Treatment of Early and Late Reflections in a Hybrid Computer Model for Room Acoustics

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ABSTRACT

The ODEON computer model for acoustics in large rooms is intended for use both in design (by predicting room acoustical indices quickly and easily) and in research (by forming the basis of an auralization system and promoting the study of various room acoustical phenomena). These conflicting demands preclude the use of either 'pure' image source or 'pure' particle tracing methods. A hybrid model has been developed, in which rays discover potential image sources up to a specified transition time or order. Thereafter the same ray tracing process is used in a different way to generate a dense reverberant decay. In this paper the computational model is described. Particular attention is paid to alternative methods of implementing the reverberant tail which avoid the problems which typically arise when joining early and late parts of a reflectogram generated with different algorithms. A companion paper [1] presents the results of calculations made with the model as implemented.

1 INTRODUCTION

The computer model discussed here is intended to be used in two ways. Firstly for research purposes, it should form the basis of a system for creating binaural room simulations. This means that the reflection sequences generated should be rich in detail and long, and that at least the early part should be as far as possible correct in its constituent reflections. At the same time ODEON should be useful to consultants in room acoustical design, providing predictions of the objective acoustical parameters of complex rooms within a reasonable time on a personal computer. The requirement of correct early reflection sequences rules out the use of a pure particle tracing technique, from which the concept of a reflected wave is absent, and suggests the use of the image source method. On the other hand the desires to obtain long rich reflection sequences and to make calculations on a personal computer are not served well by a pure image model, which would require prohibitive calculation time [2].

In recent years a number of 'hybrid' models have been developed, which contain elements of both ray tracing and image models [2-4]. These are all based on the idea that an efficient way to find branches of the image source tree having high probabilities of containing visible image sources is to trace rays from the source and note the surfaces they hit. The reflection sequences thus generated are then tested as to whether they give a contribution at the chosen receiver position, in line with image source theory. The finite number of rays used places an upper limit on the length of accurate reflectogram obtainable. Thereafter, some other method has to be used to generate a reverberant tail. This part of the task is the focus of much effort, and numerous approaches have been suggested, usually based on statistical properties of the room's geometry and absorption.

In this paper, one method will be described for generating the early reflections, and two methods for generating the reverberant tail. These three methods are all based on a two-stage process which begins with a ray tracing which functions to 'explore' the geometry of the room. The data thus generated is treated differently according to whether 'early' or 'late' reflections are being generated. We describe first the ray tracing stage of the process, followed by the method for generating early reflections, and the two methods for late reflections. In the actual implementations of these methods, the transition criterion for moving from early to late reflections is different in the two cases. Since the transition criterion is inessential to an understanding of the late reflection methods, it is in each case left unspecified until after the explanation. Special features of these computational methods (mostly for the purpose of acceleration) are described in reference [5]. These do not affect the basic principles, and are therefore not discussed here.

All the methods operate with energy variables, and no filtering is used when deriving responses.

2 RAY TRACING

For the purpose of ray tracing the following assumptions are made: Any room is composed of plane surfaces, which reflect rays specularly until some criterion is met (e.g. reflection order, path length, hitting a predefined 'diffusor'). After such a criterion has been fulfilled by a ray, it may be reflected into non-specular paths, with probabilities determined by the values of 'diffusion coefficients' assigned to surfaces. This 'diffusion' functions primarily to avoid gross errors in the late reverberation decay rate, which can occur if the ray tracing process is insufficiently 'mixing' [6]. Rays are sent out from the source and followed around the room as they become reflected, and the data thus produced is stored for use later in the determination of reflections received at a point. For a given number of rays the sequence of ray paths is only dependent on room geometry, diffusion coefficients and source position. Therefore the same ray tracing history can be used for any number of different receiver positions, for any combination of surface absorptions, and for any source directivity.

3 EARLY REFLECTIONS AT A RECEIVER

Every time a ray is reflected at a surface the position of an image source lying behind that surface is found. These image sources are sources of potential 'early reflections' and undergo rigorous checking according to Image Source Theory.

For each potential early reflection image source, it has to be determined whether that source can in fact be 'seen' from the receiver position. Once 'backtracing' [2,3] has found an image to be valid, the laws of Geometrical Acoustics are applied: The level of the corresponding reflection in the reflectogram is thus simply the product of the energy reflection coefficients of the walls involved in generating the image and the level of the source in the relevant direction of radiation. The reflection's arrival time is given by the distance to the image source and its direction is that of the image source seen from the receiver.

It is of course common for more than one ray to follow the same sequence of surfaces, and discover the same potentially valid images. It is necessary to ensure that each valid image is only accepted once, otherwise duplicate reflections would appear in the reflectogram. Therefore ODEON keeps track of the early reflection images found, by building an 'image tree'. For each flight of each ray, it is checked whether the visibility of the image source so defined has previously been determined. If so, then the process need not be repeated, and the image can be skipped.

4 LATE REFLECTIONS AT A RECEIVER

For a given image source to be discovered, it is necessary for at least one ray to follow the sequence of surfaces which define it. The longer the rays have travelled, the greater the linear distance between them, and therefore the greater the probability that a given surface is missed completely by the 'particulate wavefront' [5,7]. Thus at some point one has to give up hope of resolving all the important potential image sources, and make some other assumptions regarding the behaviour of sound in rooms (either additional to or substituted for those of Geometrical Acoustics applied for the early reflections). Many possibilities exist and have been tried out. Described here are two methods which to the best of our knowledge have not been devised elsewhere. One method is very straightforward but has some important drawbacks. The other is rather more sophisticated and better in line with real room acoustical behaviour.

4.1 'Image Source' Method for Late Reflections

With this method, the ray tracing data is used to generate positions of further image sources, just as for early reflections. The images generated are however treated in a different way, based upon a number of assumptions regarding the reverberant portion of the response;

(i) that the details of individual reflections are not of interest,
(ii) that the average build-up of reflection density in the real room follows theoretical predictions,
(iii) that the reverberant field at the receiver position is representative of that in the room as a whole,
(iv) that potential images are generated in the model at a sufficiently high rate.

If assumptions (i) and (iii) hold, then we can approximate the reverberant response at any point by that at any other, or for that matter by a reverberant response which is not specific to any point. Potential images are generated in the model at an approximately constant rate (images/second of response), determined by the number of rays N and the mean free path $\bar{l}$. An image is discovered every time a ray hits a surface, so the mean rate of potential image generation in the model is

$$I_m = \frac{cN}{\bar{l}} \tag{1}$$

According to conventional image source theory [8], the rate of reception of reflections from image sources at time t is (for sufficiently large t)

$$I_t(t) = \frac{4\pi c^3 t^2}{V} \tag{2}$$

where V is the room volume.

The ratio between the number of images expected from theory and the number of potential images generated in the model is thus:

$$\frac{I_t(t)}{I_m} = \frac{4\pi c^2 t^2 \bar{l}}{NV} \tag{3}$$

Given the homogeneous reverberant field of assumption (iii), we can state that the potential images generated by the model are representative of the true reverberant images at any point. That is, the strengths, times and directions of the individual reflections they represent are on average correct. There are however not the correct number of them, so the total energy density is wrong. We can very easily correct the energy by multiplying the strength of every image by $I_t(t) / I_m$. That is to say, accept all the potential images generated in the reverberant phase of the response as valid, and apply a time-dependent factor to their strengths to account for their incorrect total number.

Early-late Transition

In ODEON version 1.0 the early reflections are generated as described in section 3 above, and the late reflections as described in this section. The transition takes the form of a time limit; all images which lie more than a specified distance from the receiver give rise to late reflections. The transition from early to late reflections will as a rule be accompanied by a sudden jump in reflection density, as seen in Figure 1a, but the energy response will nevertheless look acceptably smooth. The sudden jump in density can be remedied by applying a 'probability-of-acceptance' rule instead of an attenuation rule to the late reflections in the interval where $I_t(t) / I_m < 1$. In this region, the probability of accepting a given reflection at time t is then given by $I_t(t) / I_m$, and no attenuation is necessary. Any differences in the values of energy indices derived with the two methods are negligible.

Although this procedure will result in an approximately correct energy response, it is not acceptable for general use unless assumptions (i) and (iv) hold. A more specific version of assumption (iv) for psychoacoustics is that the time density of potential images is high enough for the individual reflections not to be detectable as such. A glance at the expression for I_m is enough to see that this requirement is very easily met.

Advantages and Drawbacks

The combination of methods used in ODEON 1.0 has the virtue of being fairly easy for everyday practitioners and students to understand.

For auralization purposes, it is advantageous that both early and late reflections are conceptually the same: wavefronts arriving from a specified direction at a specified time, with a specified spectral content.

From assumption (iii) it can be concluded that ODEON 1.0 will not cope well with reverberation in coupled spaces, or when the reverberation process shows strong local variations.

In order to introduce some form of diffusion or 'mixing' [6] rays have to be deflected from their specular reflection paths. This leads to image sources lying in inadmissible positions (for instance the image-to-receiver distance may not always increase with reflection order), which in turn yields incorrect energy responses.

If a response is desired with a reasonably long 'early reflection' part, very large numbers of rays may be needed to resolve all the images [5].

Despite these reservations, good results can be obtained with this model in rooms which are basically convex and have a 'mixing' geometry, since diffusely diverging rays are then not essential.

4.2 'Secondary Source' Method for Late Reflections

In this method, the raytracing data is used to determine the positions of secondary sources, lying on the surfaces of the room at each collision point. Each secondary source is considered to re-radiate energy into the room which is not further reflected.

After the transition from early to late reflections, the rays are treated as transporters of energy rather than explorers of the geometry. Each time a ray hits a surface, a secondary source is generated at the collision point. If N rays have been traced, then each starts off with an N'th part of the source energy. (Note that the primary source is thereby considered to be omnidirectional for the purposes of generating reverberation.) The energy in a j'th order secondary source is then the product of this energy and all the reflection coefficients involved in the ray's history up to that point:

$$E_j = \frac{E_s}{N} \prod_{i=1}^{j} (1-\alpha_i) \tag{4}$$

where E_s is the energy of the primary source.

Each secondary source is considered to radiate into a hemisphere inside the room as an elemental area radiator. This means that the intensity reaching a receiver from a secondary source is proportional to the projected area of a notional surface element at the secondary source position, as seen from the receiver. Thus the intensity is proportional to the cosine of the angle between the surface normal at the secondary source and the vector from the secondary source to the receiver. The intensity at the receiver also falls according to the inverse square law, with the secondary source position as the origin.

The time of arrival of a late reflection is determined by the sum of the path lengths (i) from the primary source to the secondary source via any intermediate reflecting surfaces and (ii) from the secondary source to the receiver. The direction of arrival is given by the direction from the secondary source to the receiver.

A secondary source only contributes a reflection to the response if it is visible from the receiver, thus non-homogeneous reverberant fields can be modelled.

Ideally, each secondary source should send out a large number of rays which generate higher order secondary sources, and so on. This would correspond to a 'Radiosity' model of reverberation [9]. However this would clearly get out of hand very quickly, so the transport of energy to further boundaries is simulated by one ray only. This means that the number of 'energy fluxes' travelling around the room (and thus the reflection density) does not increase with reflection order as it should. The average density of late reflections is given by I_m as given in Eqn. 1. This is an upper limit, since shadowing of any room boundaries as seen from the receiver will reduce the number of secondary sources which can be seen.

Diffusion
The concept of diffusion is embodied in two aspects of the secondary source model for late reflections.

(i) If a ray is reflected from a surface in a non-specular direction, a degree of 'mixing' is introduced into the reverberation process. This is essential for the simulation of realistic decay curves. This models diffuse transport of energy from one reflection order to the next.

(ii) Each secondary source has a directivity characteristic corresponding to an aperture in a wall, behind which an ideal diffuse field exists [10]. This models diffuse re-radiation of energy from a surface which is being diffusely irradiated.

Early-late Transition
In ODEON 2.0 the early reflection model is combined with the secondary source model for late reflections, with reflection order as the transition criterion. A summary of the model is shown schematically in Figure 2. In the figure, two neighbouring rays are followed up to the sixth reflection order. The ray tracing is carried out with the early-late transition order set to 2. All the surfaces have diffusion coefficients of 1, and Lambert diffusion is operative; thus above order 2, the rays' reflection directions are chosen at random from a distribution following Lambert's law.

The two rays both find the early image sources S_1 and S_{12}. These image sources give rise to one reflection each in the response. The contributions from S, S_1 and S_{12} arrive at the receiver at times proportional to their distances from the receiver. The intensity received from a given image source is determined by the intensity of the primary source in the relevant direction and the reflection coefficients of the surfaces taking part in the generation of the image source (plus spherical spreading and air absorption).

Above order 2, each ray generates independent secondary sources situated on the reflecting surfaces. In the rectangular room these are all visible from the receiver, and thus they all give contributions to the response. The time of arrival of the contribution from a given secondary source is proportional to the sum of the ray path length from S to the secondary source plus the distance from the secondary source to the receiver. The intensity I received from a secondary source is proportional to (i) the total power P of the primary source divided by N, the number of rays, (ii) the reflection coefficients of the n surfaces upon which the ray has been reflected (including the surface upon which it is situated), and (iii) the cosine to the angle Θ between the surface normal vector and the vector from the secondary source to the receiver. Hemispherical spreading acts from the secondary source to the receiver, whilst air absorption acts along the whole path length. Thus, ignoring air absorption,

$$I = \frac{P}{N} \cdot \prod_{i=1}^{n} (1-\alpha_i) \cdot \frac{2\cos(\theta)}{2\pi r^2} \tag{5}$$

where r is the distance from the secondary source to the receiver. (The factor 2 in the numerator normalizes the radiated energy for the cosine characteristic.)

Since the boundary between 'early' and 'late' reflections is based on reflection order rather than time, the first late reflections usually arrive some time before the last of the early reflections. Thus there is typically a short period at the start of the response containing only early reflections, followed by a transition zone containing both early and late reflections and finally the remainder of the response filled with late reflections only. Figure 3 shows a typical reflectogram of early reflections. It can be seen that the density of early reflections increases up to a point and then drops again as late reflections take over. Figure 4 shows the corresponding energy response histogram and reverse-integrated decay. Note the presence now of two transitions instead of the one seen in Figure 1. The first transition line indicates the point at which the first late reflection occurs, and the second indicates the last early reflection.

Advantages and Drawbacks

The secondary source model avoids the problems found with the image source model for late reflections, and is felt to represent a better imitation of the true physical processes involved.

Again, late reflections are conceptually the same as early ones, which is an advantage for auralization systems.

One problem which occasionally occurs is attributable to the lack of splitting of rays. At a given reflection order, each secondary source has a power which takes one of many possible values. As reflection order increases, the number of possible values vastly exceeds the number of values sampled. The weight assigned to each value in the sum of energy is equal, since the distribution is unknown. Thus the occurrence of a secondary source power having very low probability can result in a poor estimate of the mean power for the given reflection order. This does not matter in terms of the total energy arriving at the receiver or early/late ratios, but an 'outlier' lying markedly above the average can lead to isolated peaks in the decay curve which disturb algorithms for automatic reverberation time estimation.

The use of a pre-specified reflection order for the transition from specular to diffuse behaviour is obviously a gross approximation to the real physics. This important parameter in the calculation needs to be chosen with some care to ensure a good prediction in a given room model. In reality, some energy is diverted from specular to diffuse paths at every reflection, until eventually the specular portion may be neglected. At present, two approaches to this are being investigated:

(i) The transition order is allowed to vary from ray to ray, and surfaces may be 'flagged' as being totally diffusing (e.g. audience, diffusors or surfaces with one or more dimension very small). Any ray hitting such a surface goes over to diffuse behaviour immediately.

(ii) Corrections are made to the energies of early specular reflections, based on Kirchhoff-Fresnel diffraction approximations [11,12]. The effect is for a high-pass filter to be applied to these reflections, with a cut-off frequency dependent on the sizes and distances of the surfaces involved in the reflection. The energy removed from the early reflections feeds new secondary sources which emit new rays.

5 CONCLUSIONS

Two complete methods for predicting the energy response from a source to a receiver have been described. Both use the same method to generate specular early reflections. The first method for generating late reflections is easy to understand but limited in its validity to rooms of basically convex form and with geometries which promote mixing. The second method for late reflections solves the problems of the first, but is less easy to grasp. The reflection order chosen for transition from early to late reflections is rather critical for the results of calculations. Under study at present are ways of making this parameter 'take care of itself'.

The ODEON 2.0 model is discussed further in a companion paper [1] with respect to prediction capabilities.

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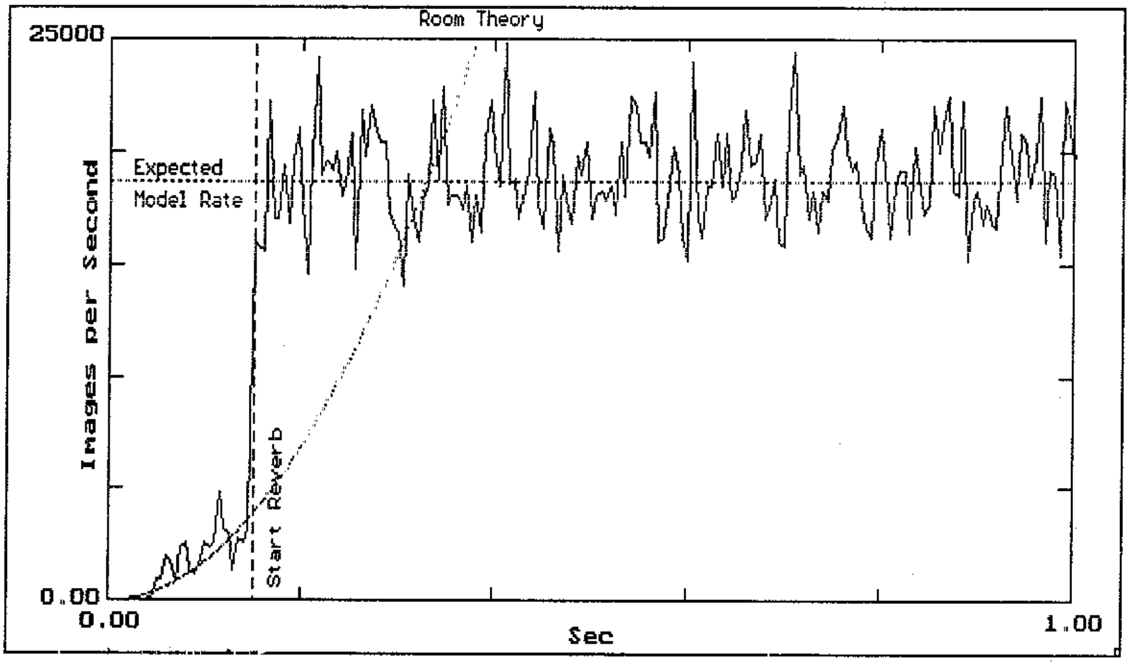
A



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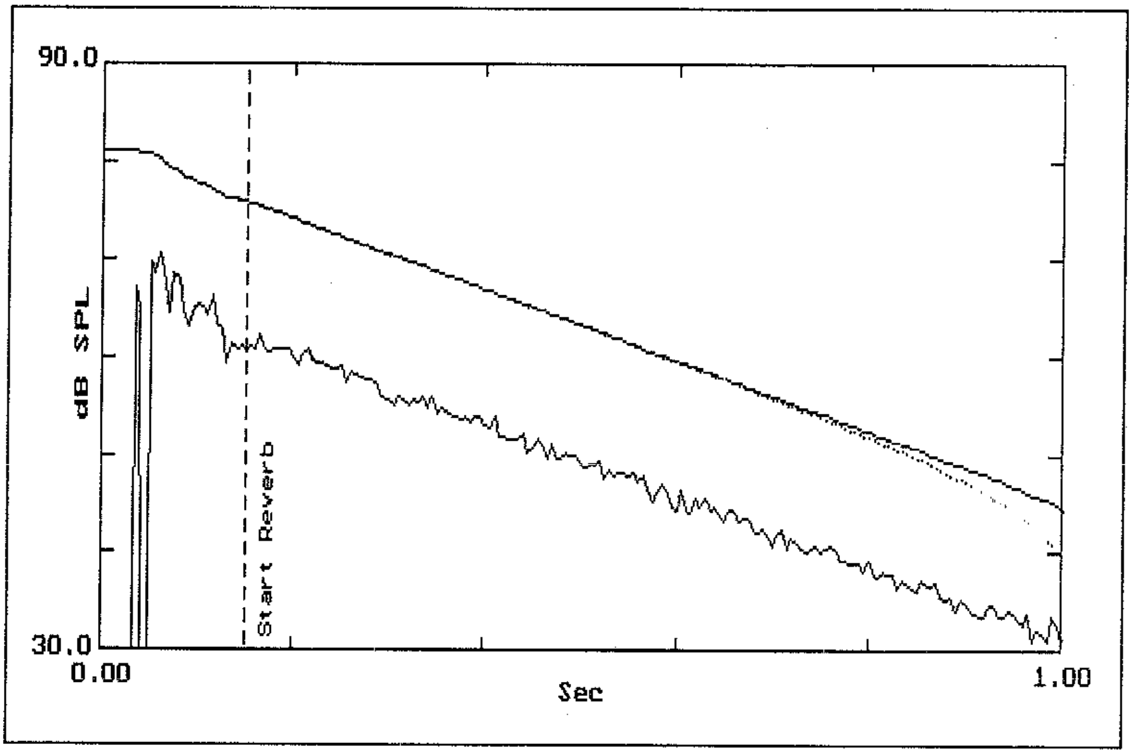

Figure 1: a) Typical result for rate of generation of accepted images in ODEON version 1.0.
b) Corresponding energy-time function and decay curve. Reverberant treatment begins 150 ms after direct sound's transmission.

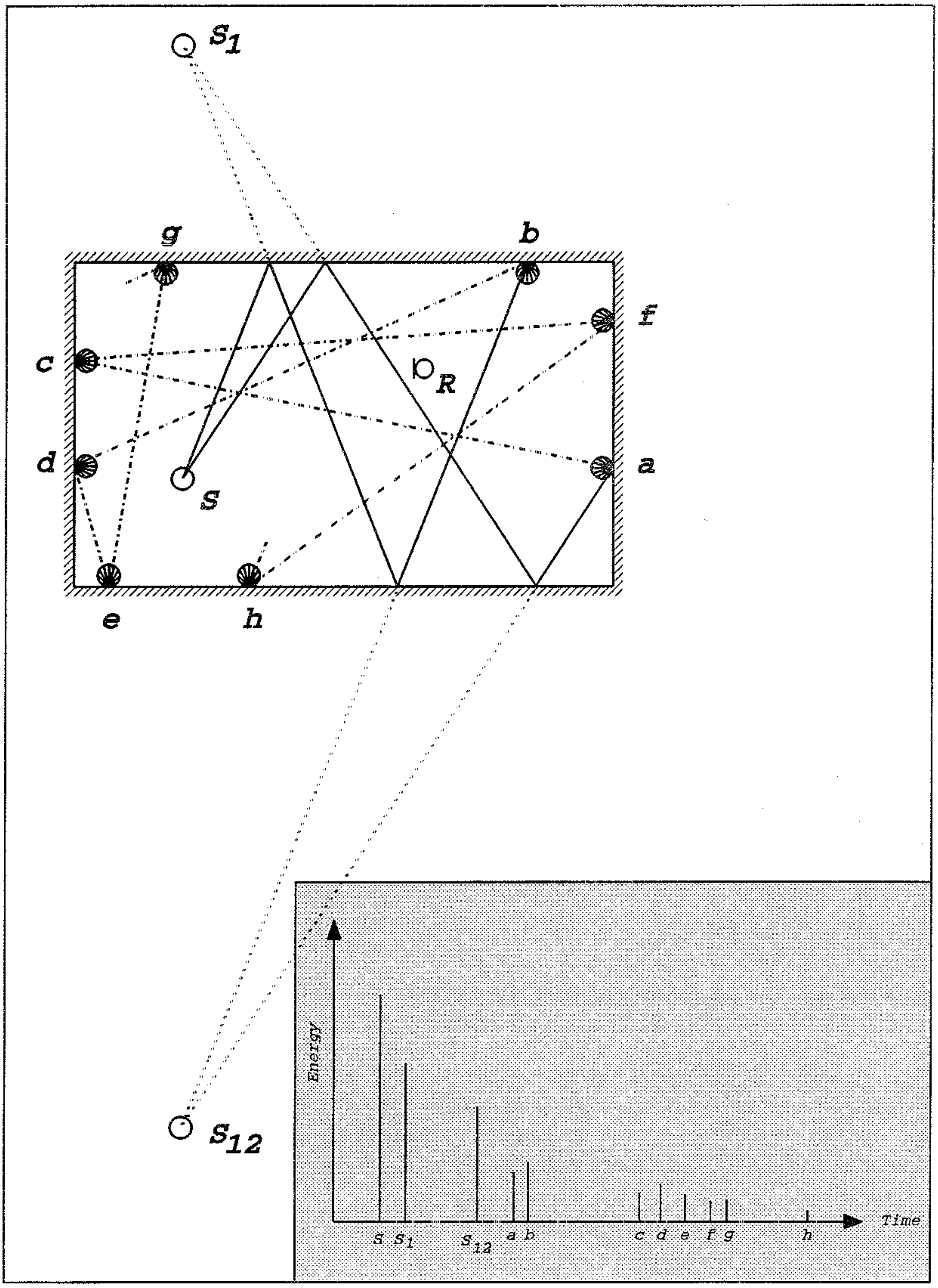

Figure 2: Summary of ODEON version 2.0 model for response calculation. Inset shows resulting reflection sequence at receiver *R*.

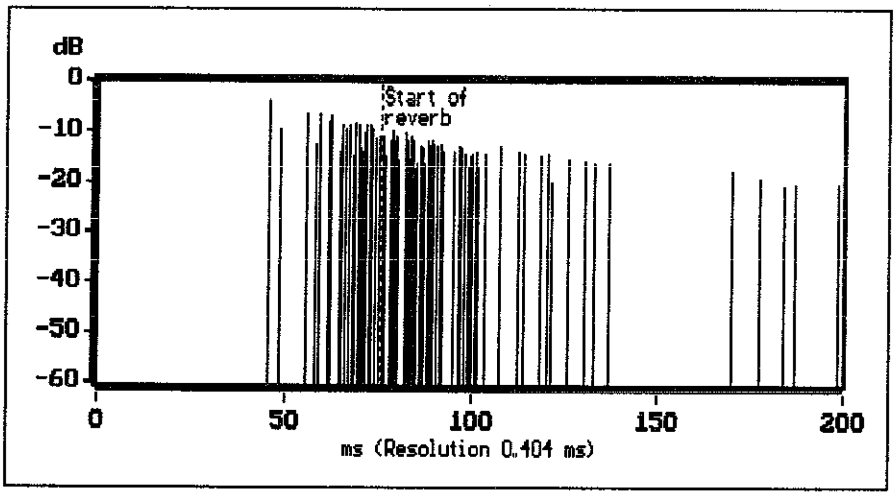

Figure 3: A reflectogram of early reflections in ODEON version 2.0. The vertical line marked 'Start of reverb' indicates the time of arrival of the earliest late reflection.

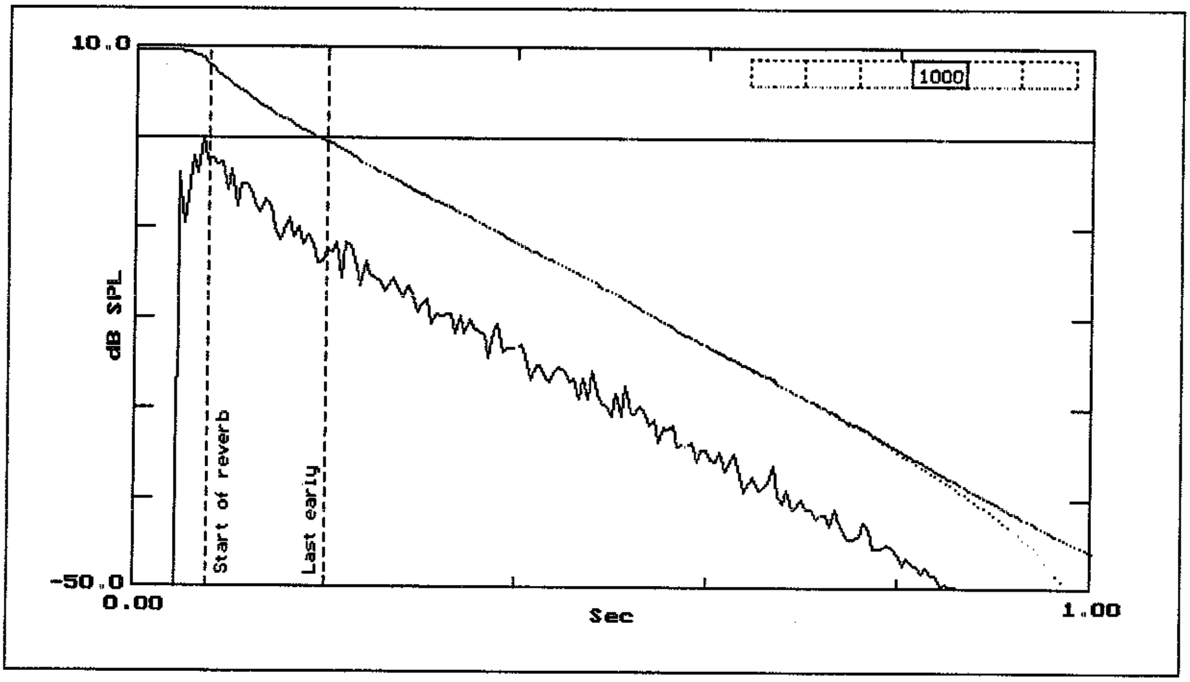

Figure 4: An energy response histogram and reverse-integrated decay curve in ODEON version 2.0.