Comparison of Non-Realtime Reverberation Models

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Introduction

This project aims to explore and implement two of the most common models for simulating reverberant spaces. The results presented have applications in many fields from architectural acoustics to effects in music production. Both models are compared with theoretical predictions from the ubiquitous Sabine equation. Qualitative evaluations are also made, for the full report see [1].

It is useful to first gain an understanding of what reverberation actually is. When an impulsive sound is created in a real world enclosed space, for example a hand clap in a cathedral, it is not just direct sound from the source to the listener that is observed. As the sound source generally radiates sound energy in all directions, what is actually heard is the direct sound followed by a series of later reflections off the various surfaces of the space.

Both methods explored in this project attempt to find the time the sound from a reflection will take to arrive, and what energy it will possess. Using this information, we can generate a 'map' of the room's reflections called an *impulse response*. This is represented digitally using a discrete array of delta functions. By convolving this with a signal, we get the original sound plus a quieter, delayed copy for each of the later reflections: this is essentially what reverberation is. The first technique for calculating this impulse response is called the *Image Source* method.

Image Source Method

The Image Source technique works on a purely geometric basis. We can treat the sound as a ray as it travels from source to listener, for high enough frequencies [2]. This means that it obeys specular reflection, that is, the angle of incidence is equal to the angle of reflection. Thus the reflection path can be greatly simplified by placing an image sound source in an adjacent 'virtual' room. The path from listener to virtual source (marked × and ◯ respectively) is then just equivalent to the reflected path (Fig. 1).

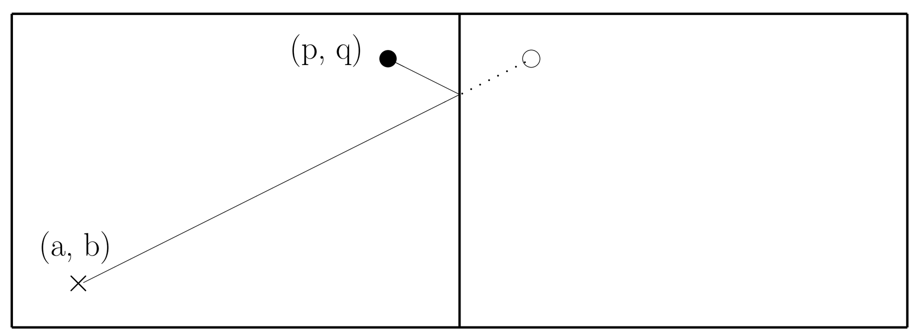

Figure 1: Equivalence of Real and Image Sources

We can extend this to account for multiple reflections by tessellating the original room with a series of virtual rooms, each containing an image source in the mirrored position. Then to find the distance for each reflection, d, it is simply a case of iterating through each room and taking the difference between the image source and the listener points. We can find the time for the reflection to occur by $t = d/c$, where $c = 343\text{ms}^{-1}$ is the speed of sound. Finally, using the fact that the energy of a sound wave dies off with inverse distance, we get the energy g:

$$g \propto \frac{1}{d}$$

Having found the time delay of each reflection and its intensity, there is now enough information to completely describe an impulse response. However, this method is much more complex to implement for non-rectangular rooms, and obstructions found in real world spaces such as columns are nearly impossible to account for. However, these complications can be overcome using a *Monte Carlo Ray Tracing* algorithm.

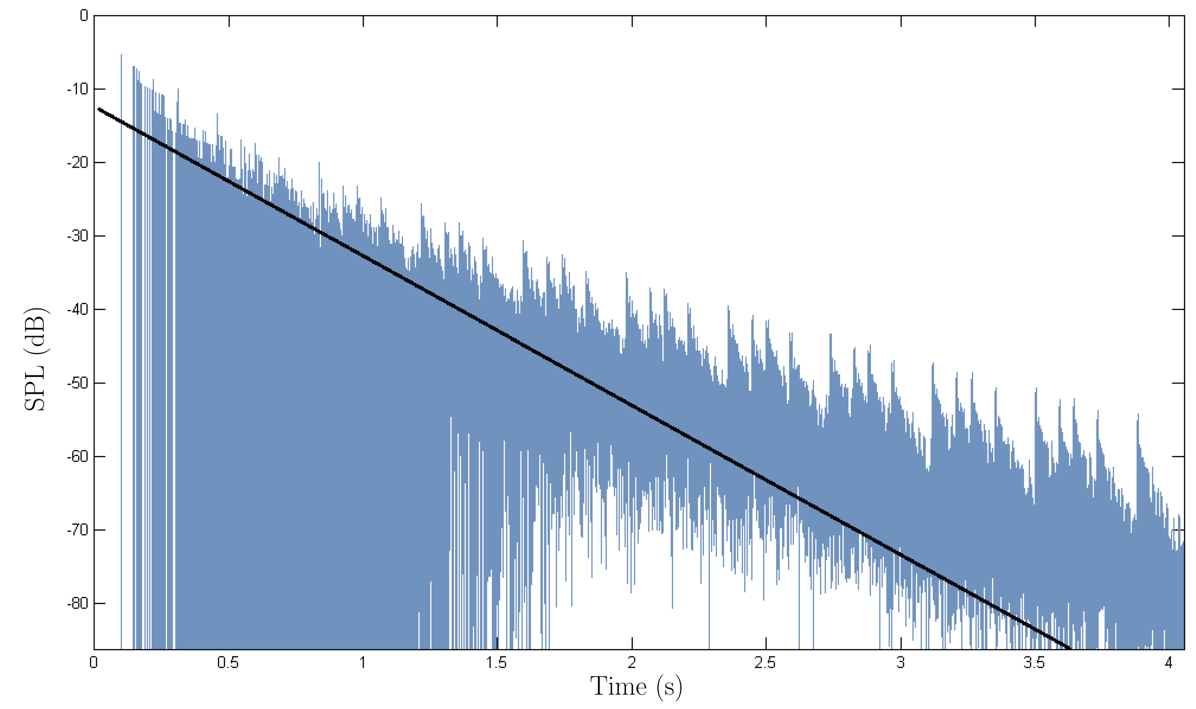

Figure 2: SPL-Time Plot for **Image Source** method for a room of dimensions $45.9623 \times 65.23354 \times 30.65432$ and absorption coefficient $\alpha = 0.3$. Black line shows that the method slightly overestimates R_t compared with the Sabine prediction.

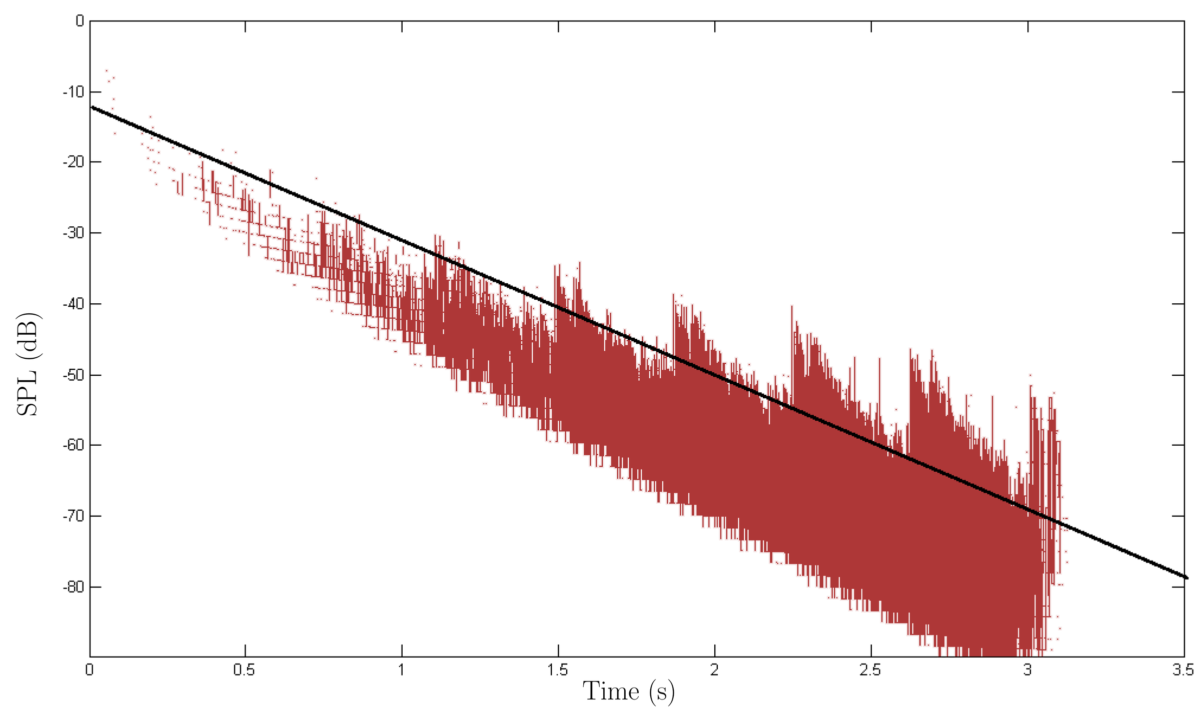

Figure 3: SPL-Time Plot for **Monte Carlo Ray Tracing** method for the same room. Black line shows that the model matches the Sabine prediction closely.

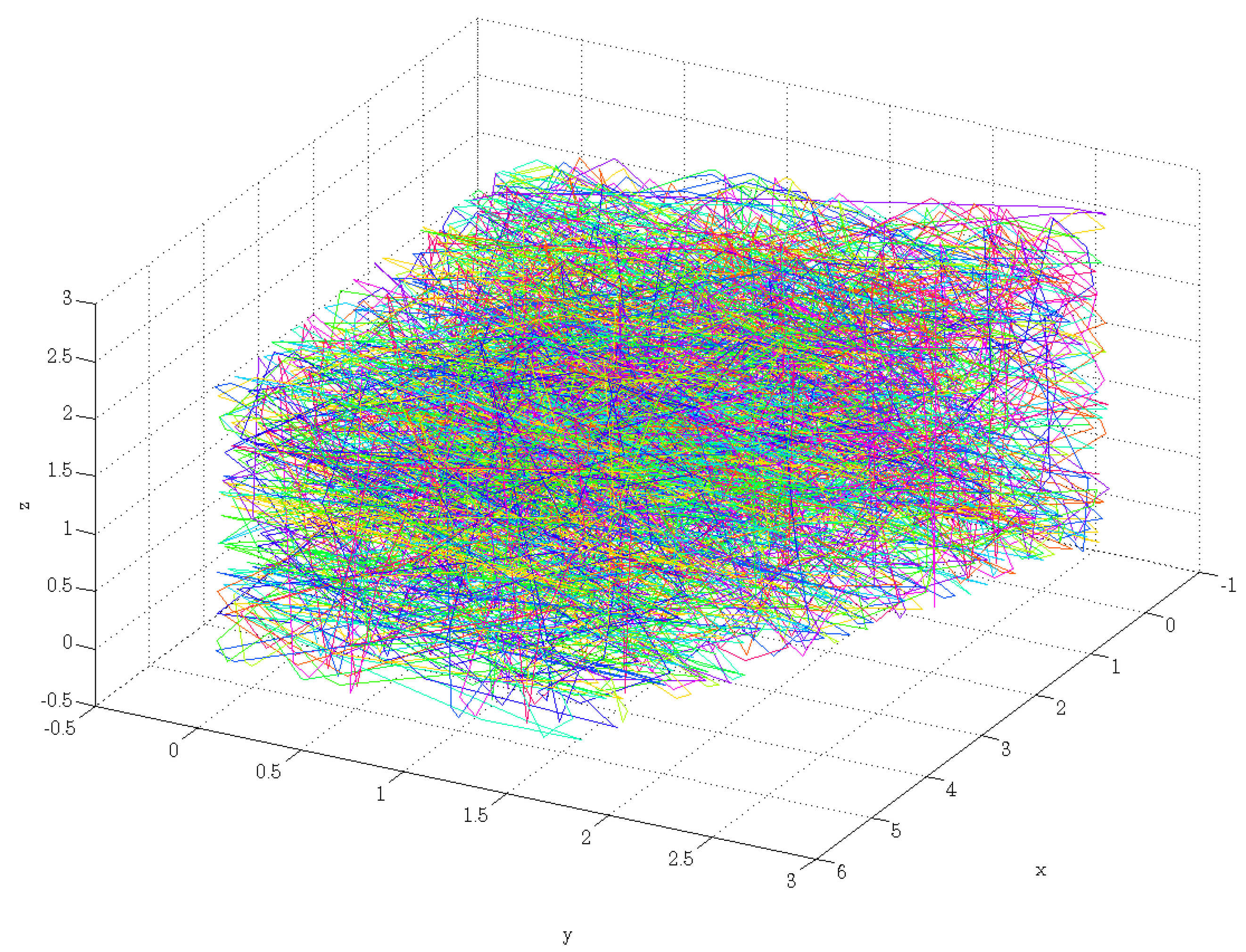

Figure 4: 3D Visual Representation of the **Monte Carlo Ray Tracing** algorithm for the University of Edinburgh's reverberation room, a space for which no two surfaces are parallel. Each colour represents a different 'ray'. While the above only shows 50 rays, typical runs can trace up to 100,000 paths!

Monte Carlo Ray Tracing Method

A Monte Carlo method is simply one with inherent randomness, so while the model reuses the ray-like assumption of the Image Source method, it does so in a non-deterministic way. By firing out rays randomly in all directions, the method explores the intricacies of the simulated space. By representing the ray as a unit direction vector and a source point, we can 'trace' its path around the room by applying basic vector algebra for reflections off surfaces. Fig. 4 demonstrates a typical run for an irregularly shaped room.

For this technique to be of use, the ray must be detected somehow. This is done by representing the detector as a small spherical region. By solving the intersection equation for a line and a sphere, the distance from sound source to detector can be found. The remaining steps are as described for the Image Source method.

The Monte Carlo Ray Tracing method has the advantage of being much much flexible; additional phenomena such as diffusion may be incorporated, and non-isotropic sound sources can be simulated. However to build up an accurate picture of a space, up to 100,000 rays may need to be traced, a process which is much more computationally intensive than the Image Source method.

Results

One of the best ways to evaluate the accuracy of either model is to see how well it predicts a quantity called the reverberation time R_t. This is the time required for the SPL (sound pressure level) to reduce by 60dB. Figs. 2 & 3 show the SPL-time graphs using each model for a rectangular room, together with the time predicted by Sabine [3]. This requires the volume V, total surface area S, and absorption coefficient α (a measure of the reflectivity of the surfaces):

$$R_t = \frac{0.161V}{S\alpha} \approx 3.24 \text{ secs.} \qquad \text{(Sabine Equation)}$$

Although the amount of 'noise' only allows confidence of around ± 0.15s, both Image Source and Monte Carlo methods are in reasonably good agreement with each other predicting $R_t \approx 3.5$s and $R_t \approx 3.4$s respectively; the Monte Carlo results appear to match the Sabine prediction to a higher degree of accuracy. Qualitatively, the output from the Image Source model suffers from a slight fluttering effect; the Monte Carlo produces a slightly smoother and more realistic output (all files available for comparison [1]).

Conclusions

While the Image Source method is significant faster than the Monte Carlo method (order of minutes compared to hours!), it doesn't perfectly reproduce the expected results. The method serves as a fair approximation, particularly if computational time is an issue, but the Monte Carlo method proves to be a closer fit. Initial reflections are not captured with such accuracy with the ray-tracing method however; an ideal solution would be a hybrid model which utilises the accurate traces of the early reflections from the Image Source and fills in the later, more dense reflections using Monte Carlo Ray Tracing techniques.

References

[1] Ewan Hemingway. Audio Results and Code from Image Source and Ray Tracing Simulations, March 2010. `http://www.ewanhemingway.co.uk/reverberationproject`.

[2] H. Kuttruff. *Room Acoustics*. Applied Science Publishers, London, 5th edition, 2009.

[3] Murray. Campbell and Clive A. Greated. *The Musician's Guide to Acoustics*, pages 532–535. Dent, London, 1987.