An hybrid beam and particle tracing with time dependant radiosity for accurate impulse response of rooms prediction

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An hybrid beam and particle tracing with time dependant radiosity for accurate impulse response of rooms prediction

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Ray-tracing is widely used for echograms prediction in room acoustics. Several ray-based technics exist, each of them with pros and cons. In this paper we propose a method that merges beam tracing, particle tracing and time dependent radiosity in order to compute accurate impulse responses. This method mixes advantages of each technique: precise direct and early specular reflections (and even diffraction) with phase information for beam tracing, mixed diffuse and specular contributions and late reverberation for particle tracing, smooth purely diffuse exchanges with radiosity. Our method builds the impulse response from pressure FRF (narrow band) computed with beam-tracing and pseudo-echograms (wide band) computed with particle tracing and radiosity, using signal-processing. It carefully avoids contribution overlapping between the three techniques.

1 Introduction

Acoustic propagation in rooms implied different phenomena as shown on Figure 1: reflection, diffusion, diffraction, absorption, ...

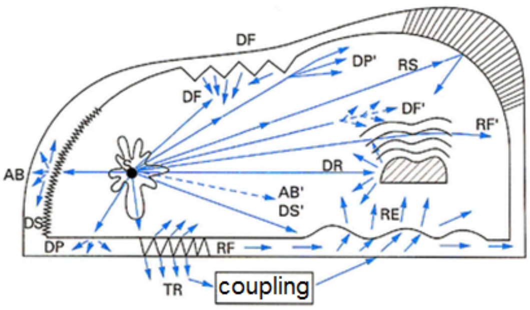

Figure 1: Different phenomena in room acoustics

Ray-tracing based techniques are widely used for impulse response (IR) computation. Several different algorithms exist, each having strengths and weaknesses. In this article we present a new technique for IR computation that combine strong points of three different techniques (beam-tracing, particle tracing, time dependent radiosity) in order to:

- finely predict main contributions,
- take into account phase and interferences,
- account for late reflections (reverberant volumes),
- precisely take into account diffusion.

We want to achieve this for system impulse response computation (and not only wide band echograms) to analyze or auralize the result.

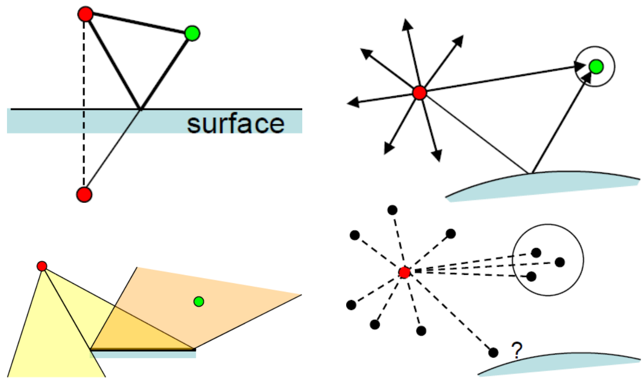

Figure 2: Image source (top, left), ray-tracing (top, right), beam-tracing (bottom, left), particle tracing (bottom, right).

Table 1: Overview of geometrical acoustics algorithms

method	geometry/ **reflexion law**	physics	pro / **cons**
image sources	planar **specular**	pressure (phase) **narrow band**	point-to-point diffraction **duration**
ray-tracing	almost any **specular**	power	**aliasing (point-to-surface)**
particle-tracing	any shape **any**	power **wide bands time**	powerful **noisy**
beam-tracing	polygons (pyramids) any (adaptive) **specular**	pressure **narrow band**	point-to-point diffraction efficiency
radiosity	any (mesh) **diffuse**	power **wide bands time**	precise **very specific**

2 Previous work

Classical geometrical acoustics are displayed on Figure 2. Advantages and drawbacks of each one are presented in table 1. For instance beam-tracing [4] is very powerful for precise early contribution computation; It computes FRF (frequency response functions, taking into account phase and interferences) but cannot take into account diffuse and late reflections. As a consequence it has been mixed with particle tracing [7] in order to handle any kind of reflection law but it is still limited to wide band echograms only. We will now take advantage of time dependent radiosity to compute pure diffuse contributions and also explain how to compute a full impulse response.

Next sections will detail some hints on beam-tracing, particle tracing and time dependent radiosity.

2.1 Beam-tracing

Beam-tracing is a trick in order to compute point-to-point paths between sources and receivers taking into account specular reflections on surface and even diffraction by edges or surfaces [5] [6]. Beam-tracing propagates wave fronts (beams) instead of thin rays. By doing this, reflections on curved surfaces can be handled accurately (see Figure 3, left). The computation of paths is independent from the computation of FRF allowing fast iterations when changing properties. Nevertheless only specular (and diffracted) paths can be computed and it is limited to low reflection orders (usually less than 20). As a consequence the IR (computed with inverse Fourier transform) is short-lived (see Figure 3, right). It could be extended using statistical reverberation (for late reflections and diffusion) but it would miss distinctive effects of the room (and bring no more information than Sabin's law).

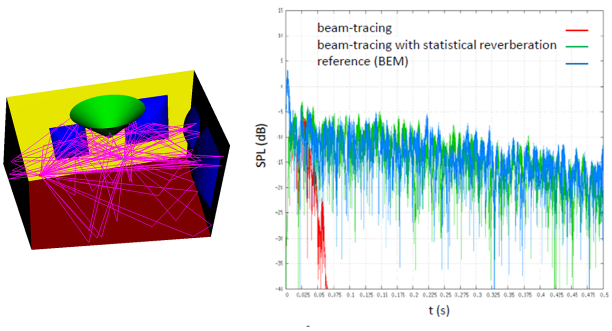

Figure 3: Example of beam-tracing: paths (left), impulse response (right, with and without statistical reverberation).

2.2 Particle tracing

Particle tracing is basically a stochastic method: particles are randomly shot from sources and each particle trajectory is traced as long as it exists. At every interaction with a surface the particle is tested with Russian roulette if it is to be absorbed (with a α probability). It is then reflected either specular or diffuse (with a δ probability, known as diffusion coefficient, 1 for a purely diffuse reflection, 0 for a specular reflection, see Figure 4). Particles are collected into volumes or on surfaces and stored into echograms (see Figure 4). The particle density in the collector is related to the acoustic intensity. Properties are wide band and computations are done band by band.

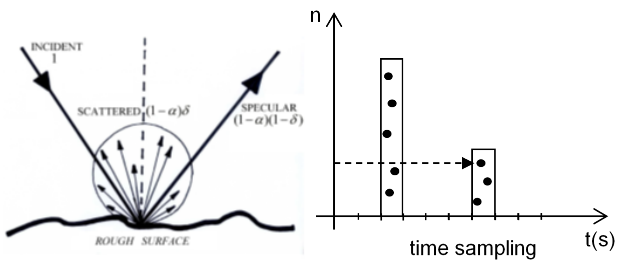

Figure 4: Diffusion coefficient (left) and particle tracing echogram (right).

Practically binary particles are replaced by weighted particles and every band are computed simultaneously.A vector of weights $[w_0; w_1; w_2 \ldots]$, with a weight for each band i is assigned to each particle. It is initialized to $[1; 1; 1 \ldots]$. For each surface $\bar{\delta}$ is the averaged diffusion coefficient over all bands. $\bar{\delta}$ is used as a probability to select between diffuse and specular reflection. The reflected weight vector is then:

$$w_{i,ref} = (1 - \alpha_i)\, w_{i,inc}\, \frac{\delta_i}{\bar{\delta}} \quad \text{for diffuse reflection} \quad (1)$$

$$w_{i,ref} = (1 - \alpha_i)\, w_{i,inc}\, \frac{1 - \delta_i}{1 - \bar{\delta}} \quad \text{for specular reflection} \quad (2)$$

With $w_{i,ref}$ the reflected energy in the band i, $w_{i,inc}$ the incident energy, α_i the absorption coefficient, and δ_i the diffusion coefficient.

These corrections balance the choice of diffuse or specular reflection according to $\bar{\delta}$ and greatly reduce computation time.

2.3 Time dependent radiosity

Radiosity is a computation technique based upon power exchanges between purely diffuse (Lambert) surfaces. It is widely used in light simulation (where most surfaces are diffuse). Radiosity (B, in W/m^2) is the total power leaving a point on a surface, per surface unit. It is equivalent to acoustic intensity. This leads to an integral equation on all surfaces. Time dependent radiosity is an extension of radiosity [2] that take into account time in order to compute echograms.

Surfaces are meshed into patches where radiosity is a constant value. Each patch holds an echogram of radiosity. As a consequence the integral equation transforms into a linear problem:

$$B_i(t) = E_i(t) + (1 - \alpha_i(t)) \sum_j FF_{ij} B_j(t - T_{ij}) \quad (3)$$

Where E_i is the power emitted by the patch (in case of surface sources), α_i the absorption coefficient of patch i, T_{ij} the time to reach patch i from patch j and FF_{ij} the form factor. This form factor is the ratio of (diffused) power leaving path i and reaching patch j. It is expressed as:

$$FF_{ij} = \frac{1}{S_i} \int_{P_i \in S_i} \int_{P_j \in S_j} \frac{\cos\theta_i \cos\theta_j}{\pi \|P_i P_j\|^2} V(P_i, P_j)\, dS_i\, dS_j \quad (4)$$

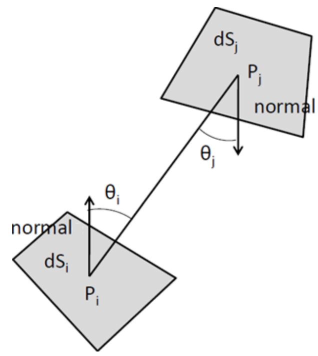

Figure 5: Form factor for radiosity.

θ_i and θ_j are defined on Figure 5. $V(P_i, P_j)$ is a visibility function from P_i to P_j (either 0 or 1). There also exist form factors from a point source to a patch (ratio of power leaving source and reaching patch) and form factors from a patch to point receiver (to collect intensity at receiver from intensity at patch). All these form factors can be precomputed as they are geometrical values.

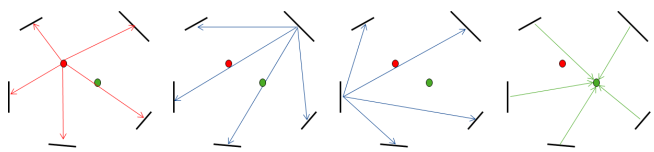

Figure 6: Radiosity solving algorithm.

Radiosity Eq. 3 can be solved by matrix inversion. Nevertheless the most efficient technique is iterative solution illustrated on Figure 6. First sources emit towards patches. Then the patch with the less shot power emits towards other patches (using form factors), and so on until the results converge or the maximum time is reached. Last intensities are collected from patches to receivers.

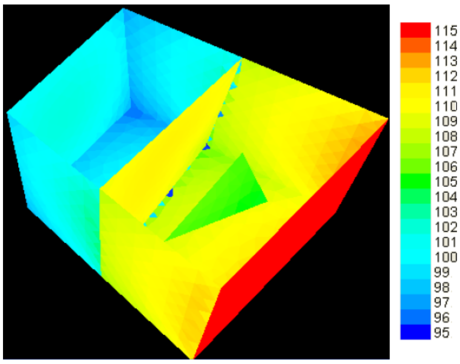

Figure 7: Example of radiosity computation for two rooms separated by a wall.

Radiosity can also take into account diffuse transmission. An example of radiosity computation for two rooms separated by a wall is displayed on Figure 7. The main advantage of radiosity versus particle tracing (in case of purely diffuse surfaces) is that there is no noise as shown on Figure 8. The particle tracing needed a lot of particles (i.e. a lengthy computation) in order to give results as good as radiosity.

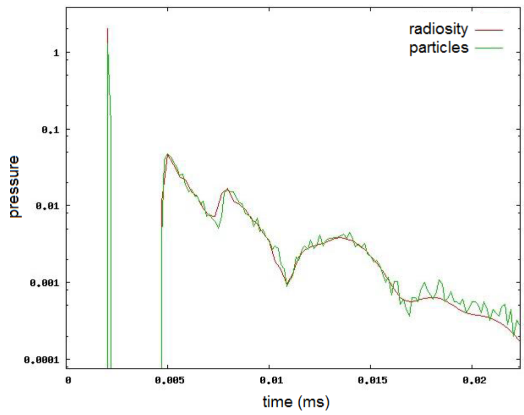

Figure 8: Particle tracing versus time dependent radiosity for a closed diffuse volume.

3 Hybrid method

3.1 Overview

We present here a hybrid method that mixes advantages of three different techniques: beam-tracing (for precise early reflections computation with interferences), particle-tracing (for late reverberation and mixed specular-diffuse contributions) and time dependent radiosity (for noise-free diffuse contributions). This method allows to compute impulse responses hence enabling auralization. An overview of the method is displayed on Figure 9.

3.2 Detailed algorithm

The main parameters of the algorithm are beam-tracing depth N (for beam-tracing), time sampling T_{max} and ΔT (for particle tracing and time dependent radiosity) and the number of particles to shoot K (for particle tracing). First beam-tracing is performed at depth N, computing specular paths between sources and receivers. It leads to narrow band FRF that are transformed into IR using fast Fourier transform. This is a partial IR accounting for direct and early specular reflections only. Second a time dependent radiosity algorithm is performed to compute wide-band pseudo echograms (one for each third octave) of purely diffuse reflections. Third a so-called "filtered" particle tracing is performed. This is the most tricky part. It stores in the same wide-band pseudo echograms only the missing contributions (mixed diffuse and specular contributions or specular paths with order $> N$). Those wide-band echograms are then transformed into IR by taking the square root with a random sign (to simulate a random phase, as diffuse reflections are incoherent). These IR (one per third octave) are then filtered by their band and summed with the beam-tracing IR to get a full IR with all contributions.

To achieve filtering in the particle tracing algorithm, the particles are initialized with a "specular" and a "diffuse" flag. When the reflection is diffuse the "specular" flag is cleared and when the reflection is specular the "diffuse" flag is cleared. When the particle reaches its $N+1^{\text{th}}$ reflection the "specular" flag is also cleared. Particle with the "specular" or "diffuse" flag are propagated but not collected in order not to overlap respectively with beam-tracing and radiosity results.

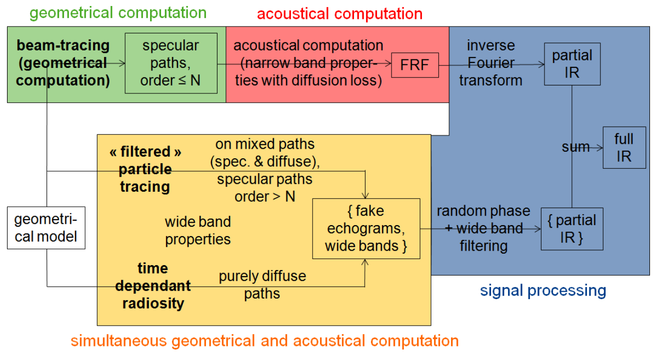

Figure 9: Overview of the full method.

3.3 Analysis

This method allows simultaneous computations on every band. Furthermore, geometric precomputations (beam-tracing, form factors) allows faster iterations (when changing acoustic properties). Compared to statistical reverberation techniques [1] it is not much time consuming and gives similar results in case of diffuse field, but as it does not assume diffuse field it is suitable for every case. Another strong point is that it is far less noisy than pure particle tracing. The radosity echograms stored on the surfaces can be used for particle storage too and reduce noise for every diffuse ended contribution (where we can freely connect from surfaces to receivers), as shown on Figure 10. This is achieved by filtering particles which latest reflection is diffuse in the particle. As a matter of fact only late specular ended contributions computed with particle tracing algorithm remain noisy.

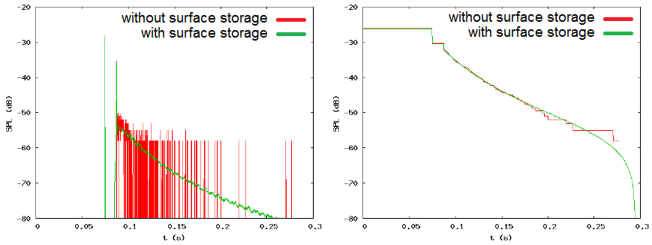

Figure 10: Surface storage reduces noise for diffuse ended contributions (left: impulse response, right: decay).

4 Example

This example is based upon data from the third Round Robin on room acoustics software [8]. The model is displayed on Figure 11. Figure 12 showcases the influence of diffusion coefficients on the shape of echograms: 4kHz octave band has far more diffusion whereas 125Hz displays more specular peaks. Figure 13 shows two impulse response: one computed with beam tracing, and one computed with both beam and particle tracing. The former gives precise early reflection specular peaks while the latter add diffuse and mixed specular and diffuse contributions. The effect of such contributions can be seen on Figure 14 where they account for most of the decay curve.

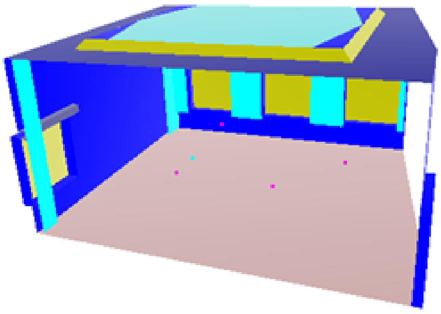

Figure 11: Round Robin III on room acoustics model.Point sources in red, receiver in green

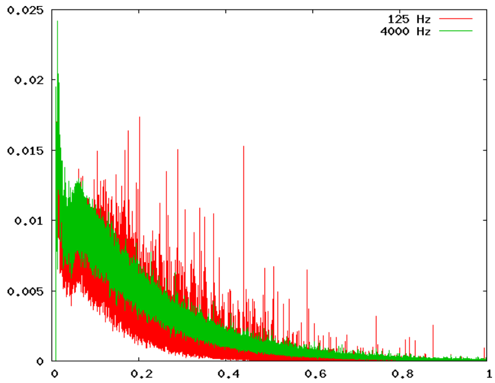

Figure 12: Large band (octave) echograms at 125Hz and 4kHZ computed on the Round Robin III model.

5 Conclusion

This article presented an original method for impulse response computation based on three different geometrical techniques. It combines advantages of both techniques while removing almost all of their weaknesses. We now plan full

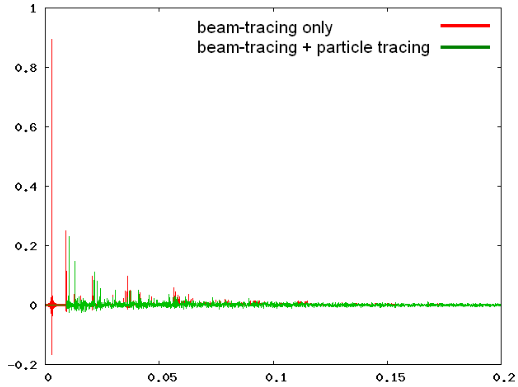

Figure 13: Synthetized impulse reponses.

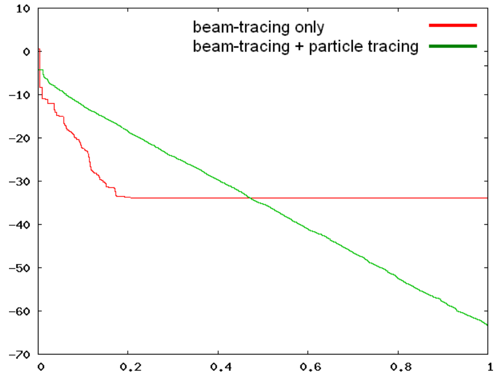

Figure 14: Synthetized decays.

comparisons between synthesized and measured impulse responses for auralization.

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