
The Use of Computer Modeling in Room Acoustics

J. H. Rindel

Technical University of Denmark

Abstract: After decades of development room acoustical computer models have matured. Hybrid methods combine the best features from image source models and ray tracing methods and have led to significantly reduced calculation times. Due to the wave nature of sound it has been necessary to simulate scattering effects in the models. Today's room acoustical computer models have several advantages compared to scale models. They have become reliable and efficient design tools for the acoustic consultants, and the results of a simulation can be presented not only for the eyes but also for the ears with new techniques for auralisation.

Keywords: room acoustics, computer models, scattering, auralisation

NOTATION

c	speed of sound in air
i	reflection order
n	number of surfaces
s	scattering coefficient of a surface
t	time
A	area of a surface in a room
N	number of rays
N_{refl}	number of reflections
N_{sou}	number of image sources
V	volume of room

1. INTRODUCTION

In acoustics as in many other areas of physics a basic question is whether the phenomena should be described by particles or by waves. A wave model for sound propagation leads to more or less efficient methods for solving the wave equation, like the Finite Element Method (FEM) and the Boundary Element Method (BEM). Wave models are characterised by creating very accurate results at single frequencies, in fact too accurate to be useful in relation to architectural environments, where results in octave bands are usually preferred. Another problem is that the number of natural modes in a room increases approximately with the third power of the frequency, which means that for practical use wave models are typically restricted to low frequencies and small rooms, so these methods are not considered in the following.

Another possibility is to describe the sound propagation by sound particles moving around along sound rays. Such a geometrical model is well suited for sound at high frequencies and the study of interference with large, complicated structures. For the simulation of sound in large rooms there are two classical geometrical methods, namely the Ray Tracing Method and the Image Source Method. For both methods it is a problem that the wavelength or the frequency of the sound is not inherent in the model. This means that the geometrical models tend to create high order reflections, which are much more accurate than would be

possible with a real sound wave. So, the pure geometrical models should be limited to relatively low order reflections and some kind of statistical approach should be introduced in order to model higher order reflections. One way of introducing the wave nature of sound into geometrical models is by assigning a scattering coefficient to each surface. In this way the reflection from a surface can be modified from a pure specular behaviour into a more or less diffuse behaviour, which has proven to be essential for the development of computer models that can create reliable results.

2. SIMULATION OF SOUND IN ROOMS

2.1 The Ray Tracing Method

The Ray Tracing Method uses a large number of particles, which are emitted in various directions from a source point. The particles are traced around the room losing energy at each reflection according to the absorption coefficient of the surface. When a particle hits a surface it is reflected, which means that a new direction of propagation is determined e.g. according to Snell's law as known from geometrical optics. This is called a specular reflection.

In order to obtain a calculation result related to a specific receiver position it is necessary either to define an area or a volume around the receiver in order to catch the particles when travelling by, or the sound rays may be considered the axis of a wedge or pyramid. In any case there is a risk of collecting false reflections and that some possible reflection paths are not found. There is a reasonable high probability that a ray will discover a surface with the area A after having travelled the time t if the area of the wave front per ray is not larger than $A/2$. This leads to the minimum number of rays N

$$N \geq \frac{8 \pi c^2}{A} t^2 \quad (1)$$

where c is the speed of sound in air. According to this equation a very large number of rays is necessary for a typical room. As an example a minimum surface area of 10 m^2 and propagation time up to only 600 ms lead to around 100,000 rays as a minimum.

The development of room acoustical ray tracing models started some thirty years ago but the first models were mainly meant to give plots for visual inspection of the distribution of

The Journal was received on 1 August 2000 and was accepted for publication on 10 September 2000.

reflections [1]. The method was further developed [2], and in order to calculate a point response the rays were transferred into circular cones with special density functions, which should compensate for the overlap between neighbouring cones [3]. However, it was not possible to obtain a reasonable accuracy with this technique. Recently, ray tracing models have been developed that use triangular pyramids instead of circular cones [4], and this may be a way to overcome the problem of overlapping cones.

2.2 The Image Source Method

The Image Source Method is based on the principle, that a specular reflection can be constructed geometrically by mirroring the source in the plane of the reflecting surface. In a rectangular box-shaped room it is very simple to construct all image sources up to a certain order of reflection, and from this it can be deduced that if the volume of the room is V , the approximate number of image sources within a radius of ct is

$$N_{refl} = \frac{4\pi c^3}{3V} t^3 \quad (2)$$

This is an estimate of the number of reflections that will arrive at a receiver up to the time t after sound emission, and statistically this equation holds for any room geometry. In a typical auditorium there is often a higher density of early reflections, but this will be compensated by fewer late reflections, so on average the number of reflections increases with time in the third power according to (2).

The advantage of the image source method is that it is very accurate, but if the room is not a simple rectangular box there is a problem. With n surfaces there will be n possible image sources of first order and each of these can create $(n-1)$ second order image sources. Up to the reflection order i the number of possible image sources N_{sou} will be

$$N_{sou} = 1 + \frac{n}{(n-2)} ((n-1)^i - 1) \approx (n-1)^i \quad (3)$$

As an example we consider a 15,000 m³ room modelled by 30 surfaces. The mean free path will be around 16 m which means that in order to calculate reflections up to 600 ms a reflection order of $i = 13$ is needed. Thus equation (3) shows that the number of possible image sources is approximately $N_{sou} = 29^{13} \approx 10^{19}$. The calculations explode because of the exponential increase with reflection order. If a specific receiver position is considered it turns out that most of the image sources do not contribute reflections, so most of the calculation efforts will be in vain. From equation (2) it appears that less than 2500 of the 10^{19} image sources are valid for a specific receiver. For this reason image source models are only used for simple rectangular rooms or in such cases where low order reflections are sufficient, e.g. for design of loudspeaker systems in non-reverberant enclosures [5, 6].

2.3 The Hybrid Methods

The disadvantages of the two classical methods have led to development of hybrid models, which combine the best features of both methods [7, 8, 9]. The idea is that an efficient way to find image sources having high probabilities of being valid 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. This is called a visibility test and it can be performed as a tracing back from the receiver towards the image source. This leads to a sequence of reflections, which must be the reverse of the sequence of reflecting walls creating the image source. Once 'backtracing' has found an image to be valid, then the level of the corresponding reflection is simply the product of the energy reflection coefficients of the walls involved and the level of the source in the relevant direction of radiation. The distance to the image source gives the arrival time of the reflection.

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 and cause errors. Therefore it is necessary to keep track of the early reflection images found, by building an 'image tree'.

For a given image source to be discovered, it is necessary for at least one ray to follow the sequence which define it. 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 reverberation 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. One method, which has proven to be efficient, is the 'secondary source' method used in the ODEON program [9]. This method is outlined in the following.

After the transition from early to late reflections, the rays are treated as carriers of energy rather than explorers of the geometry. Each time a ray hits a surface, a secondary source is generated at the collision point. The energy of the secondary source is the total energy of the primary source divided by the number of rays and multiplied by the reflection coefficients of the surfaces involved in the ray's history up to that point. Each secondary source is considered to radiate into a hemisphere as an elemental area radiator. Thus the intensity is proportional to the cosine of the angle between the surface normal and the vector from the secondary source to the receiver. The intensity of the reflection 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 reflection is determined by the sum of the path lengths from the primary source to the secondary source via intermediate reflecting surfaces and the distance from the secondary source to the receiver. As for the early reflections a visibility test is made to ensure that a secondary source only contributes a reflection if it is visible from the receiver. Thus the late reflections are specific to a certain receiver position and it is possible to take shielding and convex room shapes into account.

Figure 1 illustrates in schematic form how the calculation model behaves. In the figure, two neighbouring rays are followed up to the sixth reflection order. The transition order is set to 2, so above this order the rays' reflection directions are chosen at random from a distribution following Lambert's law (see later). The first two reflections are specular, and both rays find the image sources S_1 and S_{12} . These image sources give rise to one reflection each in the response, since they are visible from the receiver point R . In a

more complicated room this might not be true for all image sources. The contributions from S , S_1 and S_{12} arrive at the receiver at times proportional to their distances from the receiver. Above order 2, each ray generates independent secondary sources situated on the reflecting surfaces. In the simple box-shaped room these are all visible from the receiver, and thus they all give contributions to the response. In Figure 2 is displayed the response identifying the contributions from the source, the two image sources and the eight secondary sources.

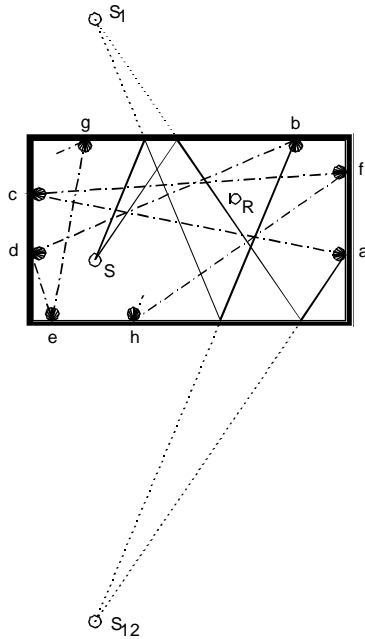


Fig. 1. Principle of a hybrid model. The rays create image sources for early reflections and secondary sources on the walls for late reflections

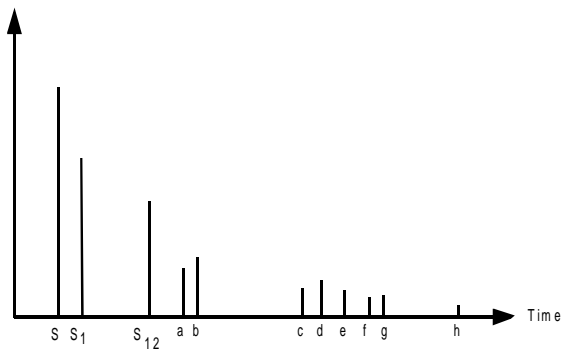


Fig. 2. Reflectogram for the receiver R in Fig. 1

In a complete calculation the last early reflection (from an image source) will typically arrive after the first late reflection (from a secondary source), so there will be a time interval where the two methods overlap. This is indicated on the calculated energy response curve in Figure 3. Also shown is the decay curve, which is the reverse-integrated impulse response. This is used for calculation of reverberation time and other room acoustical parameters.

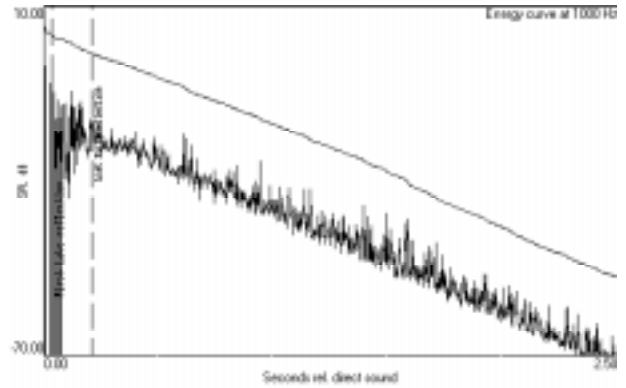


Fig. 3. Energy response curve and decay curve calculated with a hybrid model

In the hybrid model described above it is a critical point at which reflection order the transition is made from early to late reflections. Since the early reflections are determined more accurately than the late reflections one might think that better results are obtained with the transition order as high as possible. However, for a given number of rays the chance of missing some images increases with reflection order and with the number of small surfaces in the room. This suggests that the number of rays should be as large as possible, limited only by patience and computer capacity. However, there are two things, which make this conclusion wrong. Firstly, the probability of an image being visible from the receiver decreases with the size of the surfaces taking part in its generation, so the number of reflections missed due to insufficient rays will be much fewer than the number of potential images missed. Secondly, in real life, reflections from small surfaces are generally much weaker than calculated by the laws of geometrical acoustics, so any such reflections missed by the model are in reality of less significance than the model itself would suggest. Actually, the efforts of an extended calculation may lead to worse results.

Recent experiments with the ODEON program have shown that only 500 to 1000 rays are sufficient to obtain reliable results in a typical auditorium, and an optimum transition order has been found to be two or three. This means that a hybrid model like this can give much better results than both of the pure basic methods and with much shorter calculation time. However, this good news is closely related to the introduction of diffusion in the model.

3. DIFFUSION OF SOUND IN COMPUTER MODELS

The scattering of sound from surfaces can be quantified by a scattering coefficient, which may be defined as follows: The scattering coefficient s of a surface is the ratio between reflected sound power in non-specular directions and the total reflected sound power. The definition applies for a certain angle of incidence, and the reflected power is supposed to be either specularly reflected or scattered. The scattering coefficient may take values between 0 and 1, where $s = 0$

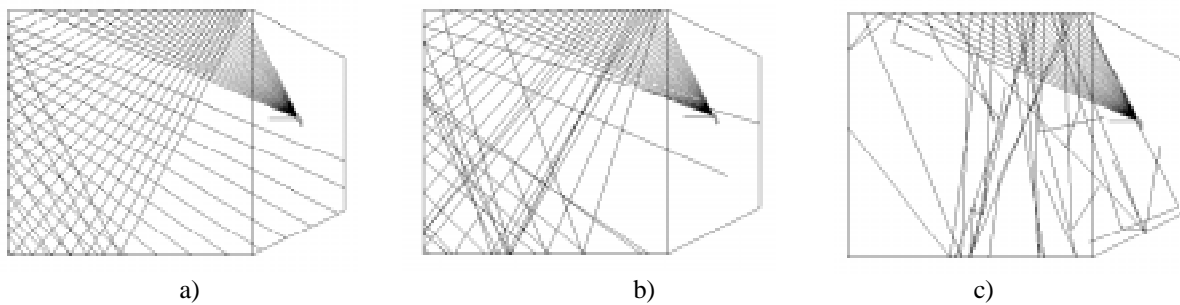


Fig. 4. Reflections of rays with different scattering coefficients of the surfaces. a: $s = 0$, b: $s = 0.2$, c: $s = 1$.

means purely specular reflection and $s = 1$ means, that all reflected power is scattered according to some kind of 'ideal' diffusivity. One weakness of the definition is, that it does not say how the directional distribution of the scattered power is; even if $s = 1$ the directional distribution could be very uneven.

Diffuse reflections can be simulated in computer models by statistical methods [10]. Using random numbers the direction of a diffuse reflection is calculated with a probability function according to Lambert's cosine-law, while the direction of a specular reflection is calculated according to Snell's law. A scattering coefficient between 0 and 1 is then used as a weighting factor in averaging the co-ordinates of the two directional vectors, which correspond to diffuse or specular reflection, respectively.

An example of ray reflections with different values of the scattering coefficient is shown in Fig. 4. For simplicity the example is shown in two dimensions, but the scattering is three-dimensional. All surfaces are assigned the same scattering coefficient. Without scattering the ray tracing displays a simple geometrical pattern due to specular reflections. A scattering coefficient of 0.20 is sufficient to obtain a more diffuse result.

By comparison of computer simulations and measured reverberation times in some cases where the absorption coefficient is known, it has been found that the scattering coefficient should normally be set to around 0.1 for large, plane surfaces and to around 0.7 for highly irregular surfaces. Scattering coefficients as low as 0.02 have been found in studies of a reverberation chamber without diffusing elements. The extreme values of 0 and 1 should be avoided in computer simulations, as they are not realistic. In principle the scattering coefficient varies with the frequency - scattering due to the finite size of a surface is most pronounced at low frequencies, whereas scattering due to irregularities of the surface occurs at high frequencies.

It is a big problem how to get information about scattering coefficients of surfaces. For that reason ISO has started a working group with the purpose to describe a measuring method for the scattering coefficient of surfaces, [11].

4. ACCURACY AND CALCULATION TIME

Recently an international round robin has been carried out [12] with 16 participants; most of them developers of

software for room acoustical simulations. In a 1800 m³ auditorium eight acoustical criteria as defined in [13] were calculated for the 1kHz octave band in the ten combinations of two source positions and five receiver positions. Seven different participants made measurements in the same positions and the average results were used for comparison. Drawings, photos, material descriptions and absorption coefficients were provided. It came out that only three programs could be assumed to give unquestionably reliable results. The results of these programs differ from the average measurement results by the same order of magnitude as the individual measurement results. So, the reproducibility of the best computer simulations can be said to be as good as a measurement, which is quite satisfactory. It is interesting to note that the best programs use some kind of diffuse reflections, whereas the results from purely specular models were more outlying. It is also typical that the best programs do neither require extremely long calculation times nor extremely detailed room geometries.

5. ADVANTAGES OF COMPUTER MODELS COMPARED TO SCALE MODELS

It is quite obvious that a computer model is much more flexible than a scale model. It is easy to modify the geometry of a computer model, and the surface materials can easily be changed by changing the absorption coefficients. The computer model is fast, typically a new set of results are available a few hours after some changes to the model have been proposed. But the advantages are not restricted to time and costs. The most important advantage is probably that the results can be visualised and analysed much better because a computer model contains more information than a set of measurements done in a scale model with small microphones.

5.1 The Reflectogram as a Tool

The reflectogram displays the arrival of early reflections to a receiver. When the early reflections are calculated from detected image sources, it follows that each single reflection can be separated independently. In addition to arrival time and energy of the reflection, it is also possible to get information about the direction and which surfaces are involved in the reflection path. The latter can be very useful if

a particular reflection should be removed or modified, e.g. to avoid an echo problem.

5.2 Display of Reflection Paths

The reflection paths for all early reflections may be visualised in 3D and analysed in detail. An example is shown in Fig. 5. During the design of a room it may be interesting to see which surfaces are active in creating the early reflections. Although it is difficult to extract specific results from such a spatial analysis, it can help to understand how a room responds to sound.

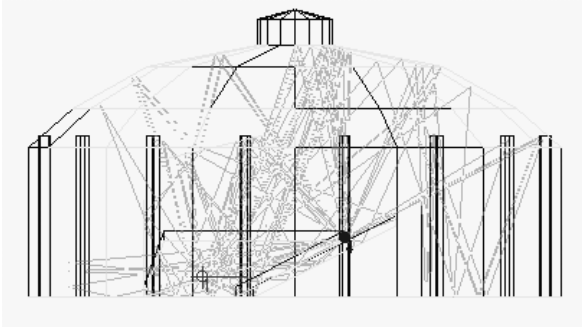


Fig. 5. Reflection paths up to third order from a source to a receiver

5.3 Grid Response Displays

With a computer model it is straightforward to calculate the response at a large number of receivers distributed in a grid that covers the audience area. An example is shown in Fig. 6. It can be extremely useful for the acoustic designer to see a mapping of the spatial distribution of acoustical parameters. Uneven sound distribution and acoustically weak spots can easily be localised and appropriate countermeasures can be taken.

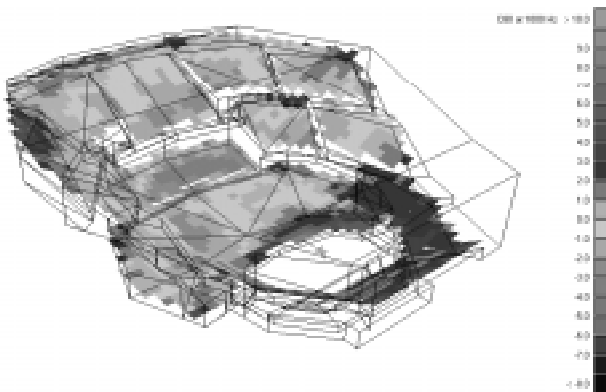


Fig. 6. Mapping of an acoustic parameter calculated in a grid that covers the audience area in a concert hall

5.4 Auralisation

It is an old idea that it might be possible to listen to sound in a room by a simulation technique using the impulse response from a room model. This technique, to make a room model audible, has been called auralisation (in analogy to visualisation), see Kleiner et al. [14] for an overview.

The auralisation technique offers the possibility to use the ears and listen to the acoustics of a room already during the design process. Several acoustical problems in a room can

easily be detected with the ears, whereas they may be difficult to express with a parameter that can be calculated.

In principle it is possible to use impulse responses measured in a scale model for auralisation. However, the quality may suffer seriously due to non-ideal transducers. The transducers are one reason that the computer model is superior for auralisation. Another reason is that the information about each reflection's direction of arrival allows a more sophisticated modelling of the listener's head-related transfer function.

The auralisation options available in the ODEON programme are based on binaural technology allowing three-dimensional presentation of the predicted acoustics over headphones. In the receiver point the BRIR (Binaural Room Impulse Response) is calculated. This is a pair of impulse responses, one for each ear of a listening person with the head in the receiver position. An example of a calculated BRIR is shown in Fig. 7. The HRTF (Head Related Transfer Function) used for this calculation is taken from an artificial head, which represents an average human head. The listening signal is an anechoic recording, which can be speech, song, music, hand clapping or whatever could be relevant for a listening test. This anechoic signal is brought into the room by a convolution of the signal with the calculated BRIR. All calculations including the ray tracing, received reflections at a receiver point, binaural filtering and convolution are carried out by ODEON in a one step process, so there is no need for pre- or post processing. The binaural filtering is highly optimised and includes complete room and binaural filtering of each reflection.

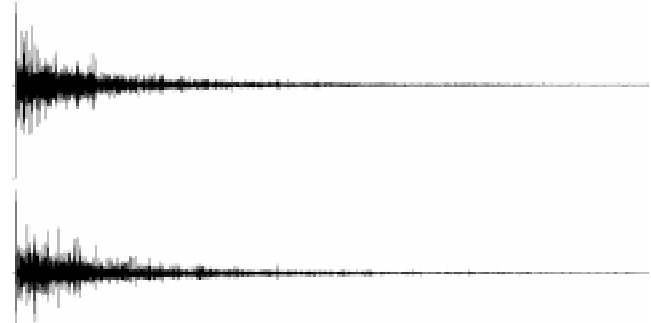


Fig. 7. A calculated pair of impulse responses (BRIR) that can be used for auralisation

Full filtering is essential for a high quality auralisation that allows simulation of special room acoustic effects like coupled rooms, frequency dependent reverberation etc. Typical 10.000 – 100.000 reflections are used, and the sampling frequency is 44.1 kHz. Calculation time is approximately 20 seconds for creating the BRIR, and the time for the convolution is approximately the same as the length of the signal on a computer with 600 MHz clock frequency.

6. CONCLUSION

Computer techniques for simulation of sound in rooms have improved significantly in recent years, and for the consultant the computer model offers several advantages compared to the scale model. The scattering of sound from

surfaces has appeared to be very important in room acoustical simulation technique, and this has created a need for better information about the scattering properties of materials and structures. Although the model can handle the scattering, the knowledge about which scattering coefficients to use is still very sparse. However, a measuring method for the scattering coefficient is being developed by ISO.

REFERENCES

1. A. Krokstad, S. Stroem, & S. Soersdal, "Calculating the Acoustical Room Response by the use of a Ray Tracing Technique" *J. Sound Vib.* **8**, 118-125 (1968).
2. A. Kulowski, "Algorithmic Representation of the Ray Tracing Technique" *Applied Acoustics* **18**, 449-469 (1985).
3. J.P. Vian, & D. van Maercke, "Calculation of the Room Impulse Response using a Ray-Tracing Method" Proc. *ICA Symposium on Acoustics and Theatre Planning for the Performing Arts*, Vancouver, Canada (1986) pp. 74-78.
4. T. Lewers, "A Combined Beam Tracing and Radiant Exchange Computer Model of Room Acoustics" *Applied Acoustics* **38**, 161-178 (1993).
5. J.B. Allen, & D.A. Berkley, "Image method for efficiently simulating small-room acoustics" *J. Acoust. Soc. Am.* **65**, 943-950 (1979).
6. J. Borish, "Extension of the image model to arbitrary polyhedra" *J. Acoust. Soc. Am.* **75**, 1827-1836 (1984).
7. M. Vorländer, "Simulation of the transient and steady-state sound propagation in rooms using a new combined ray-tracing/image-source algorithm" *J. Acoust. Soc. Am.* **86**, 172-178 (1989).
8. G.M. Naylor, "ODEON - Another Hybrid Room Acoustical Model" *Applied Acoustics* **38**, 131-143 (1993).
9. G.M. Naylor, "Treatment of Early and Late Reflections in a Hybrid Computer Model for Room Acoustics" *124th ASA Meeting*, New Orleans (1992) Paper 3aAA2.
10. U. Stephenson, "Eine Schallteilchen-computer-simulation zur Berechnung für die Hörsamkeit in Konzertsälen massgebenden Parameter". *Acustica* **59**, 1-20 (1985).
11. ISO/CD 17497. Acoustics – Measurement of the random-incidence scattering coefficient of surfaces. July 2000.
12. M. Vorländer, "International Round Robin on Room Acoustical Computer Simulations" Proc. *15th International Congress on Acoustics*, Trondheim, Norway (1995) vol.II pp. 689-692.
13. ISO 3382 "Measurement of the reverberation time of rooms with reference to other acoustical parameters" (1997).
14. M. Kleiner, B.-I. Dalenbäck & P. Svensson, "Auralization - An Overview," *J. Audio Eng. Soc.* **41**, 861-875 (1993).