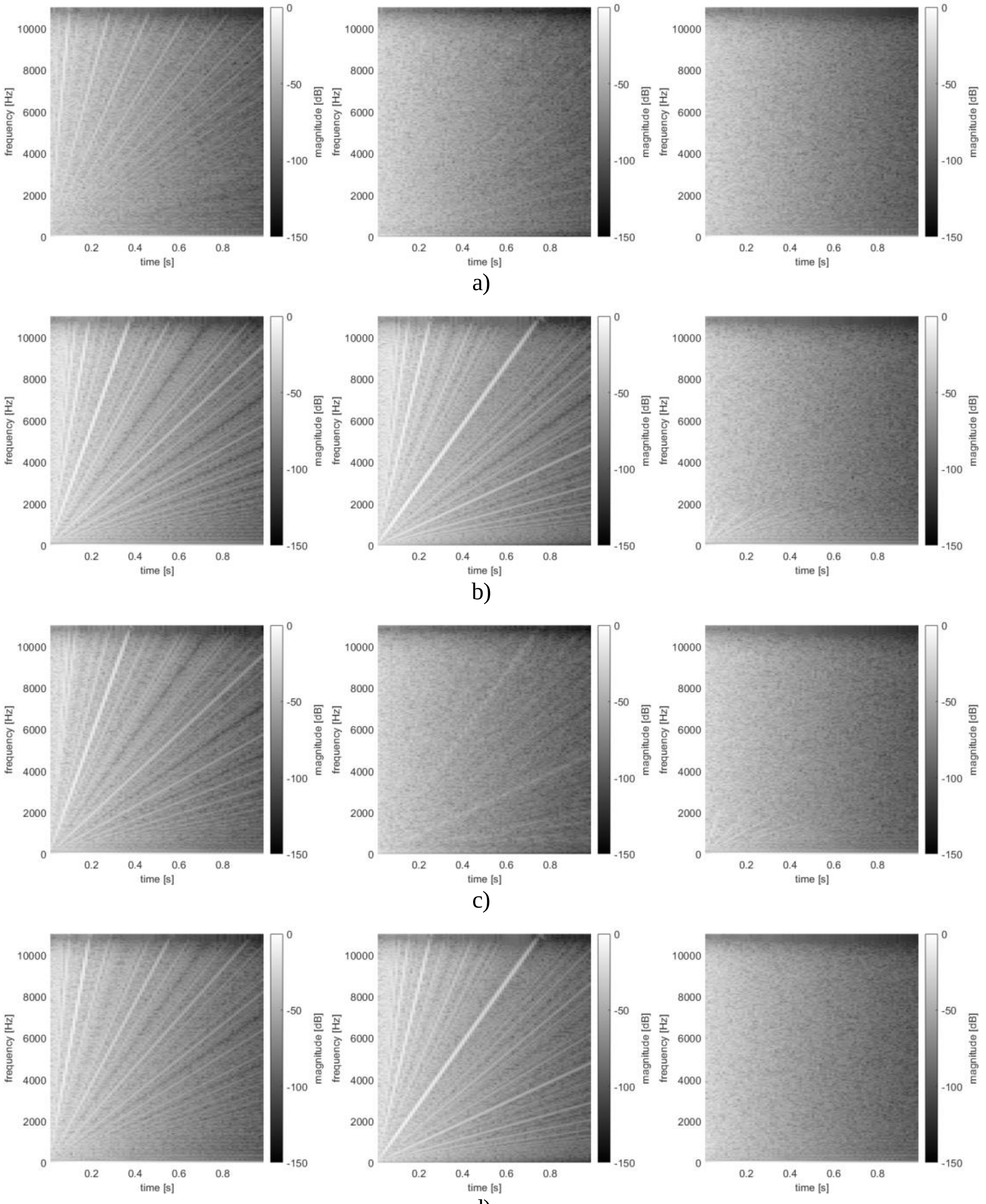


Figure 1. Spectrograms of RIRs generated for 4 microphone positions: original Allen and Berkley's method (left column), modified Allen and Berkley's method with reflection coefficients set to negative values (middle column), and RIM method (right column). Microphone positions for the panels a) – d) are given in Table 1.

resolution of the delays of specular reflections has been somewhat decreased to achieve better SEI computation runtimes.

To illustrate the achieved speed of computation, Table 2 presents the SEI runtimes obtained for two room setups – the first one presented in the paper by de Sena et al. [2] and the second one from Allen and Berkley's paper [3]. SEI was calculated for a 2D grid of receiver positions (points) of constant height with a discretisation step of 0.05 m in both the x- and y- directions, and set in the z-direction at the 1 m height in the first room and at 2.57 m in the second one. The simulations were performed on a desktop computer with an Intel i7-10700 CPU and 16 GB of RAM. It should be noted that the results were obtained with no parallelisation of tasks, that could be implemented, for instance, via Matlab parallel pool.

Figure 2 presents the values of SEI obtained for the first room setup, whereas Figure 3 shows the spectrograms for three receiver positions with different SEI values. It can be observed that the SEI measure accurately captures the sweeping echoes intensity across the 2D room slice. Figure 4 presents a visual assessment of the sweeping echoes intensity for the room setup in [3], indicating a different pattern than for the first setup due to a different source position. Figure 5 confirms that for the second room setup as well, SEI captures the intensity of sweeping echoes.

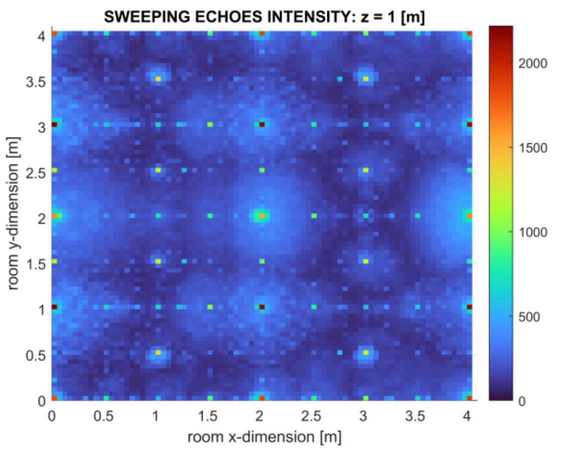


Figure 2. Sweeping echoes intensity for the room setup in [2].

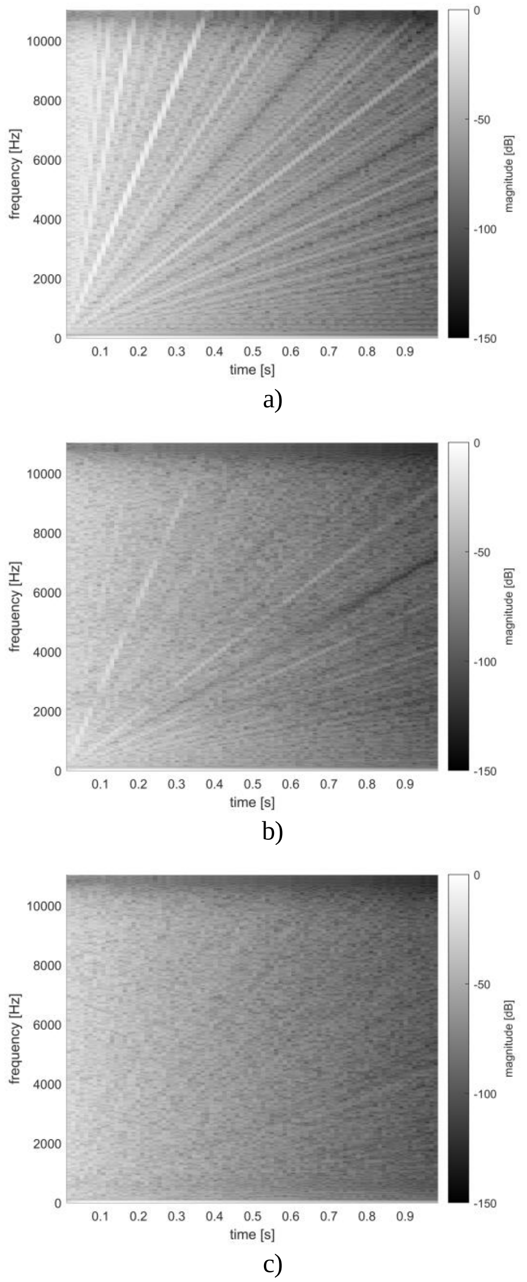


Figure 3. Spectrograms of RIRs for the room setup in [2]. Receiver positions and SEI: a) [2, 3, 1] m, SEI = 2184, b) [2.05, 1.95, 1] m, SEI = 581, c) [0.85, 1.25, 1] m, SEI = 77.

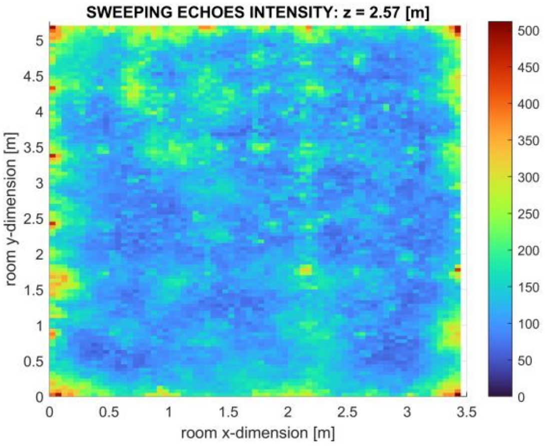
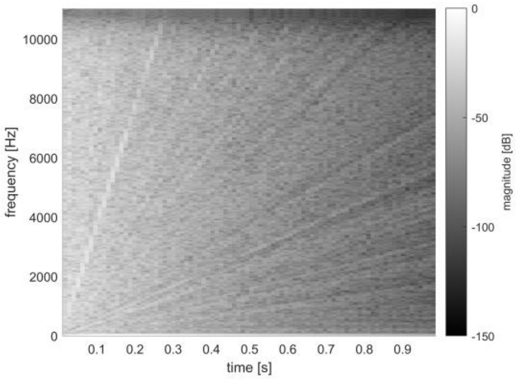
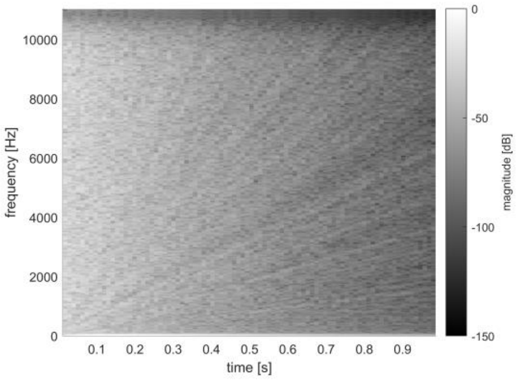


Figure 4. Sweeping echoes intensity for the room setup in [3].



a)



b)

Figure 5. Spectrograms of RIRs for the room setup in [3]. Receiver positions and SEI: a) [2.15, 1.75, 2.57] m, SEI = 319, b) [1, 2.65, 2.57] m, SEI = 62.

Table 2. SEI runtimes for two room setups.

Room dimensions [m]	Source position [m]	Total runtime [s]	Runtime per point [ms]
[4,4,4]	[1,2,2]	257	39
[3.43,5.15,4.29]	[1.29,4.29,1.72]	284	40

4. CONCLUSION

An overview of the approaches utilised for sweeping echoes management in open-source software for ISM-based room acoustics modelling was presented in this paper. Two approaches were identified – the randomisation of the positions of image sources and the use of negative reflection coefficients, of which the former proved to be superior. Furthermore, the analysis of the open-source software code showed that more than 50 % of the identified ISM-based software packages have no module for the management of sweeping echoes phenomenon in generated RIRs. Finally, due to the importance of the early specular reflections both in ISM-only and ISM-hybrid room modelling software, as they provide a sense of presence to a listener and enhance the perception of the sound, a novel tool for sweeping echoes intensity estimation across 2D room slices was created. A relevant direction for future research includes fine-tuning the underlying procedure for SEI estimation, and its more thorough evaluation on a larger set of room geometries.

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