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Pyramid tracing vs ray tracing for the simulation of sound propagation in large rooms

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Abstract

The aim of this paper is to introduce a new computational model (RAMSETE) for the simulation of sound propagation in large rooms; the model can easily be adapted to work outdoor, and can consider diffraction effects around screen edges and sound paths passing through (light) panels.

However, this paper focuses on room acoustics, and particularly on rooms with non-Sabinian behaviour. In fact, the Pyramid Tracing algorithm does not involve an hybrid computation scheme, with a reverberant tail superposed to the deterministic early reflections estimate, as it is common with other diverging beam tracers (cone tracers, gaussian beam tracers, etc.). This make it possible to study also sound fields characterised by double-slope sound decays, inside spaces with not comparable dimensions and inhomogeneous sound absorption.

It is well known that the same capabilities were already present in the (original) Ray Tracing scheme, but requiring much longer computation time. In fact, a correct Ray Tracing implementation can be considered as the reference standard for any (faster) numerical code based on the Geometrical Acoustics assumptions.

After a brief introduction to some important details of the two algorithms, the results obtained in three cases are presented. The first is a typical Sabinian room (a reverberating chamber), the second is the coupling of two rooms with different average absorption (a theatre with its stage), the third is a typical industrial building (having an height very little compared to other dimensions) with non-uniform sound absorption (baffles under the ceiling).

The results show how the Pyramid Tracing can give results very similar to the original Ray Tracing, provided that a proper adjustment of the parameters is performed. On the other hand, the magnitude of the errors that can be done with improper parameter settings is delimited and discussed.

1. Introduction to the two algorithms

Before we can present the results of the comparison tests, it is better to explain briefly the working principles of the two codes used here. Both of them run on a standard PC, under MS-Windows, and share the same input and output file formats, so the comparison is easy.

All the files are plain-ASCII, with auxiliary strings embedded to make easy to understand the meaning of each row of data. The input data file is produced by a dedicated 3D CAD program, and the output files are processed through a set of graphical utilities capable of reconstructing, from the "raw" impulse response data, the usual descriptors used in room acoustics: Levels, Early-to-Late ratios, Lateral Efficiency, Center Time, STI, etc. . The only difference during the post processing is that the impulse responses produced by the pyramid tracing must be corrected prior to calculating such parameters, as explained in another paper (Farina [1]).

1.1 The Ray Tracing program

The Ray Tracing program used here is the evolution of a computer code initially developed from the author and Prof. Alessandro Cocchi (University of Bologna, Italy) for the study of large, non-Sabinian spaces (Farina[2]). The details of this code were never published before.

The original Ray Tracing scheme is assumed: a large number of non-diverging rays is isotropically traced from the (point) source, bouncing specularly over the room boundaries, where part of their energy is absorbed. The receivers are spheres of proper radius, and the detection mechanism make it possible to compute the Sound Energy Density (J/m^3) inside the receiver volume, as shown in fig. 1.

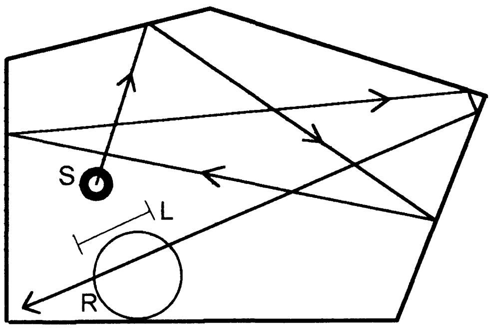

Figure 1 - Conceptual scheme of the Ray Tracing algorithm

The contribution W' to the total energy density W that each ray leaves inside the receiving sphere is proportional to the length of the intersection L and to the initial energy reduced for multiple absorption on the boundary surfaces (with absorption coefficients α_i) and for the air absorption (with coefficient γ multiplied for the path length x):

$$W' = \frac{P_{wr} \cdot Q_{\vartheta}}{N_{rays} \cdot c \cdot V_{sphere}} \cdot L \cdot \left[\prod_i (1-\alpha_i)\right] \cdot e^{-\gamma \cdot x} \tag{1}$$

This formulation avoids the common inconsistencies present in other detections schemes (as surface intensity over the sphere surface or over a circular disk), that are not physically compatible both with free field and reverberant spaces.

Another remarkable point is the ray generation at the source. Although the Ray Tracing scheme requires a random generation, it must be ensured that the generation is almost uniform on the surface of a spherical source (the source directivity Q_θ is managed along with the energy assigned to each ray, as shown in eqn 1). The simple assumption of three random generators for the three versor components of the ray is not correct, as this produce a "cube of rays" instead of a sphere; it is possible to "cut away" the corners of the cube (discarding each vector having modulus greater than 1), but it was preferred to employ a semi-probabilistic generator, in which the sphere surface is mathematically divided in a large number of equal areas (actually 400=20x20), each of them being "brushed" with the random generators.

This task was accomplished employing just two random generators (RND1 and RND2), and projecting their values over the sphere to obtain the versor components of the ray:

$$\begin{aligned} v_x &= 2 \cdot \sqrt{\frac{i+\mathrm{RND1}}{20} - \left(\frac{i+\mathrm{RND1}}{20}\right)^2} \cdot \cos\left(2 \cdot \pi \cdot \frac{j+\mathrm{RND2}}{20}\right) \\ v_y &= 2 \cdot \sqrt{\frac{i+\mathrm{RND1}}{20} - \left(\frac{i+\mathrm{RND1}}{20}\right)^2} \cdot \sin\left(2 \cdot \pi \cdot \frac{j+\mathrm{RND2}}{20}\right) \\ v_z &= 1 - 2 \cdot \frac{i+\mathrm{RND1}}{20} \qquad i = 0..19 \qquad j = 0..19 \end{aligned} \tag{2}$$

This is equivalent to cutting the sphere with 20 iso-z planes, equally spaced along the z axis, and then dividing each circle again in 20 parts, as shown in figure 2. Obviously this causes the single facets to have very different shape, but all have the same area.

The generation is then repeated many times, until the wanted number of rays (usually more than 100.000) is reached.

This Ray Tracing program has proven to be very accurate and reliable, provided that a very high number of rays is generated. This is easily verified, as the program can proceed indefinitely, increasing the number of rays (in packets of 400) until a convergence criterion is satisfied (for example on the SPL in a particular receiver, that must stabilise within a pre-defined tolerance).

A further validation of this Ray Tracing program has been obtained through participating at the benchmark organised by Verbandt & Jonckheere [3] in 1992: in that case this ray tracing code (labelled 8aS in that comparison) resulted perfectly aligned with the other 7 (more famous) participants.

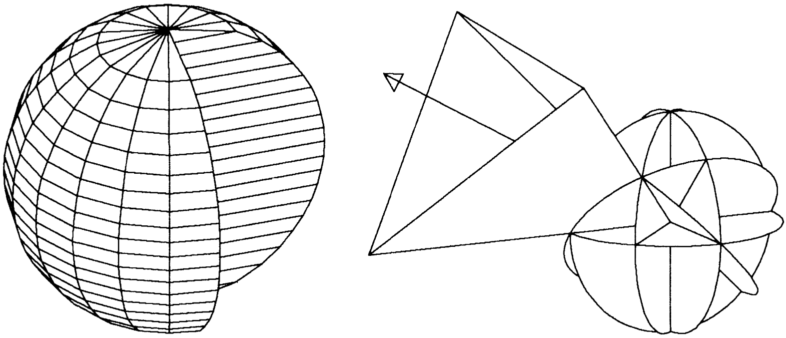

Figure 2 - subdivision of the source's surface in facets of equal area (Ray Tracing, left) and in triangular beams (Pyramid Tracing, right)

1.2 The Pyramid Tracing program

Ramsete is one of the first pyramid tracing codes that was developed for room acoustic simulations. At the time of its first appearance (1993), only the work of Lewers [4] reported a "triangular beam tracing" hybrid method.

In the Pyramid Tracing scheme, triangular beams are generated at the sound source, as shown in fig. 2. The central axis of each pyramid is traced as usual, being specularly reflected when it hits on a surface. The three corners of the pyramid follow the axis, being reflected from the same plane where it hits.

The receivers are points, and a detection occurs when this point is inside the pyramid being traced. In this case, a pseudo-intensity contribution I' is recorded (along with the time elapsed since pyramid emission) for each octave band:

$$I' = \frac{P_{wr} \cdot Q_{\vartheta} \cdot \prod_i (1-\alpha_i)}{4 \cdot \pi \cdot x^2} \cdot e^{-\gamma \cdot x} \qquad (3)$$

in which x is path length, γ is the absorption coefficient of air, Q_θ is the directivity factor and P_{wr} is the acoustic power of the source.

Ramsete is not an hybrid model: the tracing of pyramids is prosecuted up to the whole time length required to analyse the impulse response, and no point of transition exist between the "early" part of the decay and the "late" one. The author already published the details of the tail correction algorithm (Farina [1]).

For the purposes of the present work, it is necessary to recall here the meaning of the two numerical parameters α and β, the value of which need to be adjusted to model non-sabinian spaces with a little number of pyramids.

α: is the exponent to be applied to the current time, to find the number of reflected waves arriving to a receiver in the time unit (usually called temporal echo density). For example, in Sabinian room α=2, in a tunnel-like room it approaches 1, while in a very low room (only 2 counterpoised surfaces) the temporal echo density is constant, so the exponent α is 0. in some cases α can also be very greater than 2.

β: is a coefficient inserted in the formula for calculating the **critical time t_c**: this is defined as the time at which the "true" temporal echo density (that usually increases with time) is equal to the "false" constant echo density produced by the pyramid tracing (that is simply proportional to the number of pyramids, and inversely proportional to the mean free path). The parameter β can adjust t_c from infinity (no correction, β=0) to the Sabinian value (β=0.3).(Farina[1])

Another point thatneeds to be explained here is the capability to treat "holed" and "obstructing" surfaces, as this greatly speeds up the program. Usual surfaces are quadrilateral plane faces, defined by the coordinates of their vertexes. If they are declared "obstructing", additional tests are made to find the sound attenuation of pyramids "passing through" the panel and being diffracted from its free edges (automatically located). On a surface it is also possible to "attach" three types of entities: doors, windows and holes. Doors and windows are rectangular areas, having absorption coefficients and sound reduction indexes different from that of the wall. The holes are closed polylines, that define regions where the pyramids can freely pass through an obstructing wall.

These features produce a noticeable reduction in computing time, as the number of (main) surface is reduced, and the complete set of tests is conducted on the "obstructing" surfaces only. Figure 3 show an example (from Ramsete Cad) of these modelling capabilities.

Although Ramsete is not a Montecarlo method, still a convergence to the "right" values can be seen increasing the number of pyramids traced: the goal of this work is to find the right values of coefficients α and β, making it possible to obtain correct results using just 256 pyramids or even less, with computations times reduced to a couple of minutes for each sound source in the worst cases.

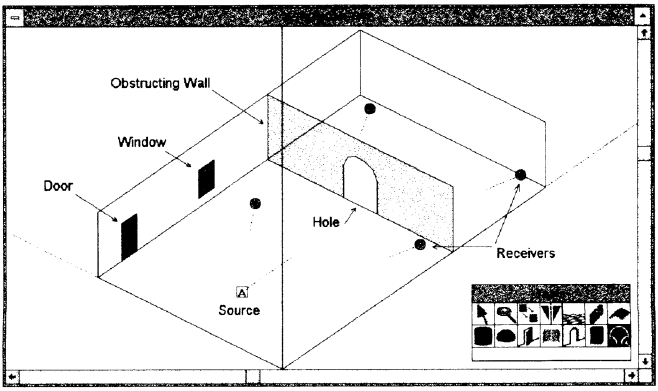

Figure 3 - Advanced Surface Attributes in Ramsete

2. Comparison between the two algorithms

2.1 A Sabinian room

Figure 4 shows the geometry of a classic reverberant chamber:

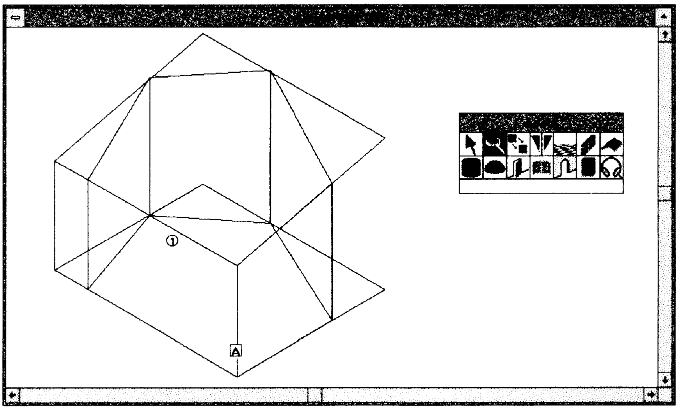

Figure 4 - Geometry of a Reverberant Chamber

In this case the absorption coefficients are the same everywhere, so the acoustic field is surely Sabinian, and just one receiver need to be considered.

The comparison is made plotting on the same graph the Backward Integrated Impulse Response in dB for the octave band of 1 kHz, computed with the Ray Tracing (128000 Rays) and with the Pyramid Tracing (the latter with various number of pyramids). In figure 5 the comparison is made twice: on the left the Ramsete's responses are reported without tail correction, on the right the same are corrected with the theoretical values of α=2 and β=0.3. It can be shown that these values make the Pyramid Tracing nearly coincident with the Ray Tracing, even for a very little number of pyramids.

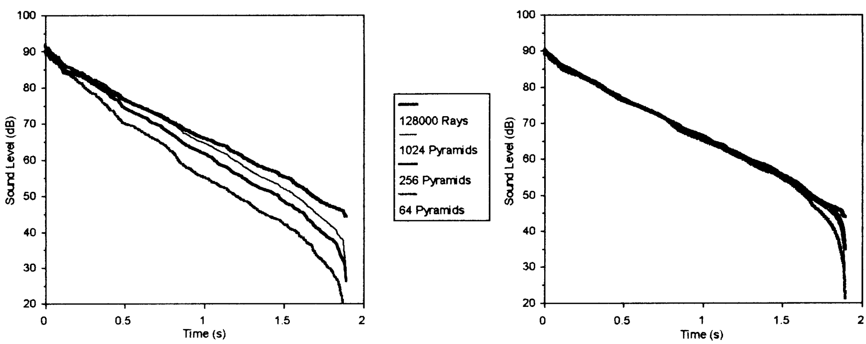

Figure 5 - Comparison of Decay Curves in a Reverberant Chamber

The accuracy of the results can be checked comparing the numerical values of the reverberation time T30 with that obtained by the Ray Tracing **(2.768 s)**:

Table 1 - Values of T30 computed with Ramsete

Number of Pyramids	T30 w/out correction	T30 with correction
1024	2.368	2.614
256	2.136	2.828
64	1.784	2.691

2.2 Coupled Volumes with different absorption

In figure 6 both the geometry and the results are reported for this case: it is the Theatre Buero Vallejo recently built in Spain, at Alcorcon (near Madrid), with architectural project of Isicio Ruiz. The simulation is representing the hall completely furnished, while the stage is empty (and reverberating) at all.

The graph in fig. 6 shows the Impulse Response (not integrated) in the octave band of 1 kHz obtained in receiver # 19 with the Ray Tracing program and with Ramsete at various number of pyramids, the latter being corrected with α=5.78 and β=0.0153. The double slope of the decay is quite evident.

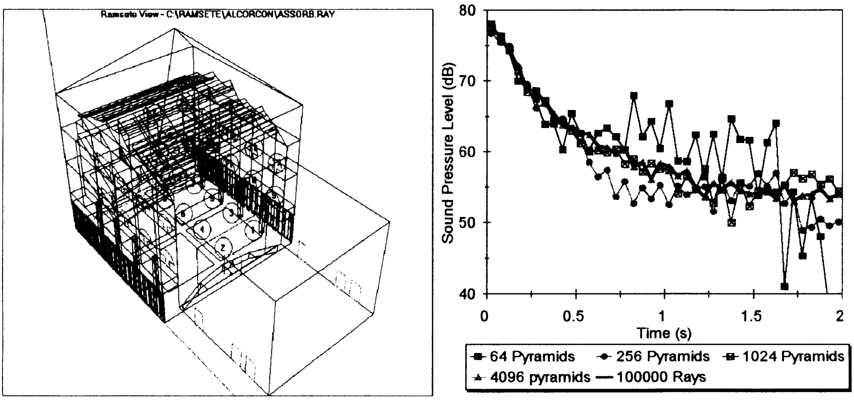

Fig. 6 - Geometry (left) and Impulse Responses (right) of coupled volumes

In this case the results show very large discrepancies with 64 Pyramids, and also with 256 pyramids the results are quite poor. Nevertheless, increasing the number of pyramids to 1024 or more, the responses become practically indistinguishable from the Ray Tracing results, while the computation times are still reasonable (7min+43s for 1024 pyramids on a 486 DX-2 66 MHz).

2.3 A very low room with non uniform absorption

Figure 7 shows both the geometry and the results obtained: the room being a typical industrial building, the most interesting acoustic property in this case is the SPL decrement (in dBA) with the source-receiver distance.

The reference results (ray tracing, 160000 rays) are compared with a single run of Ramsete (1024 pyramids), presented here with two different sets of the post-processing coefficients α and β. The first set (Ramsete1, α=1.6, β=0.2) produces results very similar to the ray tracing.

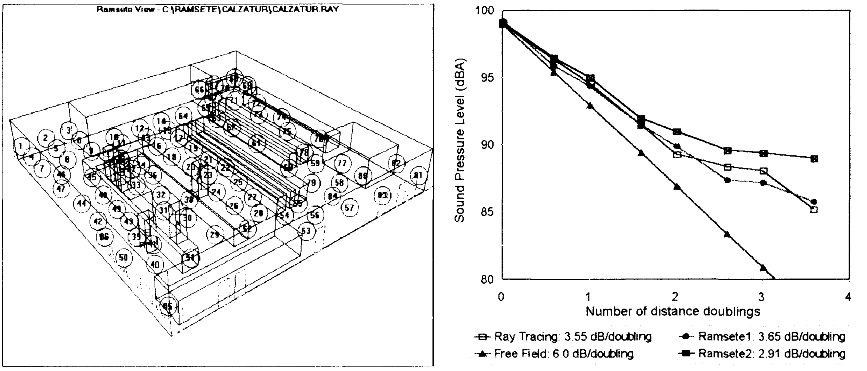

Figure 7 - A very low industrial building (with absorbing ceiling)

It must also be noted how adopting wrong values of α and β (Ramsete2) causes large SPL differences only in points very far from the source: the dotted line in fig. 7 is relative to the Sabinian values of α and β (2.0 and 0.3 respectively), and this overestimates the sound level of a maximum of 3.8 dB.

3. Conclusions

The pyramid tracing algorithm has the main advantage of being very fast, but the tail correction required is quite delicate. As it was shown here, a proper adjustment of the post-processing parameters α and β is required to obtain results comparable with a "reference" (and very slow) Ray Tracing program.

The values of the parameters that produce good results can be obtained with the simple rule used for the above cases: α and β were chosen as the values that minimise the sum of squared differences between the results obtained with two different pyramid generations (i.e. 256 and 4096 pyramids).

An automatic adjusting utility is actually being implemented to make this "self-calibration" easy for everyone.

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