Evaluation of room acoustic qualities and defects by use of auralization

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ABSTRACT

Auralizations generated by room acoustic computer modeling programs may be used as a tool for evaluation of acoustic qualities and defects, some of which are not easily detected by objective measures. Examples include reverberance, flutter echoes, perceived room size and distance, apparent source width, listener envelopment, and sound propagation in coupled rooms. In order to reach a sufficiently high level of realism in auralizations for such room acoustic applications it is necessary that all parts of the simulation chain are modeled with sufficient accuracy. In particular it is found that the modeling of source directivity and the late room reflections (the reverberation tail) need careful consideration in order to achieve reliable and realistic sounding results. However, when implemented in the software the application for practical use can be simple and quick.
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INTRODUCTION

Auralization is a technique that has developed to a state that allows many useful applications in research and in room acoustic design. The acoustic quality in the state-of-the-art auralization may be sufficient if the purpose of auralization is to demonstrate the difference between alternative room acoustic designs that give different reverberation times, or to demonstrate the difference between basic room shapes like rectangular, fan shape, circular shape etc. [1]. The modeling of the transfer function or room impulse response from source to receiver, and the modeling of the receiver by a head related transfer function (HRTF) was first simplified by combining a reverberation tail with a number of more accurately calculated early reflections [2]. Although this principle is still being used in some room acoustic programs, it obviously has the drawback that echoes and other room acoustical defects cannot be simulated. The software that was used for all the auralization examples described in the following is ODEON 6.5 which calculates the late reflections by a very accurate ray tracing – radiosity method; see the annex for a brief description. Using this method a very satisfactory agreement with dummy head recordings in real rooms with a complicated geometry has been obtained [3, 4].

The aim of the present paper is to demonstrate through examples that auralization can be an important tool for evaluation of acoustical qualities and defects in room designs. Actually, the ability to demonstrate room acoustical defects is by far the most important requirement for auralization to be accepted as a design tool; it is little helpful to auralize the qualities, if there is no warning for possible defects.

THE AURALIZATION CHAIN

Auralization is the result of a long chain of modeling, assumptions, approximations, and calculations. Logically, the chain can be considered from the source to the receiver:

- **Source**
  - Anechoic recording, microphone position(s)
  - Directivity, resolution in frequency and space
  - Modelling – normally a point source
- **Room**
  - Reflections, scattering
  - Early and late reflections, 3D incidence, RIR
- **Receiver**
  - HRTF, generation of BRIR
  - Reproduction method (headphone/loudspeakers)
  - Level of reproduction, calibration

Being a long chain, it is obvious that the quality of the auralization is mostly influenced by the weakest link in the chain. Since the introduction of auralization a lot of efforts have been devoted to the accurate modeling of the receiver, with emphasis on localization, the front-back confusion etc. The importance of modeling the source directivity has been studied recently and currently a new multi-channel method is being developed as an attempt to improve this part of the chain [5 - 9]. However, when auralization is used as a tool for room design, which is to focus of the present paper, the accurate room modeling is by far the most important part of the chain. If the auralization results are presented through loudspeakers instead of headphones, what is often the case, there is obviously no need for the HRTFs, and the accurate receiver modeling is the least important part of the simulation. However, the level of reproduction should always be considered with great care.

ROOM ACOUSTIC QUALITIES

The goal of the auralizations in relation to room design can be divided into qualities and defects. Some of the room acoustic qualities that auralization should make audible could be:
- Reverberance (early decay)
- Clarity
- Strength
- Localization of source
- Apparent source width (ASW)
- Listener envelopment (LEV)
- Balance between stage and pit for opera

ROOM ACOUSTIC DEFECTS

Some of the room acoustic defects that auralization should make audible could be:
- Too much reverberation
- Echo
- Flutter echo
- Coloration due to periodic reflections
- Delayed sound from coupled volumes

Although the qualities may be the goal in any acoustical design, the possible defects are actually the more important ones for auralization, if this is considered a useful tool in the design process. The main reason for using auralization in addition to the more objective figures and numbers delivered by the simulation tools is the possibility of using the ears for detection of some possible acoustic problems, not clearly reflected in the objective acoustic parameters.

ECHO IN A SPORTS STADIUM

The Danish National football stadium in Copenhagen is also used for concerts. A sliding roof (140 m x 94 m) was constructed for the purpose of the European Song Contest in May 2001. The ODEON software was used for the simulation of the acoustical conditions with the new roof design. The simulations were made with the planned loudspeakers as sound sources including directivity and time delays, and with the planned acoustic treatment of the surfaces. The volume is 800.000 m^3 and the measured RT at mid frequencies is 2,3 s. The main problem was to avoid audible reflections, and for that purpose the auralization function was found very useful [10].

In the presentation the echo problems are auralized by using a trumpet as a single source on the stage, see fig. 1. The calculated reflectogram in a receiver position at the rear balcony is shown in fig. 2.
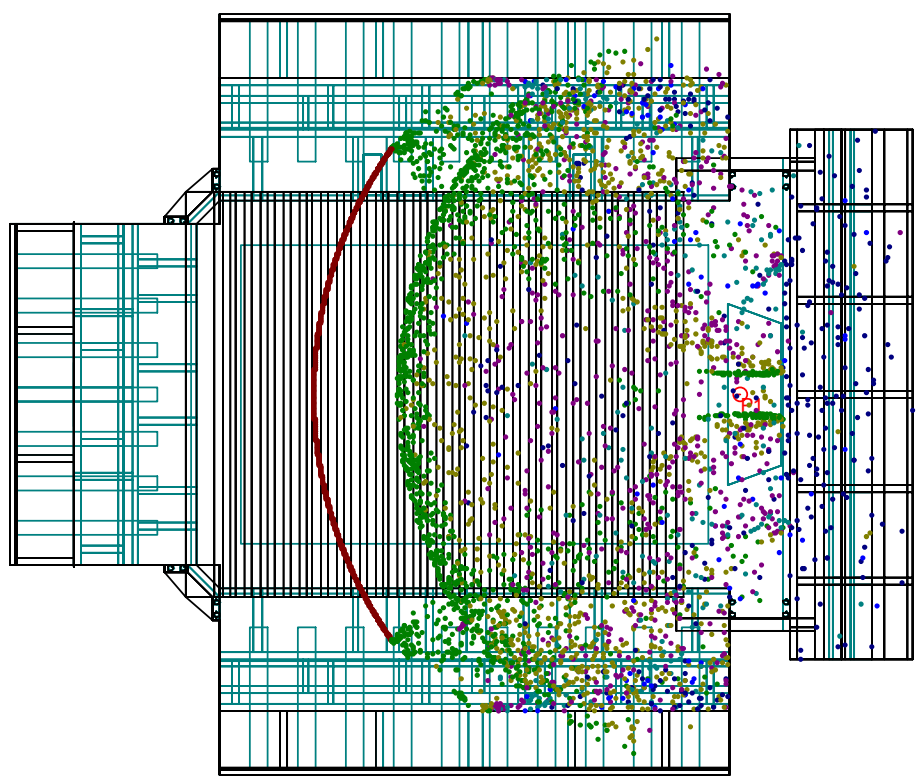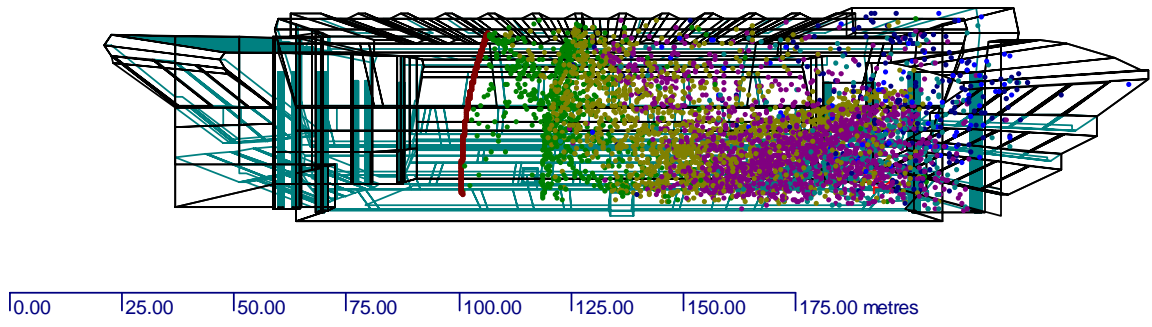
Fig. 1. Section and plan of the roofed sports stadium. A source position is shown on the stage and balls indicate a spherical wavefront after 95 m of propagation.
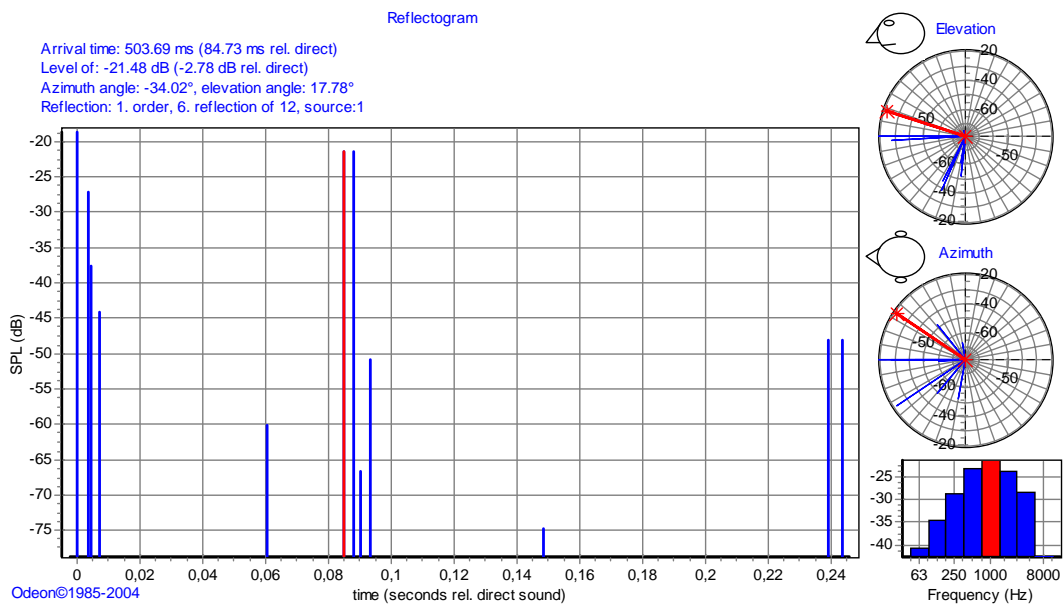
Fig. 2. Reflectogram showing 1st and 2nd order reflections in a receiver point at the rear balcony. Strong reflections arrive with a delay around 85 ms which causes an audible echo.

FLUTTER ECHO IN AN OPEN YARD

This example is an open yard called 'Grønnegaard' in Copenhagen. In the summer time this place is used for concerts and theatre performance. Main dimensions: 84 x 60 m and the height of surrounding building facades varies between 4,1 m and 9,2 m. The measured reverberation time at mid frequencies (500 – 1000 Hz) is 1,7 s. The auralizations demonstrate strong series of echoes, which becomes even stronger when the trees are removed from the model. For further details see ref. [11]


Fig. 3. A view into the digital model of the yard. The threes are modelled to be scattering and partly transparent.

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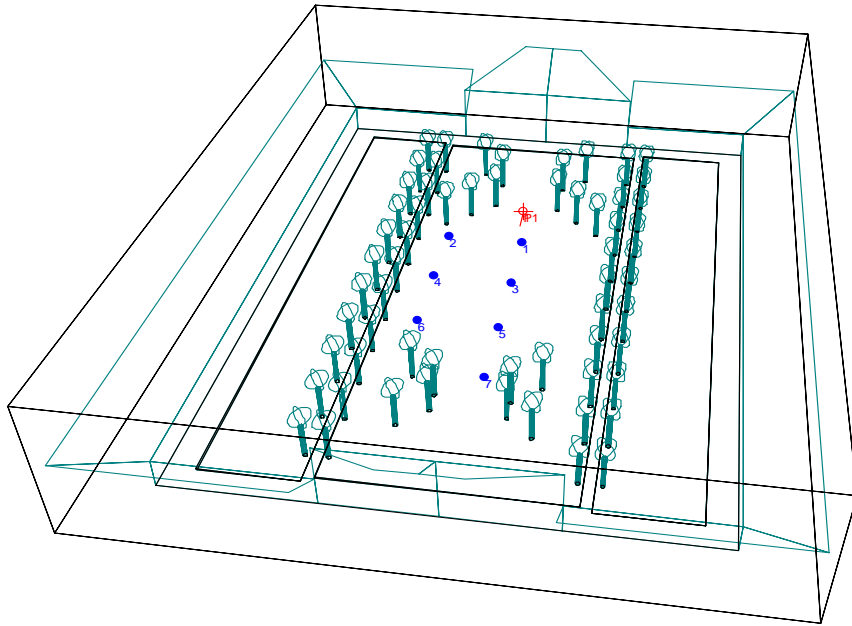
Fig. 4. The digital model with a source position and seven receiver positions. Receiver 5 is used for the suralization.

FLUTTER ECHO IN A CHAMBER MUSIC HALL

A strong flutter echo is demonstrated in the computer model of a small concert hall, The Queens Hall, Copenhagen, see Fig. 5. Shortly before the inauguration the problem was recognized and diffusing panels were installed on the side walls. As demonstrated in the auralizations, the diffusers make an audible difference by practically removing the flutter echo.
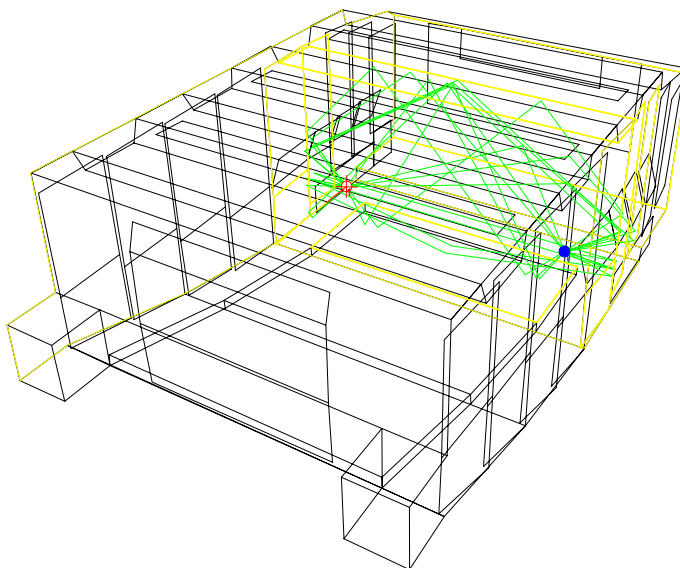
Fig. 5. Early reflections with source and receiver in front of the stage.
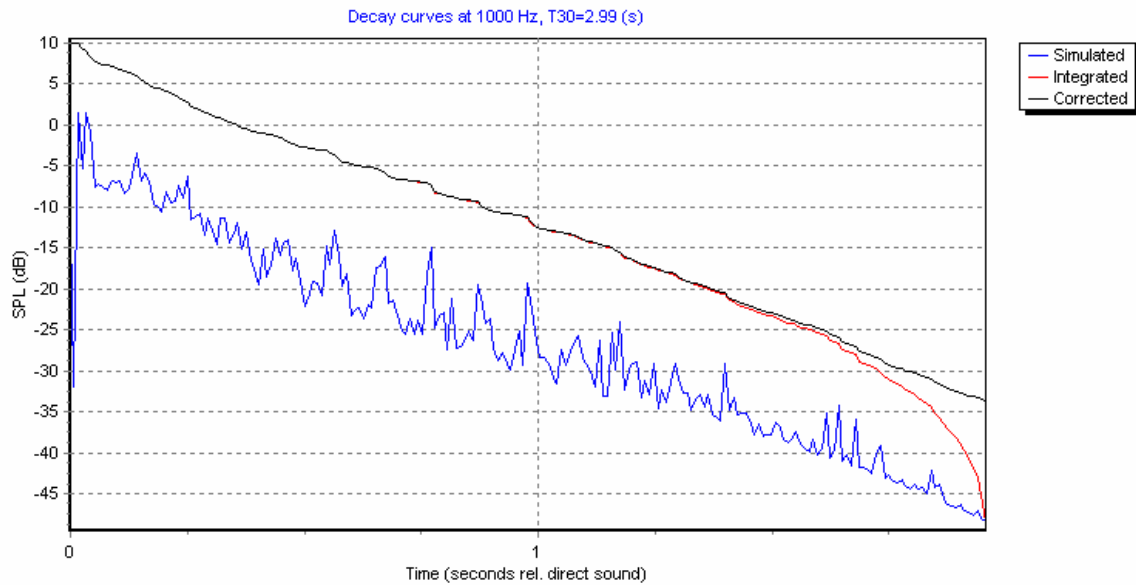
Fig. 6. Calculated decay curve and integrated impulse response (Schroeder curve) at 1000 Hz in the case of smooth side walls.

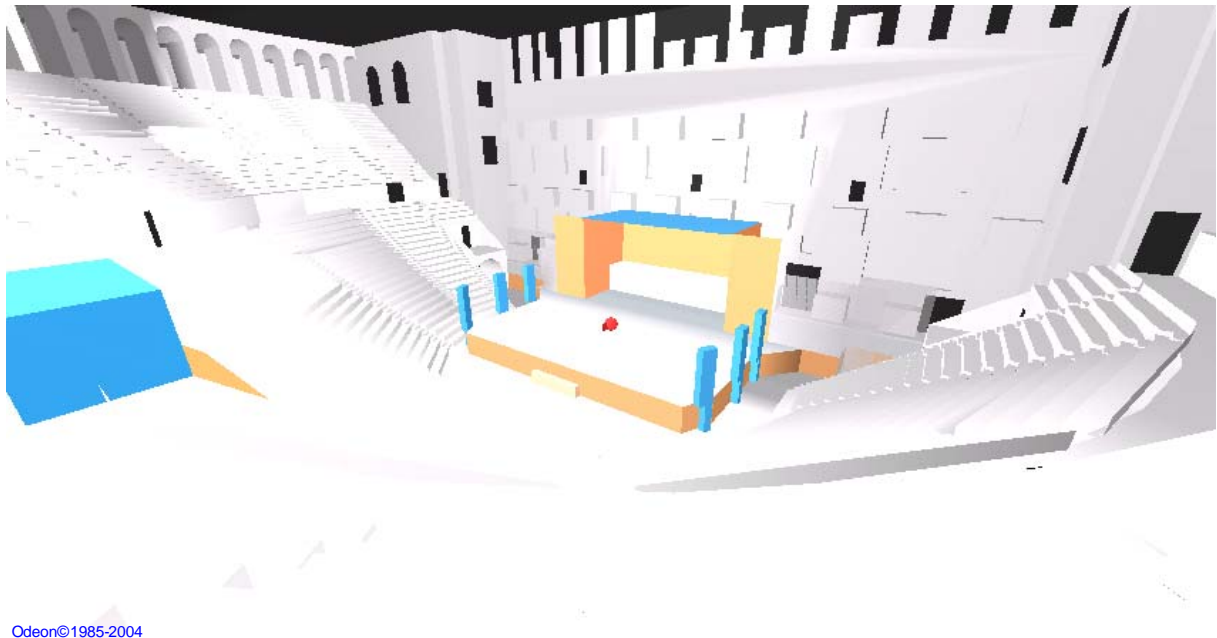**SURFACE SCATTERING IN AN OPEN AIR THEATRE**

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Fig. 7. A view into the digital model of the Roman theatre in Aspendos equipped with a modern stage.

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This example is from a model of the Roman theatre in Aspendos, Turkey. As seen in fig. 7 there is a modern stage included, as was the case when acoustic measurements mere made in the theatre. A scattering coefficient of 0,7 was applied to the seating area, 0,4 to the proscenium, and 0,2 to all other surfaces. There was no need of frequency dependent scattering coefficients to get a good match with measured reverberation time in the whole frequency range, 125 – 4000 Hz, se ref. [12, 13].

Two examples of auralization are presented, one with the realistic high scattering of the seating area, and one with no scattering at all. Without the scattering the decay curves show a double slope, see fig. 8, and a much longer reverberation time is calculated. However, the initial decay is not affected, and it is interesting to observe that the clarity, strength and several other acoustic parameters have practically not changed, see Table 1. When listening to the two auralizations they seem to be very similar; the longer reverberation can only be heard at the end of the phrase, and it is week.
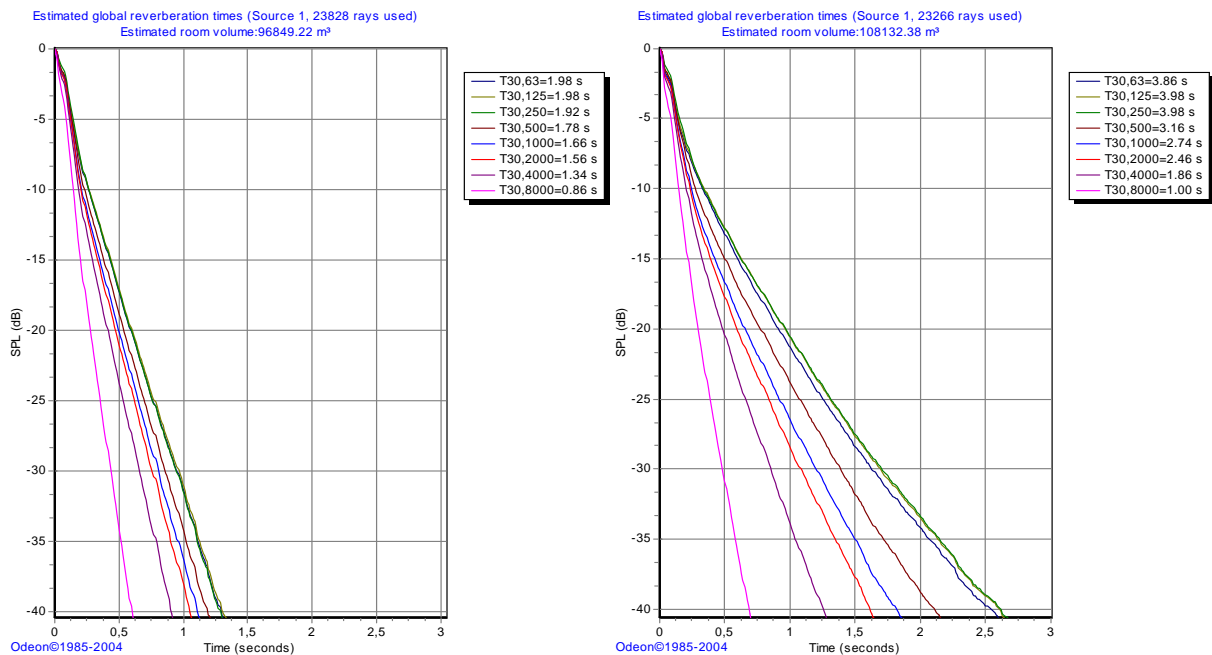

Fig. 8. Calculated global decay curves in the Roman theatre with the source on the stage. Left: with scattering and a good match with measured data. Right: without scattering.

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Average 500 - 1000 Hz octaves	With scattering	Without scattering
T30 (s)	1,9	3,1
EDT (s)	1,6	2,0
G (dB)	- 5,0	- 4,6
C80 (dB)	5,1	5,3
D50	0,64	0,65
Ts (ms)	63	61
LF	0,08	0,02
STI	0,66	0,66

Table 1. Calculated room acoustic parameters in the listening position 33,5 m from the source, used for the auralization example.

COMPARISON OF THE SOUND IN 3D AND 2D ROOMS

In order to elaborate a little more on the findings from the previous example, the Roman theatre is compared to a concert hall having the same reverberation time and the auralizations are made in the same distance from the source, see fig. 9. It should be noted that the listener is in a closer position than in the previous example, and thus the acoustic parameters are not the same. The calculated impulse responses for one ear are shown in fig. 10. Listening to the auralizations they sound very different; the Roman theatre having a lover level but also much higher clarity compared to the concert hall. The calculated acoustic parameters are stated in Table 2.
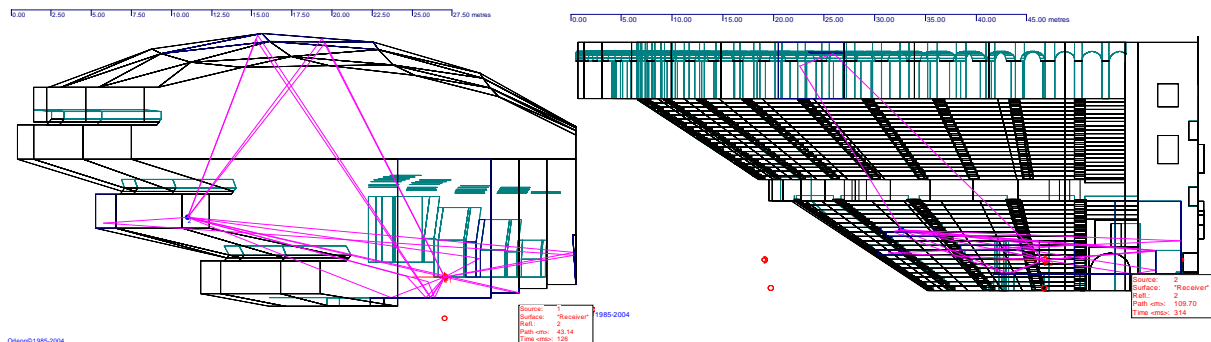

Fig. 9. Section of the digital models of the Danish Radio Studio One Concert hall (left) and the Roman theatre in Aspendos (right). Early reflections to the receiver are shown.
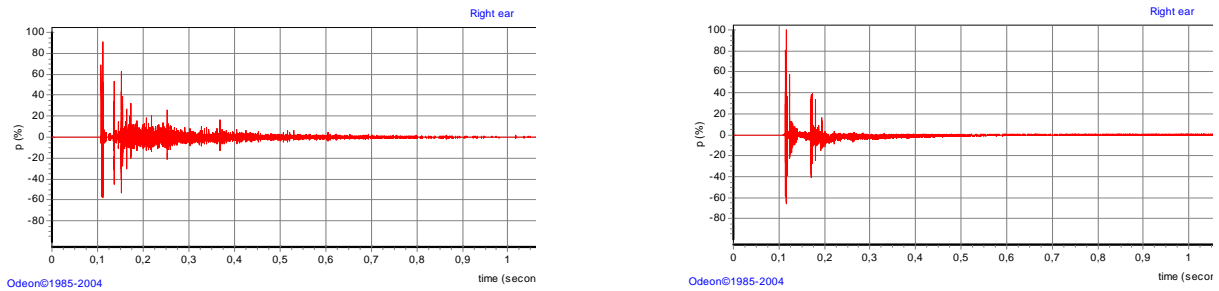
Fig. 10. The first part of calculated impulse responses used for the auralizations. Only right ear responses are shown. Left: the concert hall, right: the Roman theatre.

Average 500 - 1000 Hz octaves	Concert Hall	Roman Theatre
T30 (s)	1,7	1,7
EDT (s)	1,8	1,3
G (dB)	5,3	- 0,7
C80 (dB)	- 0,1	5,4
D50	0,35	0,66
Ts (ms)	117	54
LF	0,09	0,07
STI	0,37	0,66

Table 2. Calculated room acoustic parameters in the listening position 17 m from the source, used for the auralization examples.

BALANCE BETWEEN STAGE AND PIT IN AN OPERA THEATRE

Balance in opera theatres and the influence of the directional characteristic of the sound sources have been studied recently by using computer simulations, see ref. [7]. The principle is the combine two simulations, one representing the singer on the stage and the other representing the orchestra in the pit. For auralization is needed a two channel anechoic recording with the singer and the orchestra separated. The presented auralization examples are made from a model of the winning (but never realized) proposal for the Compton Verney Opera in UK, see fig. 11.

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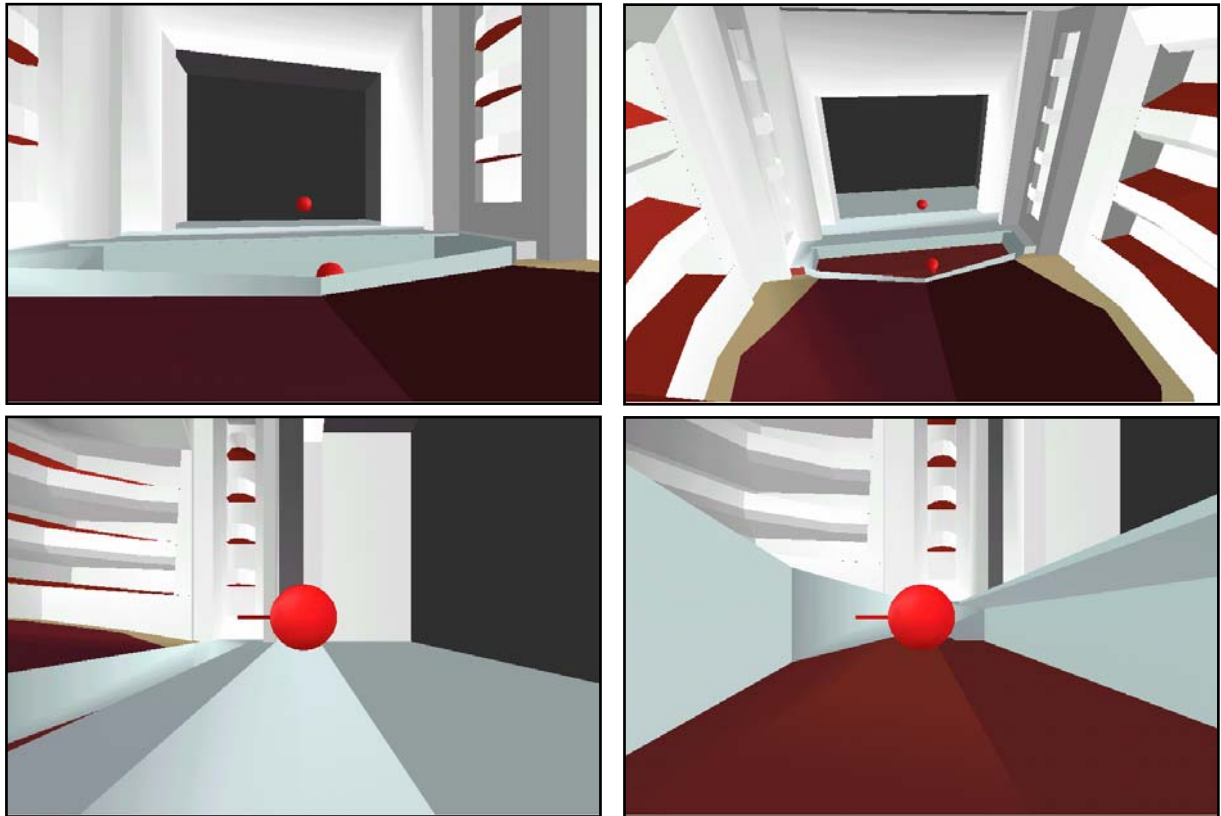
Fig. 11. View into the digital opera house from four different listener positions. The two sources used to represent the singer and the orchestra are shown as red balls with a nose.

CONCLUSION

In auralization it is crucial that there is a sufficient accuracy in all parts of the modeling chain. It is not sufficient that the receiver is modeled with a very precise HRTF, if there are too rough simplifications in the source modeling or in the room modeling. All parts of the chain from anechoic recording of the source signal to the presentation of the final auralization to the listener must be modeled with an adequate accuracy. Some of the difficulties in the room modeling are how to model the surface scattering and the phase shift of sound reflections.

One of the most important uses of auralization for room acoustic evaluation is to demonstrate acoustical defects like echo and flutter echo. However, these defects are strongly related to late room reflections, which means that also late reflections need to be accurately modeled; the commonly accepted assumption that late reflections can be modeled by a 'reverberation tail' added to the early reflections is a big mistake since this would not allow the simulation of room acoustical defects.

The auralization examples referred to above demonstrate some interesting differences between what we can hear and the traditional room acoustical parameters as defined in ISO 3382: The reverberation time is not a reliable objective measure of what we hear in a room during a performance; instead EDT, and even more the clarity parameters like C80 are closely

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related to what we hear. In the Roman open-air theatre there is an extremely uneven distribution of sound absorption (totally absorbing 'ceiling'), and thus the scattering coefficient of the surfaces has a very strong influence on the reverberation time. The demonstration to turn off the scattering from surfaces showed that the early reflections are not so much influenced and the auralization examples sound quite similar.

Auralization is a tool, which can contribute important information about the qualities and in particular the defects in room acoustic designs. The major value may be in relation to acoustic properties like echo, flutter echo, and balance, which cannot be expressed by the currently used room acoustical parameters. It may be noted that for these applications the accurate modeling of the receiver (e.g. with personal HRTF) is not a key point; the effects may be clearly audible even with a presentation through loudspeakers instead of headphones. This contrasts other applications of the auralization technique where it is more important to obtain a correct localization.

Annex
Room acoustic modelling. Early and late reflections in ODEON

In ODEON the early and late reflections are treated differently. Up to second or third order reflections a combined image source / radiosity method is used. As shown by an example in fig. 12 the specular part of a first order reflection is modelled by an image source and the energy is attenuated by $(1-\alpha)(1-s)$, where α is the absorption coefficient and s is the scattering coefficient of the surface. Fig. 13 shows the diffuse part of the reflection from the same surface, the energy being attenuated by $(1-\alpha)\,s$. Typically 100 secondary sources are randomly distributed over the reflecting area, and each secondary source may radiate to a receiver according to Lambert's cosine law or some other directivity of the scattering.
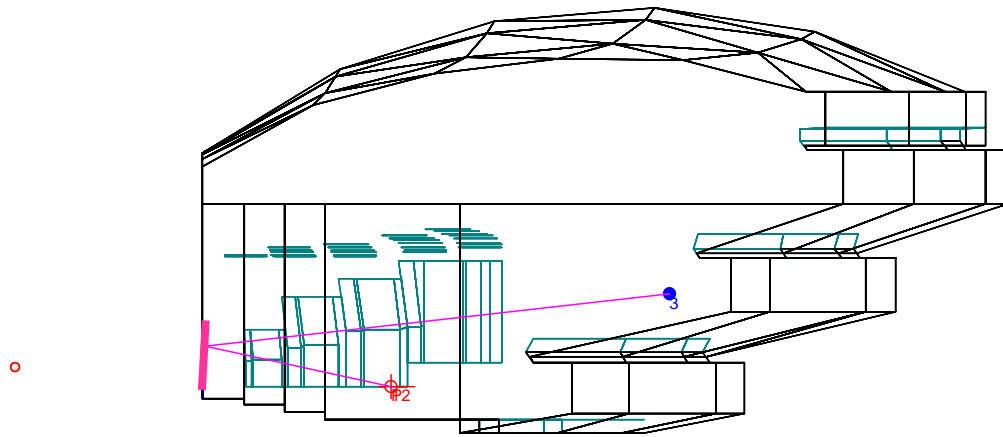

Fig. 12. Specular first order reflection from a surface. The image source is indicted outside the room to the left.
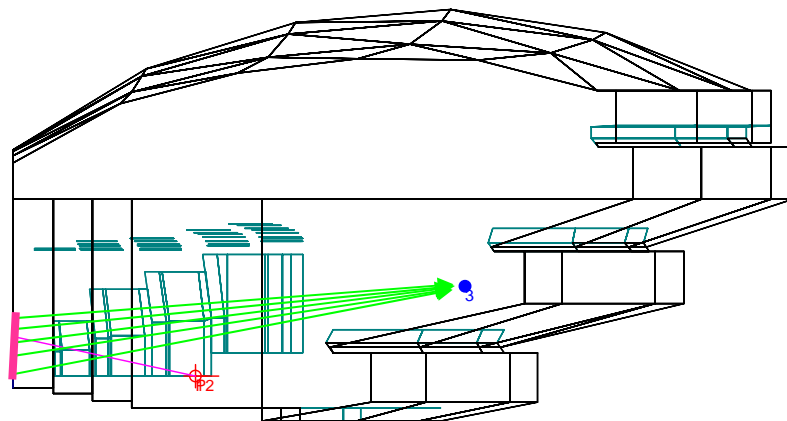

Fig. 13. Diffuse first order reflections from the same surface as in fig. 12.

The late reflections are treated by a combined ray tracing / radiosity method. In a typical calculation several thousand rays are used, each of the being traced through a large number of reflections. One single ray is highlighted in fig. 14. The rays are reflected in accordance with a weighted vector addition taking the scattering coefficient of the surface into account, see fig. 15. All reflection points on the surfaces are considered secondary sources, each have a time delay and energy in accordance with the time history of that ray. The secondary sources generated by the example ray are highlighted in fig. 14 and 16. The second part of the calculation is the receivers (represented as points) to collect contributions of late reflected energy from all visible secondary sources as shown in fig. 16. It is an important feature of the method that not-visible secondary sources do not contribute. In this way it is assured that the whole impulse response is unique to a particular receiver position in the room.
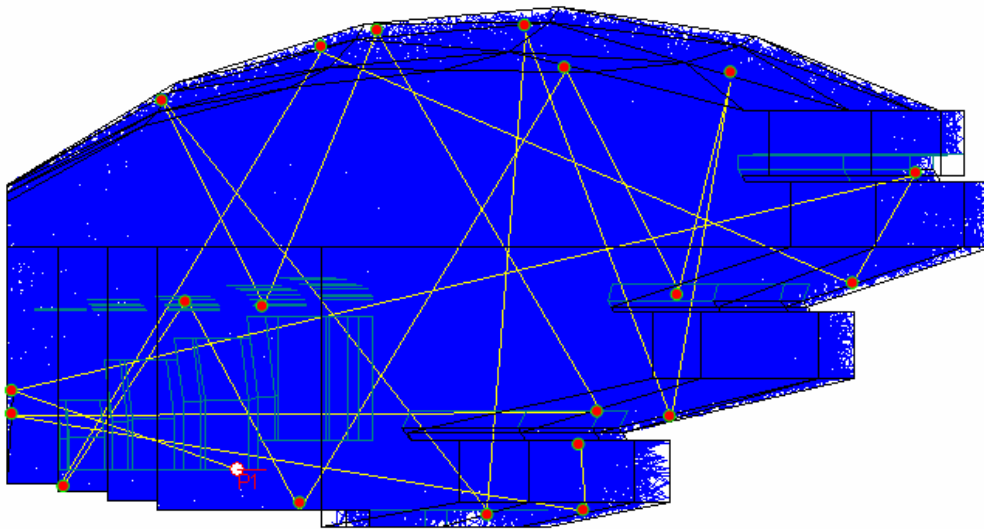

Fig. 14. Ray tracing from a source on the stage; one single ray and the generated secondary sources are highlighted.
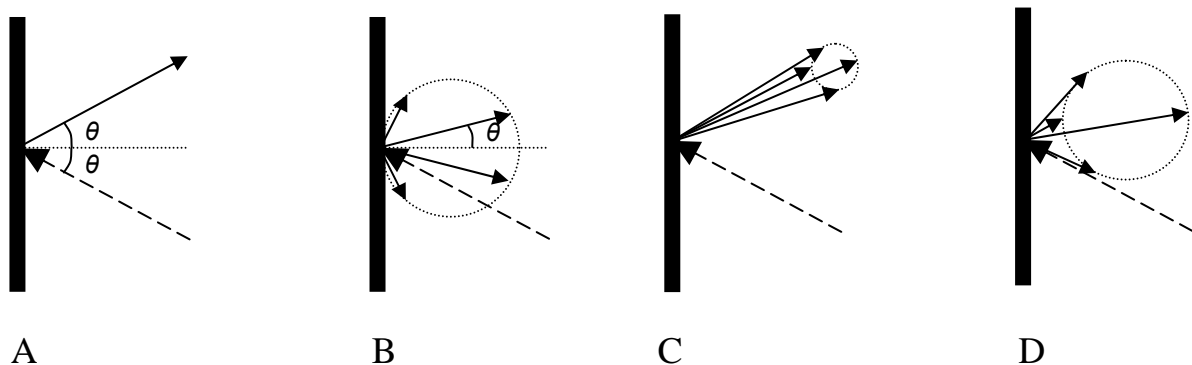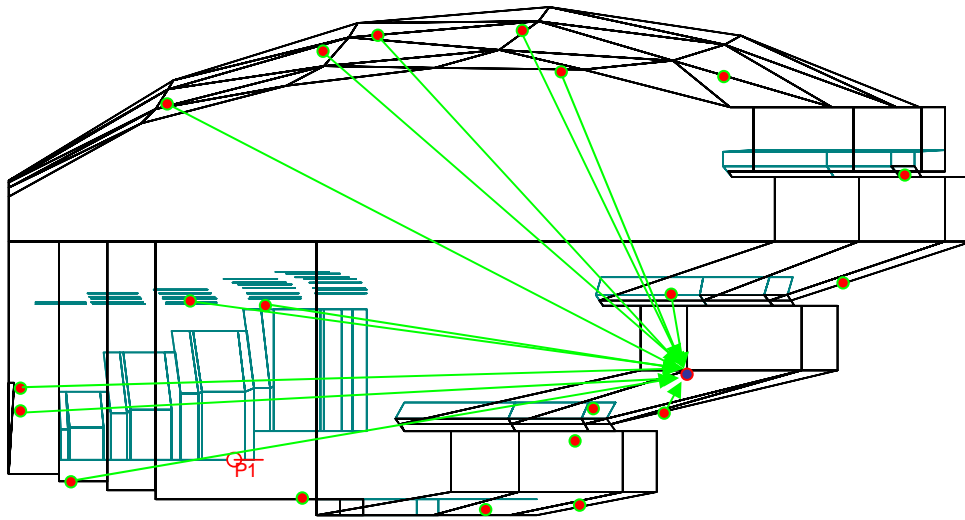

Fig. 15. The scattering of reflections in ray tracing as applied in ODEON. A: specular reflection (Snell's law), B: diffuse reflection (Lambert's law), C: zone of probability for the reflected ray with low scattering (s = 0,2), D: zone of probability for the reflected ray with high scattering (s = 0,8).

Fig. 16. A receiver point on the first balcony and the contributions it receives from visible secondary sources generated by the ray in fig. 14.

As said above the image source method is used only for the early reflections, e.g. second or third order reflections, the so-called transition order, and the ray tracing / radiosity method for the higher order reflections. There are good reasons for having such a combination of different methods for early and late reflections:

- Smooth surfaces create relatively sharp first order reflections that are better modelled by the image source method than by the more diffuse radiosity method
- Even smooth surfaces have some scattering effect which means that after two or three reflections the image source is no longer a reasonably clear image; thus the image source method will give a too sharp and clear reflection. (Compare looking into a mirror with another mirror behind you and imagine that in order to simulate sound reflections the mirror should be partly opaque, e.g. metal plates).
- First order reflections from highly diffusing surfaces are modelled much better with the image source method than with the ray tracing / radiosity method. It may sound like a paradox, but the reason is, that even if the specular reflection is missing, the randomly distributed secondary sources on the surface make a very good model of the diffuse reflection.

It should be emphasized that in order to calculate the impulse response, the sound pressure and not the sound energy has to be calculated, and thus it is necessary to take the phase of the reflections into account. In ODEON this can be done either on a random basis or using an approximate impedance model, which means that the angle of incidence is taken into account [14]. So angle dependent absorption and the possibility of phase shift are applied to the reflections. For the convolution with anechoic music the Binaural Room Impulse Response (BRIR) is need. This involves access to a data base of a Head Related Transfer Function (HRTF), i.e. the transfer of each reflection to a two-channel (binaural) impulse response taking the angle of incidence into account.

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