

The development of room acoustical modelling

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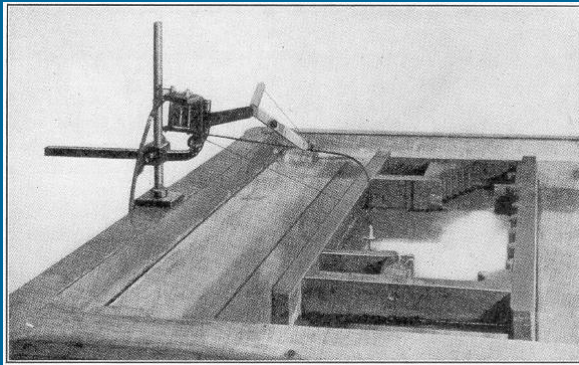
Autumn Meeting of the Swiss
Acoustical Society
Zürich, 5-6 November 2009

Outline

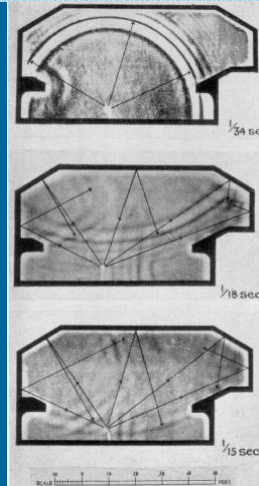
- Development of modelling technique
 - Physical models
 - Scale models
 - Computer models
- Modelling
 - Room geometry and absorption
 - Scattering
 - Validation of results
 - Auralisation
 - Source modelling
- Cases
 - Concert halls and orchestra simulation
 - PA systems
 - Diffraction over screens and barriers
 - Buildings and sound transmission



Ripple tank model

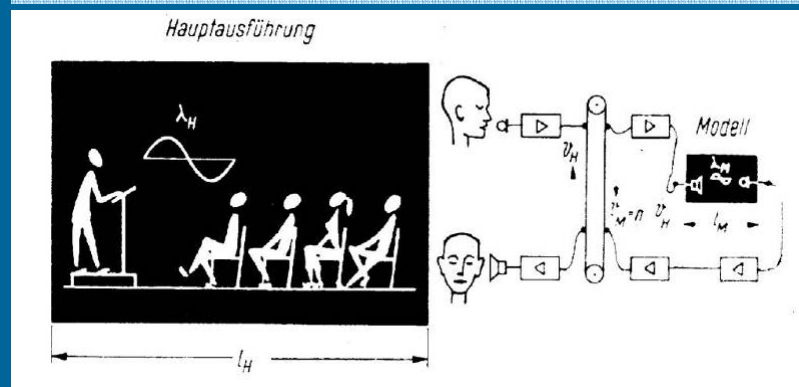


Used from 1921



3

The idea to listen to the sound in a scale model (auralisation)



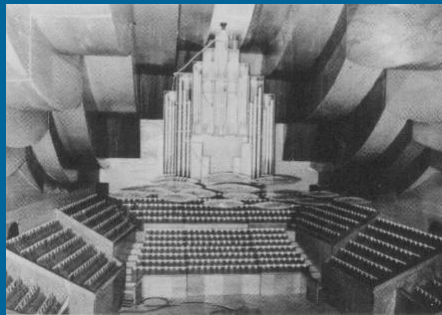
Wax drum for recording and play back of sound. Scale 1:5.
Sound quality very poor.



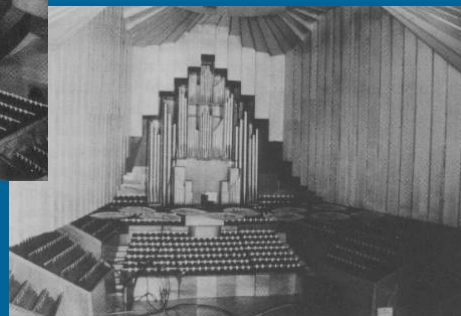
(Spandöck, 1934)

4

Scale models



Sydney Opera House,
1:10 scale models of the
Major Hall, different versions



V.L. Jordan, 1966 - 1970



5

Scale models



1:10 scale model of Yokohama Minato-Mirai Hall, Japan



6

Computer models

- Wave equation models
- Image source models
- Ray tracing models
- Particle tracing models
- Radiosity models
- Hybrid models



7

Computer Models – Wave Equation Models

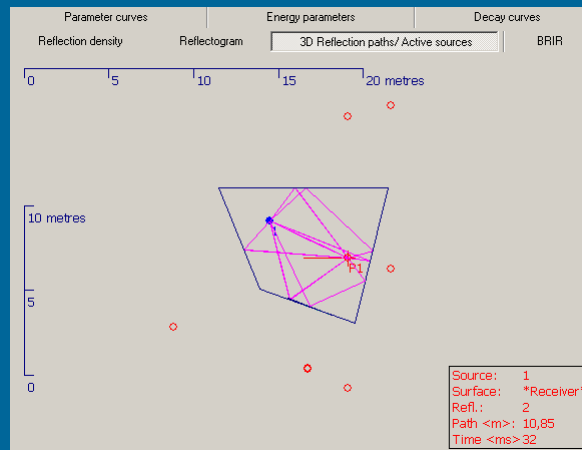
Principle: Solving of the wave equation in a grid of receiver points with assumption of certain boundary conditions.

- The calculation time increases exponentially at higher frequencies, i.e. the methods are limited to low frequencies and small rooms.
- The results are valid for single frequencies.



8

Image source model



9

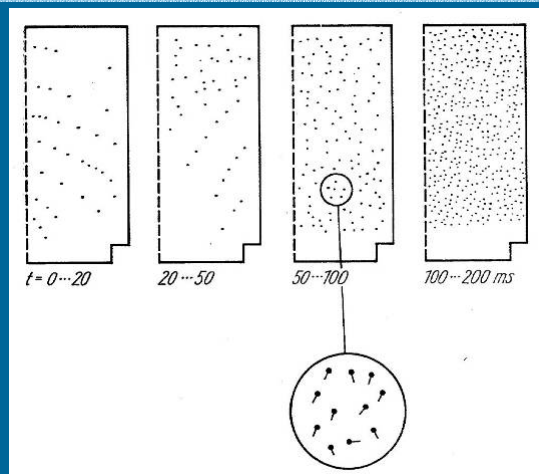
Computer Models – Ray Tracing Models

- Principle: A large number of rays are traced up to high order reflections
- The rays are collected by a surface or by a sphere around the receiver
- Early models only detected ray hits on the floor
- First reports: Krokstad, Ström & Sörsdal (1968). Stephenson (1985). Forsberg (1985)



10

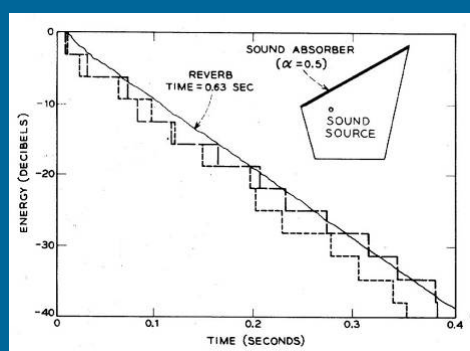
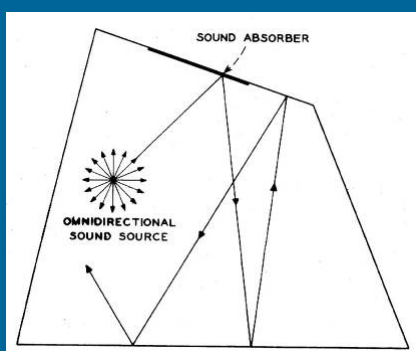
Early ray tracing model



Krokstad, Ström & Sörnsdal (1968)

11

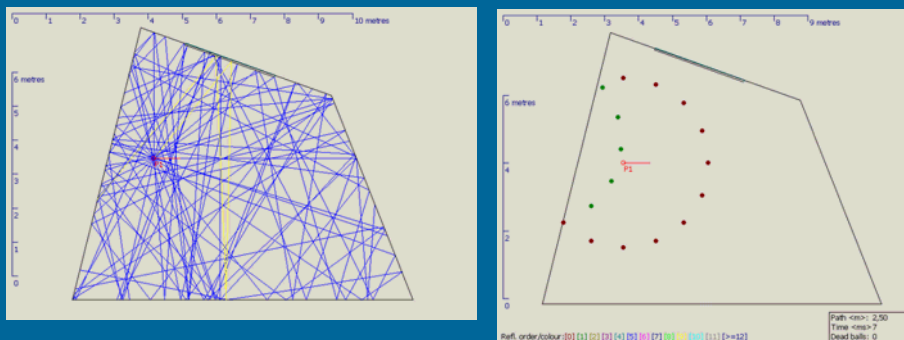
Particle Tracing Model



Schröder (1970)

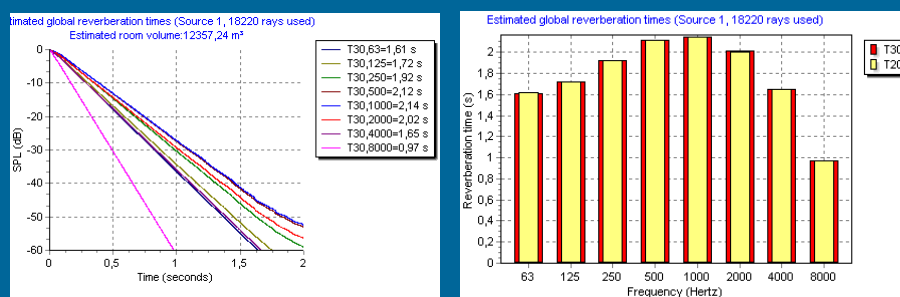
12

Particle tracing



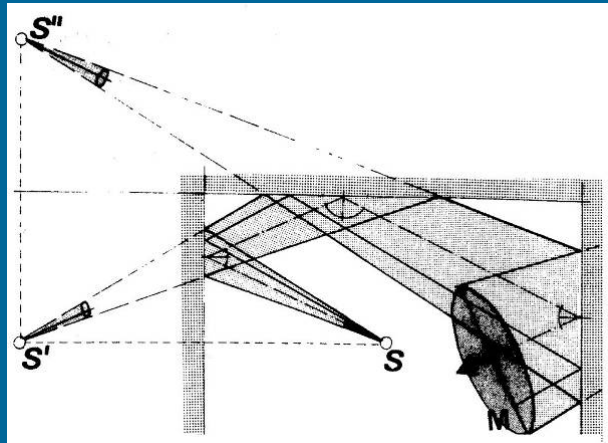
13

Particle tracing



14

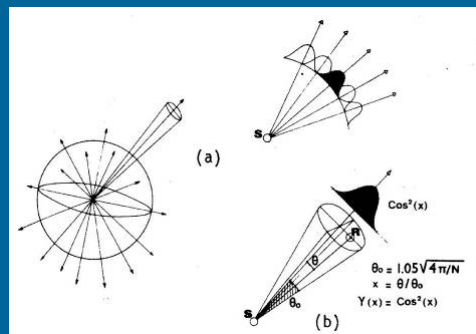
Reflection of a cone with circular cross section



Vian & van Maercke (1986)

15

Cone overlap and a weighting function

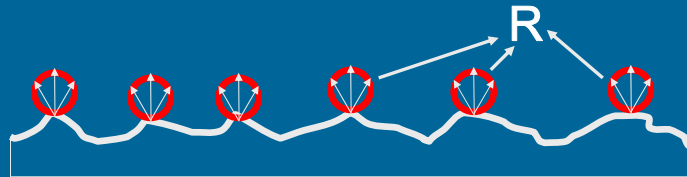


The method have serious problems for higher order reflections and geometries with many surfaces.
(Replaced by better methods in odeon around 1990).



16

Radiosity models



Principle: contributions from a large number of secondary sources located on the surfaces.
First reports: Lewers (1993).



17

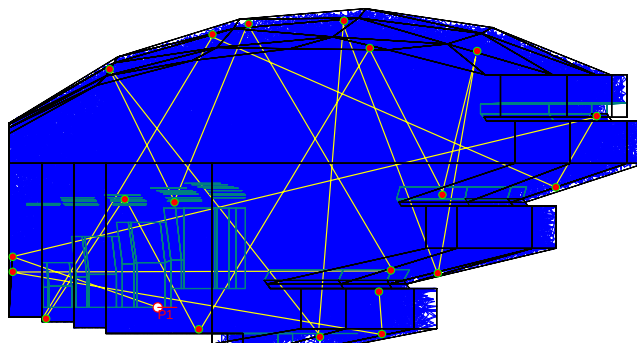
Hybrid methods

- Early reflections
 - Ray tracing used to find possible reflection sequences
 - Creating of image source tree
 - Image source method + scattering from many secondary sources
- Late reflections
 - Secondary sources created during ray tracing
 - Visibility check for allowed contributions to a receiver
 - Radiosity method for radiation from the secondary sources to receiver



18

Ray Tracing Method combined with Visibility Check

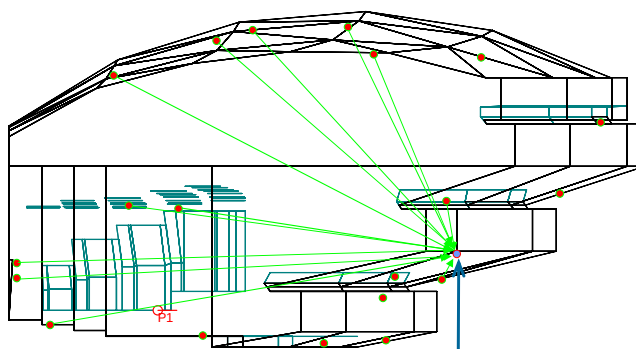


Secondary sources created at all reflection points.
Each source has time delay and frequency dependent
strength according to Ray Tracing history



19

Ray Tracing Method combined with Visibility Check



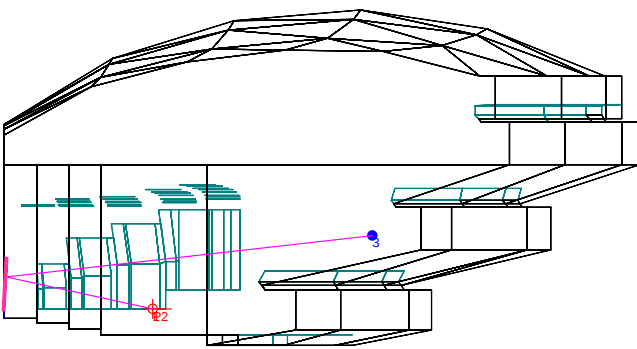
Receiver point collects contributions
from all visible secondary sources



20

Image Source Method

First order reflection - Specular part of reflection
Contribution: $(1-\alpha)(1-s)$



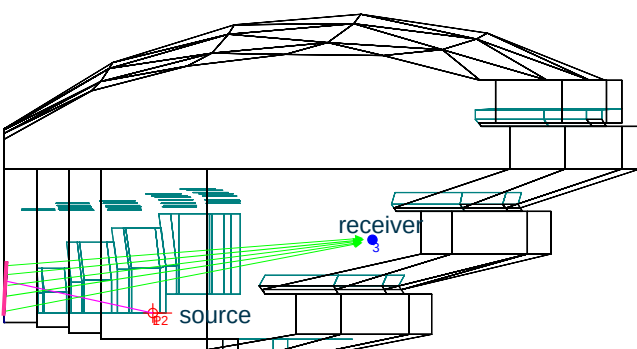
α : absorption coefficient
 s : scattering coefficient

Odeon
Room Acoustical Modelling

21

Image Source Method

First order reflection - Diffuse part of reflection
Contribution: $(1-\alpha)s$



Many secondary sources distributed over the reflecting surface

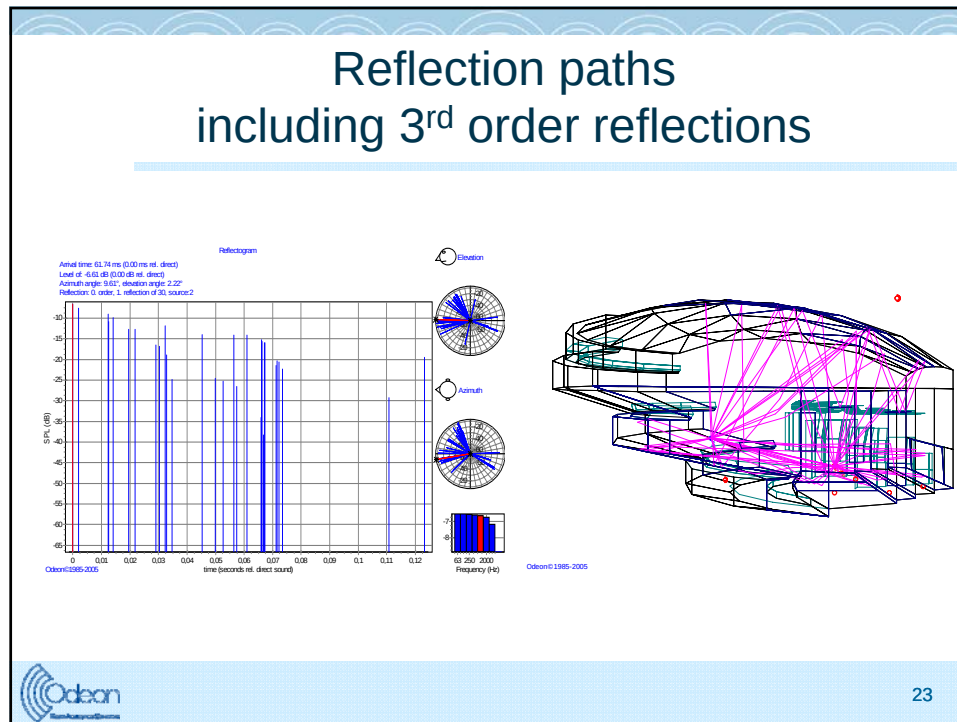
source

receiver

α : absorption coefficient
 s : scattering coefficient

Odeon
Room Acoustical Modelling

22



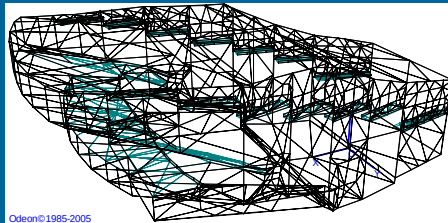
Room Modelling

- Room Geometry
 - degree of detail
 - Import from architects 3D models
- Materials
 - Absorption,
 - Scattering due to surface roughness
 - Scattering and diffraction

Odeon
Room Acoustics Software

24

Using geometries from AutoCAD

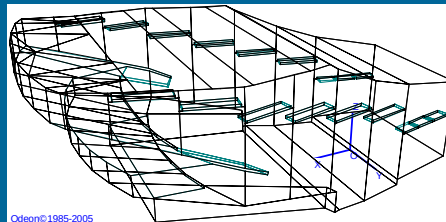


Odeon©1985-2005

Conflict with diffraction handling
AutoCAD and similar programs generate numerous irrelevant small surfaces (Example: 1362 surfaces)

Solution

Odeon DXF Import glues or stitches surfaces to make geometries more suitable (Example: 209 surfaces)



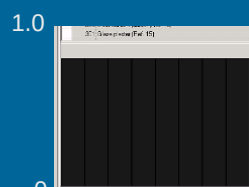
Odeon©1985-2005



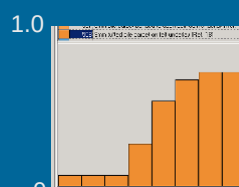
25

Acoustic colours

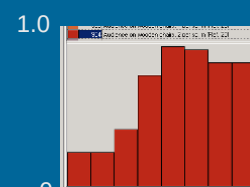
Absorption coefficients in octave bands 63 – 8000 Hz



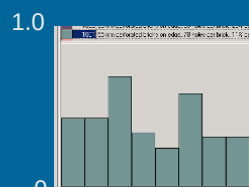
90% absorption



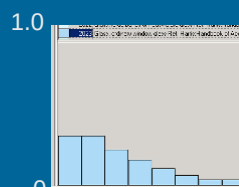
Carpet on felt



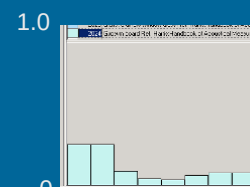
Persons on wooden chairs



55 mm perforated bricks



Glass window

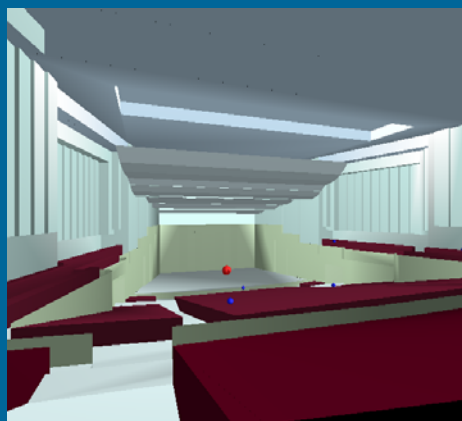


Gypsum board



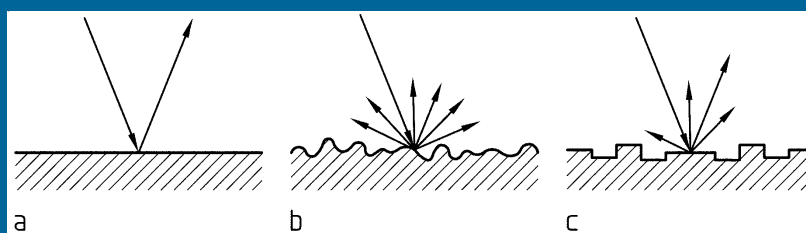
26

Acoustic colours



27

Specular and diffuse reflections



Scattering coefficient s :

The ratio between the acoustic energy reflected in non-specular directions and the totally reflected acoustic energy



28

Scattering coefficient measurement, ISO 17947-1

Measurement setup (1/10 scale)



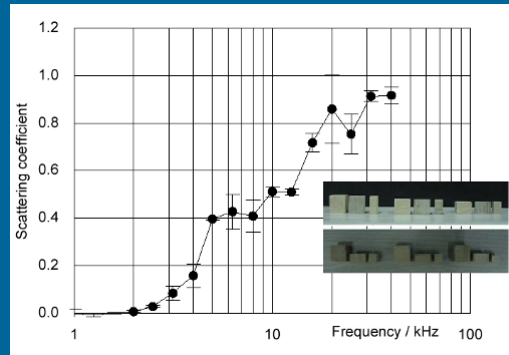
- Sound source : Multi-MLS signal
- Radial averaging : 88 times
- Base plate size : dia. 420 mm or 300 mm
- Reverberation room volume : 0.253 m³ (correspond to 253 m³ in 1/1 scale)
- 1/8 inch microphone (B&K)
- Environmental condition monitoring (Thermometer + hygrometer)



(Jin Yong Jeon, 2008)

29

Scattering coefficient measurement, ISO 17947-1



Max height 200 mm

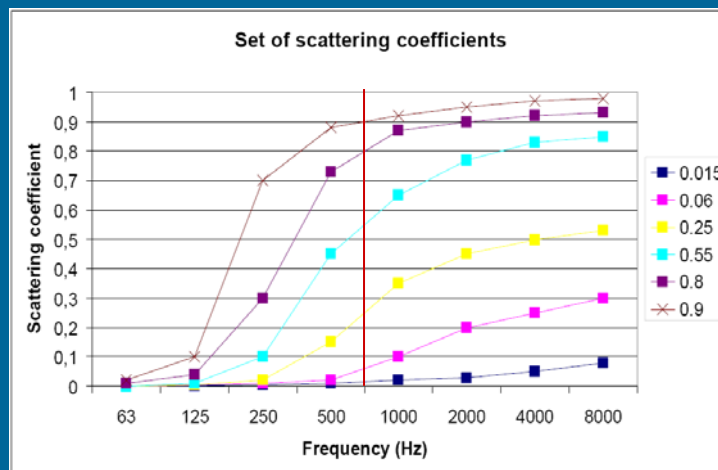


J.Y. Jeon, L. Zhu, K. Yoo
Inter-Noise 2003, Proc. pp 545 – 552



30

Frequency dependent scattering coefficient

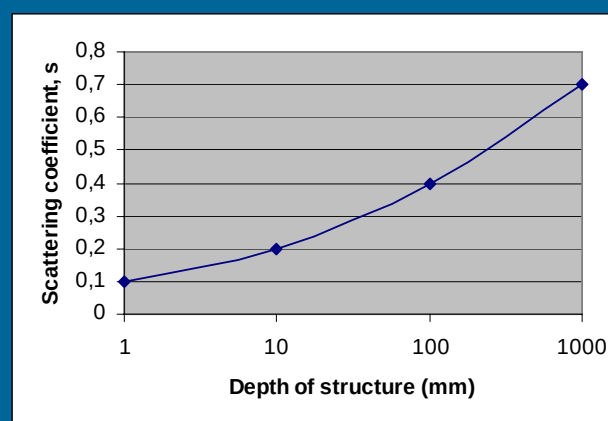


Parameter:
s @ 707 Hz



31

Guide to scattering coefficient at mid frequencies (500 – 1000 Hz)

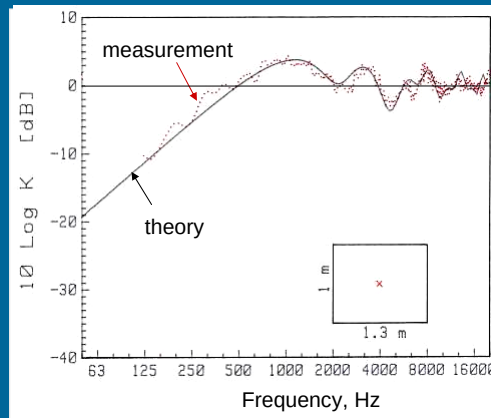


32

Reflection from finite size surface

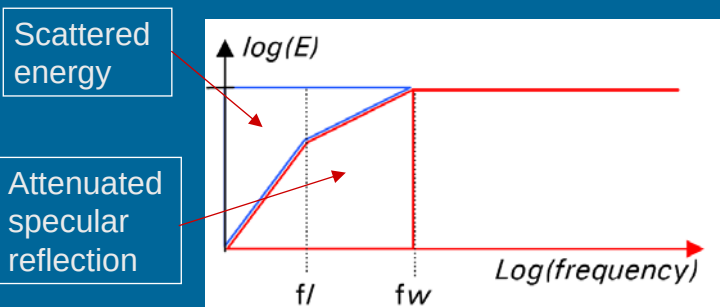


Attenuation below a limiting frequency due to diffraction



33

Scattering due to diffraction



Two cutoff frequencies defined from length and width of panel, and distance from source.



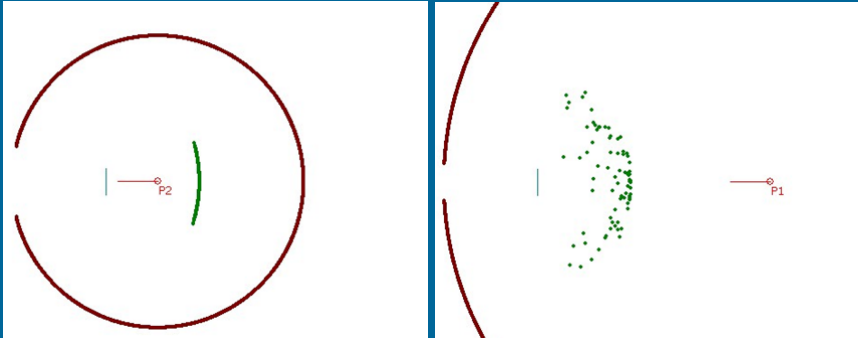
J.H. Rindel, Proc. IOA, vol. 14 (1992) 119-128

34

Reflection based scattering

Scattering depends on:

- size of reflecting surface
- distance from the source



35

Reflection based scattering coefficient

Energy which is not scattered
due to diffraction

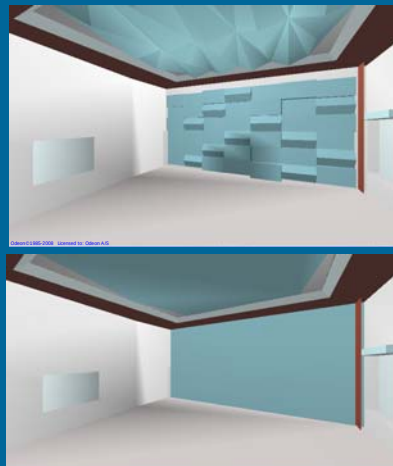
Energy which is not scattered
due to roughness

$$S_r = 1 - (1 - S_d) \cdot (1 - S_s)$$

Resulting specular fraction
i.e. not scattered due to
roughness or diffraction

36

Room Geometry Example – music studio

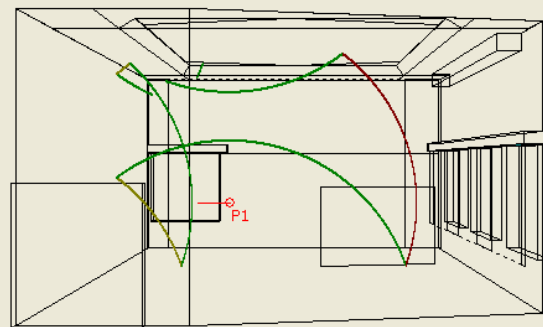


- In a detailed model the scattering comes automatically from the geometry
- In a simplified model the scattering coefficients must be set by the user



37

Simple model without scattering



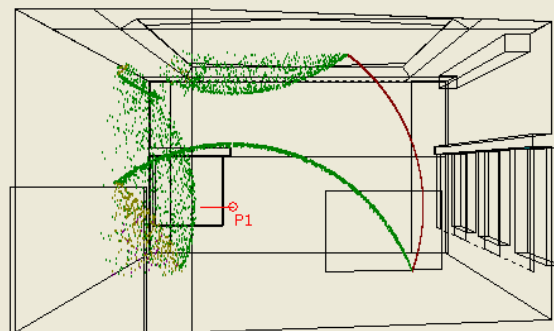
Refl. order/colour: [0] [1] [2] [3] [4] [5] [6] [7] [8] [9] [10] [11] [>=12]

Path <m>: 4,50
Time <ms> 13
Dead balls: 0



38

Simple model with scattering



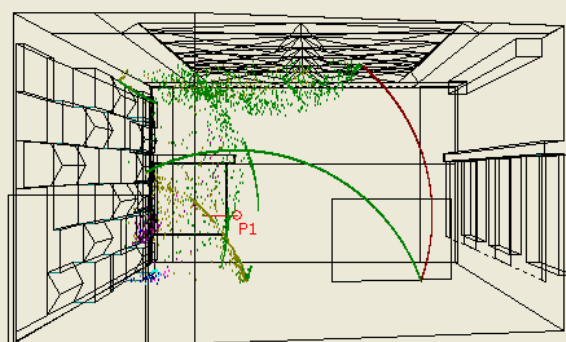
Path <m>: 4,50
Time <ms> 13
Dead balls: 0

Refl. order/colour:[0] [1] [2] [3] [4] [5] [6] [7] [8] [9] [10] [11] [>=12]



39

Detailed model



Path <m>: 4,50
Time <ms> 13
Dead balls: 0

Refl. order/colour:[0] [1] [2] [3] [4] [5] [6] [7] [8] [9] [10] [11] [>=12]



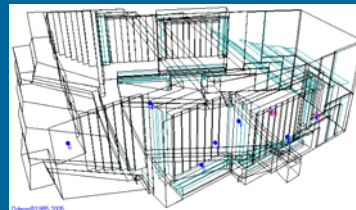
40

Validation

The Elmia hall
2nd Int. Round Robin on
Room Acoustic Computer
Simulations

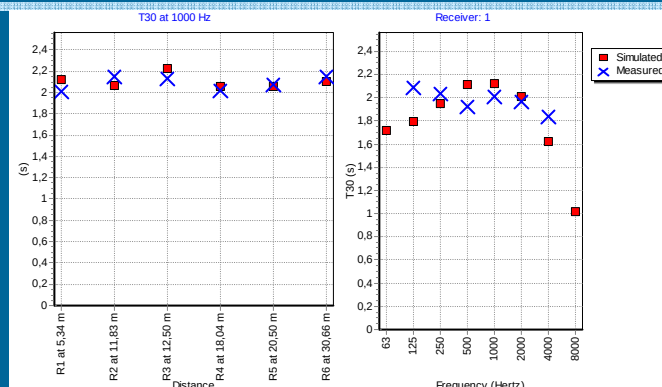
470 Surfaces

2 scattering coefficients:
• 0,65 for audience areas
• 0,05 for all other surfaces



41

Elmia Source 1, T30

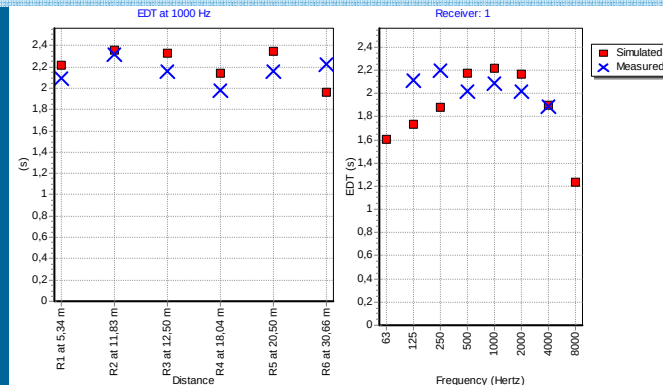


Average measured at 1000 Hz 2.09 seconds
Average deviation at 1000 Hz: -0.02 seconds (1%)
Max deviation at 1000 Hz -0.12 seconds (5.7%)



42

Elmia Source 1, EDT

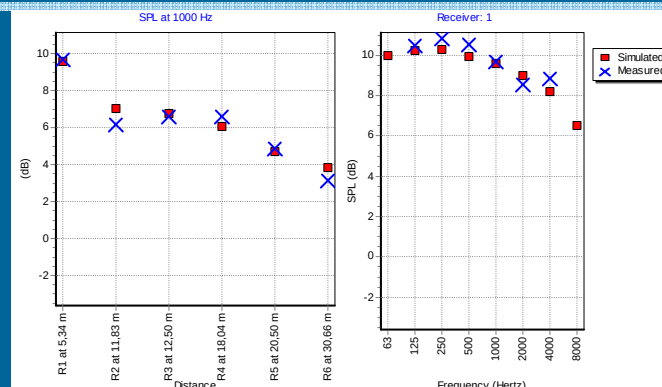


Average measured at 1000 Hz 2.15 seconds
 Average deviation at 1000 Hz: -0.07 seconds (3.3%)
 Max. deviation at 1000 Hz: -0.26 seconds (12%)



43

Elmia Source 1, SPL

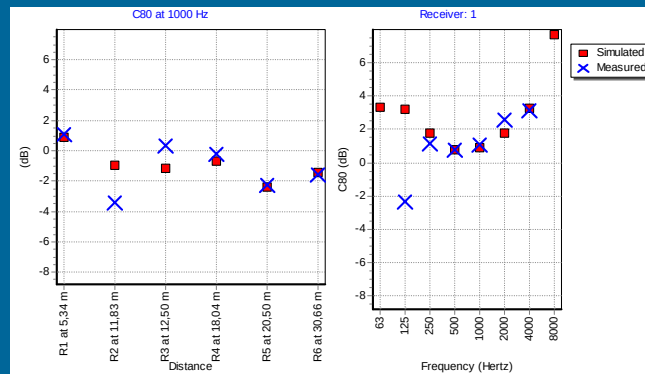


Average measured at 1000 Hz 6.2 dB
 Average deviation at 1000 Hz: -0.1 dB
 Max. deviation at 1000 Hz: -0.9 dB



44

Elmia Source 1, C80



Average measured at 1000 Hz: -11 dB
 Average deviation at 1000 Hz: 0 dB,
 Max deviation at 1000 Hz: -2.5 dB



45

Average error in JND all parameters

$$Error = \frac{\sum_{n=1}^{AP} \sum_{n=1}^{Freq} \sum_{n=1}^{Pos} \frac{|AP_{measured} - AP_{simulated}|}{SL}}{N_{AP} \cdot N_{Freq} \cdot N_{Pos}}$$

$AP_{Measured}$ = Measured value of the current acoustic parameter

$AP_{simulated}$ = Simulated value of the current acoustic parameter

SL = The subjective limen (or JND) for the current acoustic parameter

N_{AP} = Number of Acoustic parameters (7)

N_{Freq} = Number of frequency bands (500-2000 Hz in this case)

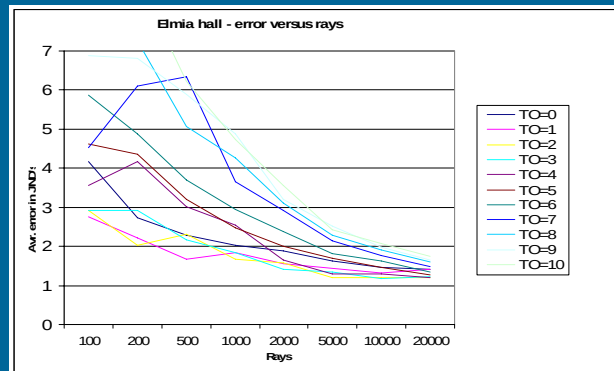
N_{Pos} = Number of measuring positions ($2 \cdot 6 = 12$)



JND: Just Noticeable Difference)

46

Number of rays and TO



TO = 2-5 and 20.000 rays yields an average error of approximately 1.2 JND



TO: Transition Order

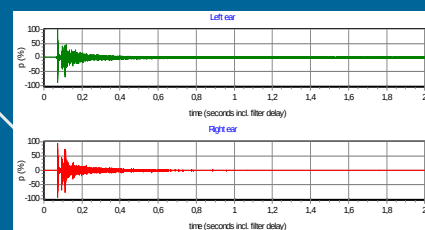
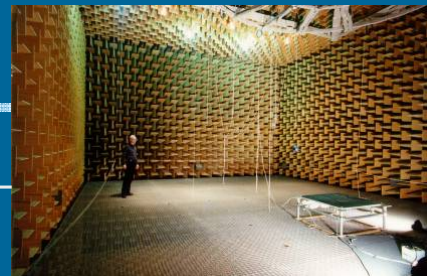
47

Auralisation

Anechoic recording, e.g. a trumpet

Room impulse response
Calculated by simulation

Result of the convolution



48

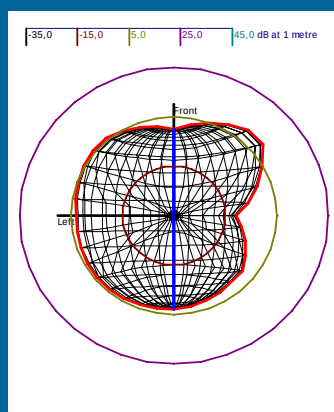
Source Modelling

- Point source with directivity
- Multi channel auralisation (one instrument)
- Multi source auralisation (orchestra)



49

Anechoic recordings

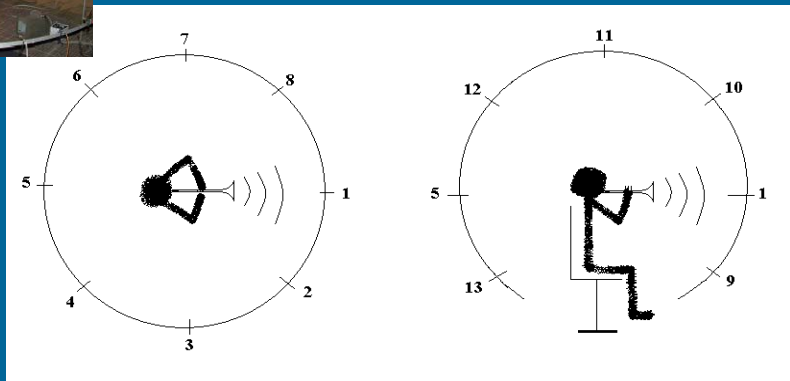


Directivity of violin in
horizontal plane
4 kHz octave band



50

Anechoic recording of the clarinet



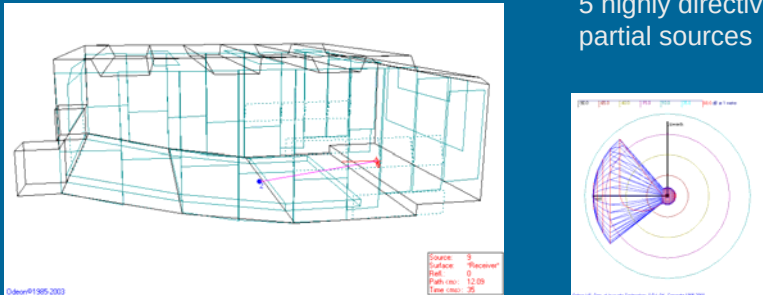
The left diagram is a top-down view of a circular chamber. A clarinet is positioned at the center, with sound waves emanating from its bell. Thirteen microphone positions are marked around the perimeter, numbered 1 through 13 in a clockwise direction starting from the right. The right diagram is a side view of a person sitting and playing a clarinet. The person is positioned on the left side of a semi-circular chamber. Thirteen microphone positions are marked around the perimeter, numbered 1 through 13 in a clockwise direction starting from the right. A small lightbulb icon is located to the right of the diagrams.



51

Chamber music hall used for auralisation

5 highly directive partial sources

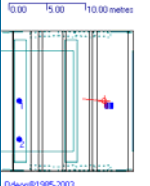


Volume: 5.500 m³ T₃₀ : 1,8 s Distance: 12 m

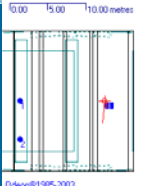


52

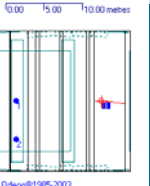
5 channel auralisation – one by one



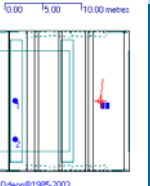
Front 



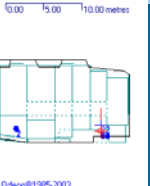
Left



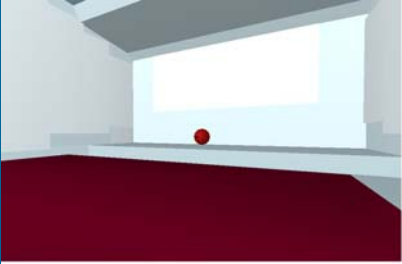
Back



Right



Up



Total


53

Multi-source auralisation of a symphony orchestra

- One instrument at a time
- Visual synchronisation
- Aural synchronisation
- Multiple microphones








54

Recording – one instrument



55

Example: Brahms, 4th Symphony

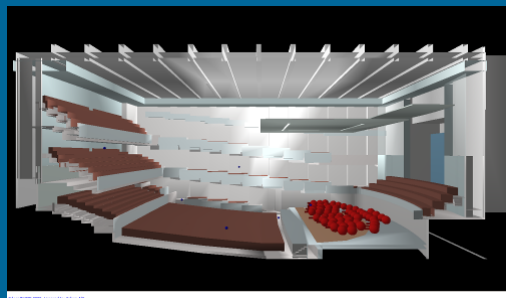
Beginning of
third
movement



56

Room model with full audience

Symphonic Hall, Århus, Denmark



Courtesy of COWI and Artec

Reverberation time occupied 2.3 s

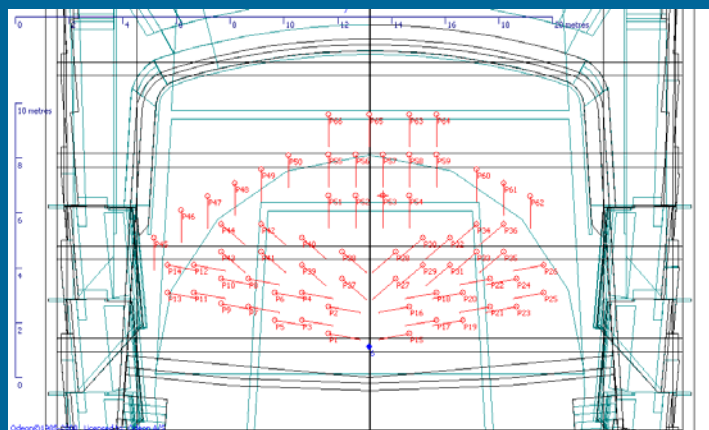


57

Orchestra setup

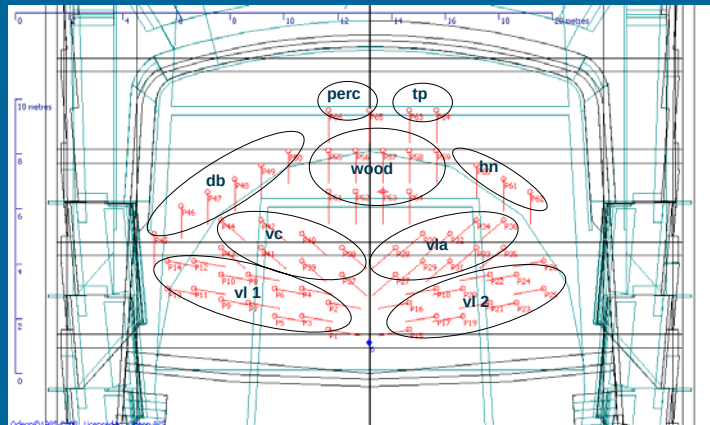
66 sources

Directivity of musical instruments in octave bands (DOREMI project, Otondo & Rindel)



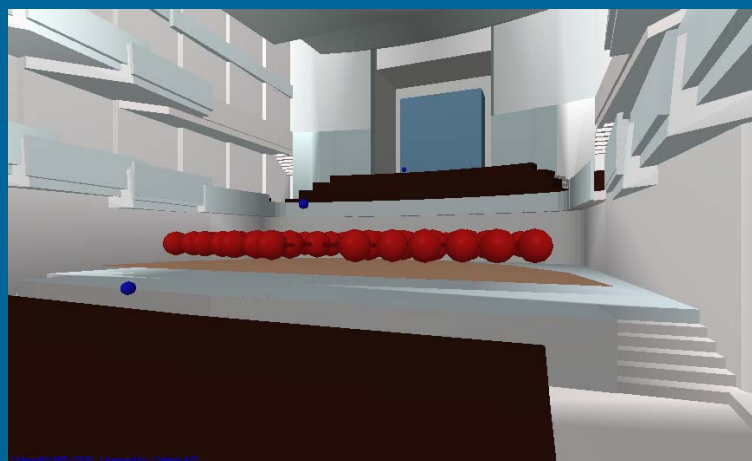
58

Orchestra setup

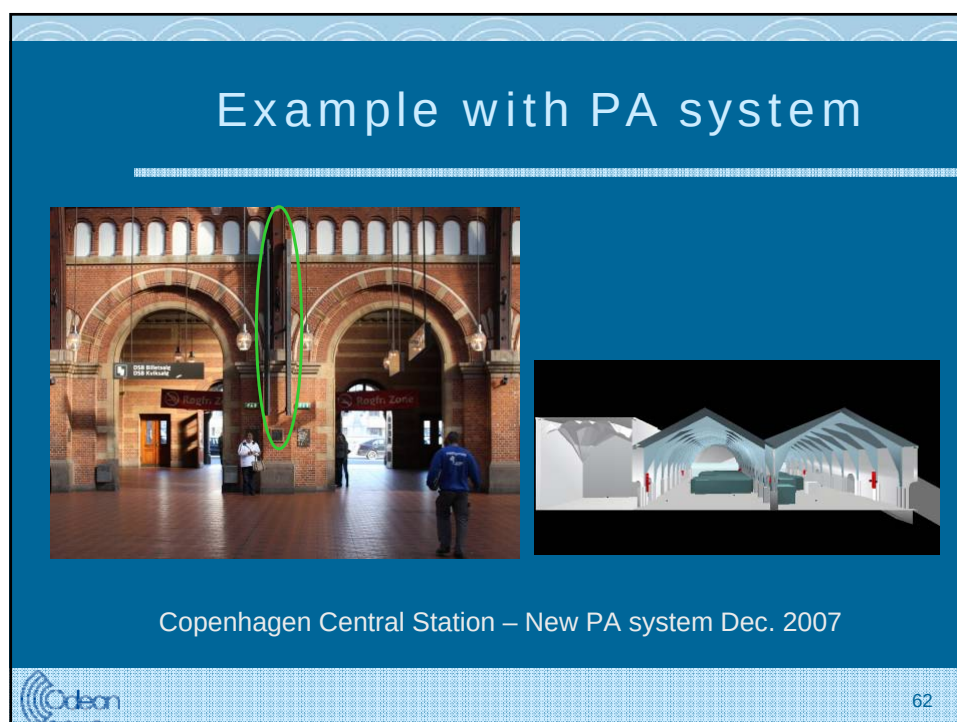


59

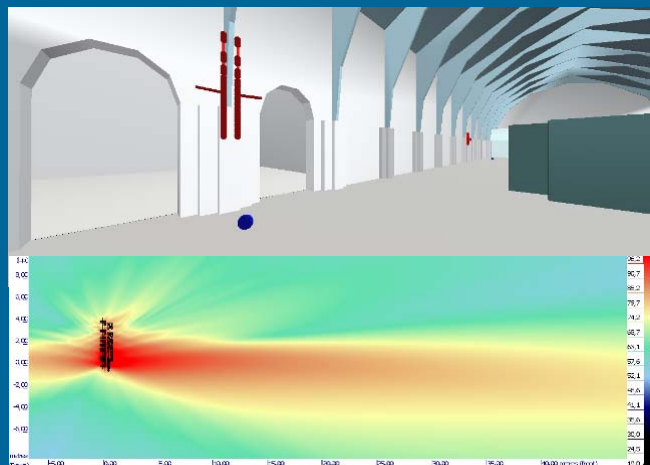
Receiver in the stalls



60



Modelling line array speakers



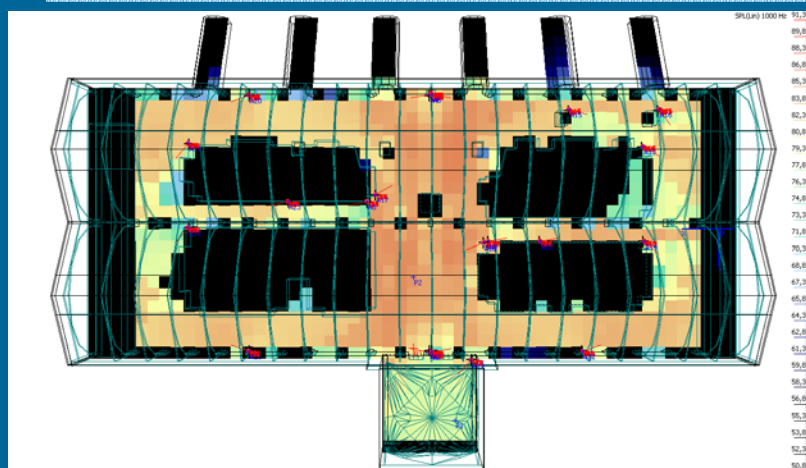
20 Intellivox line arrays with 32 units each

Calculated near field radiation @ 1 kHz



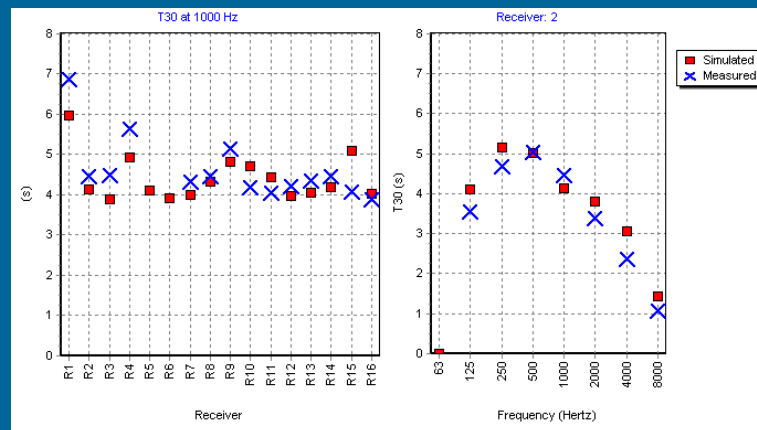
63

Direct sound, SPL @ 1 kHz



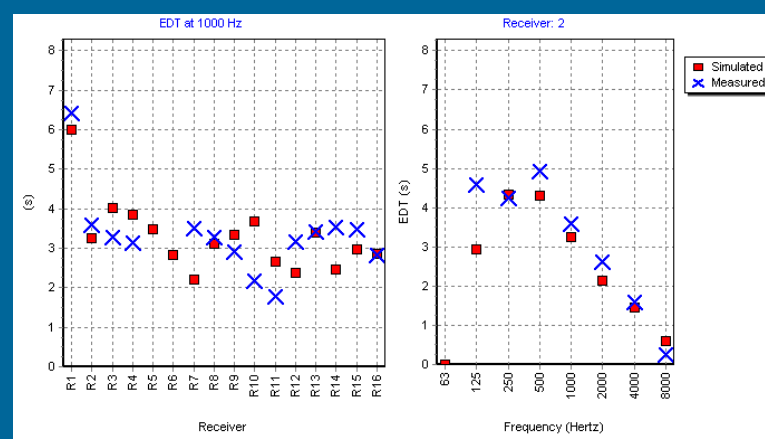
64

Measured and simulated, T_{30}



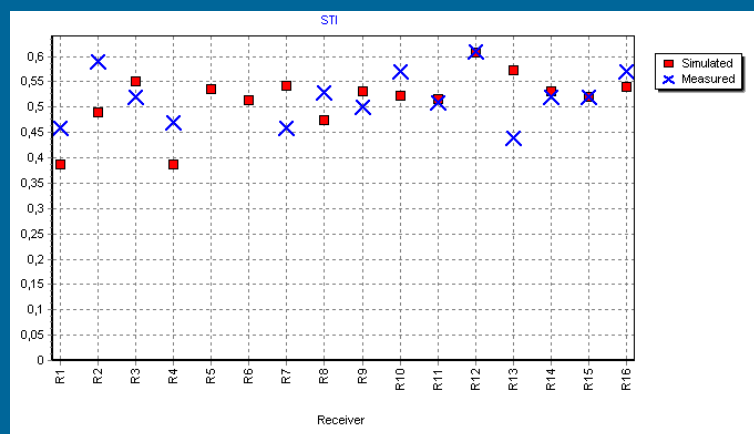
65

Measured and simulated, EDT



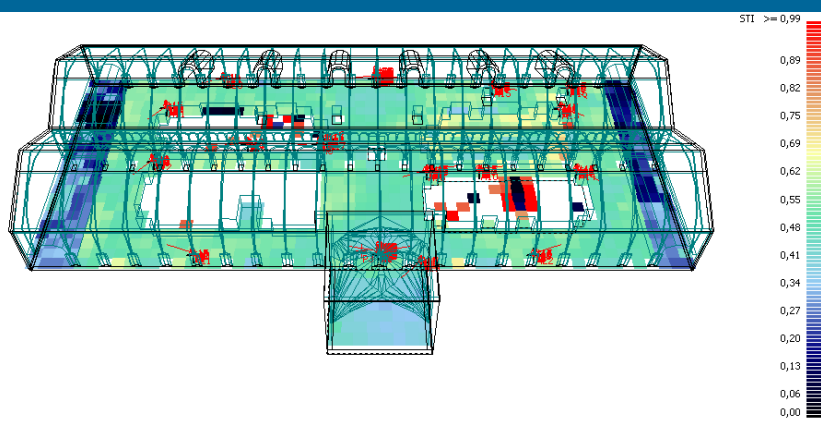
66

Measured and simulated, STI



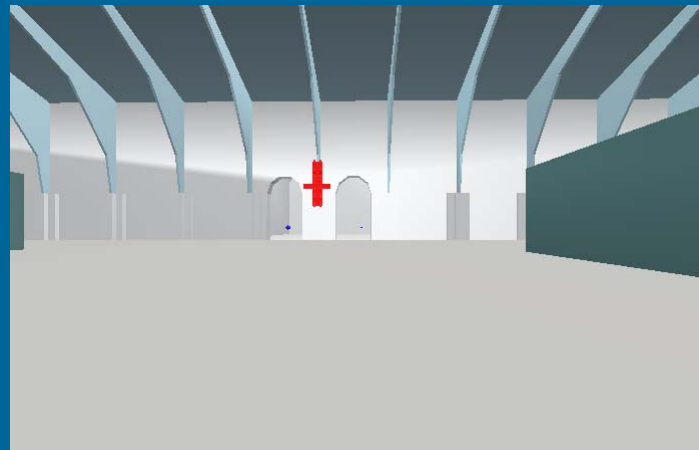
67

STI calculated in grid map



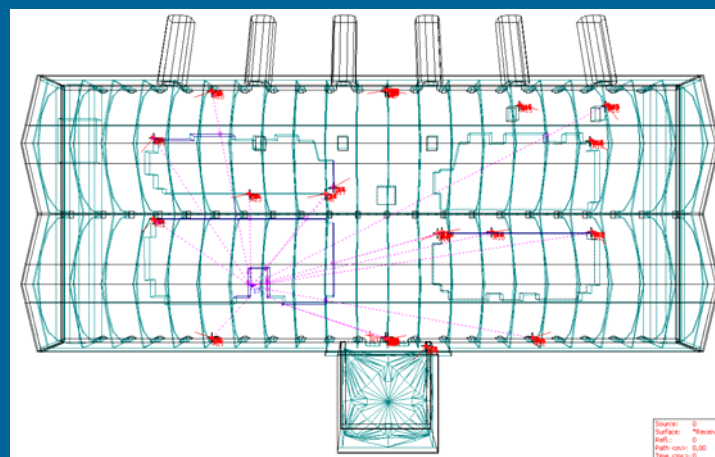
68

Auralisation of PA system



69

Diffracted sound

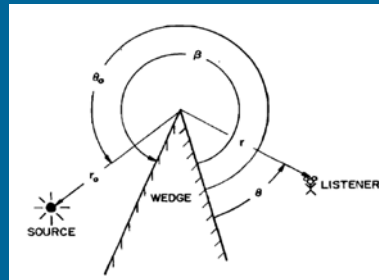


Source: 0
Surface: "Receiver"
Path: 0
Path: 0.00
Time: 0.00

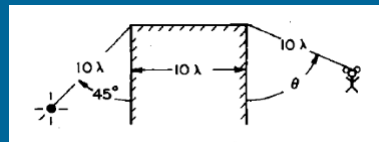


70

Modelling diffraction



Theory: Extension of the geometrical theory of diffraction by use of auxiliary Fresnel functions



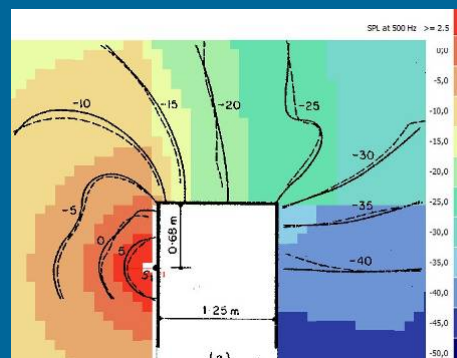
Ref.: A.D. Pierce, Diffraction of sound around corners and over wide barriers, *J. Acoust. Soc. Am.*, **55**, 1974, 941-955.



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71

Verification against measured results



Ref.: T. Kawai, Sound Diffraction by a Many-Sided Barrier or Pillar, *Journal of Sound and Vibration*, **79**, 1981, 229-242.



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72

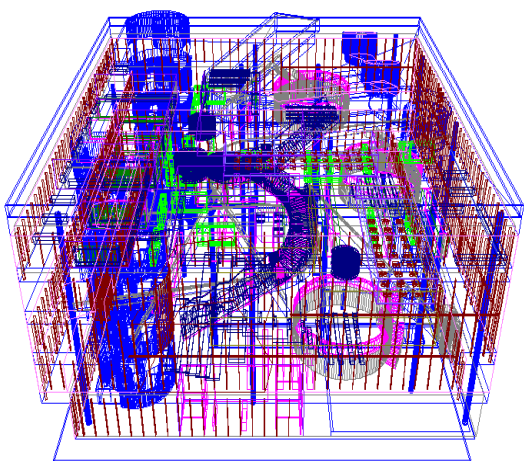
 **Modelling buildings**

- Example: New high school with open plan design, "Ørestad Gymnasium", Copenhagen. Architects: 3xN



73

 **Preparation of building model**



Wireframe picture of model imported using the dxf format

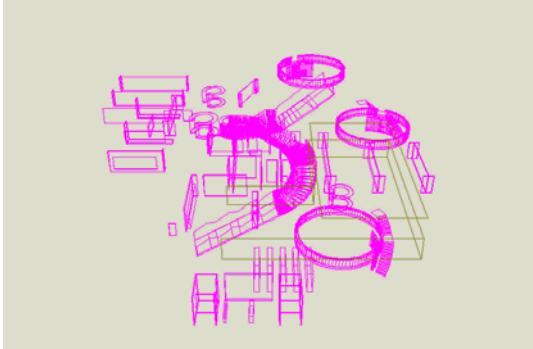
36.585 surfaces
15 layers

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74



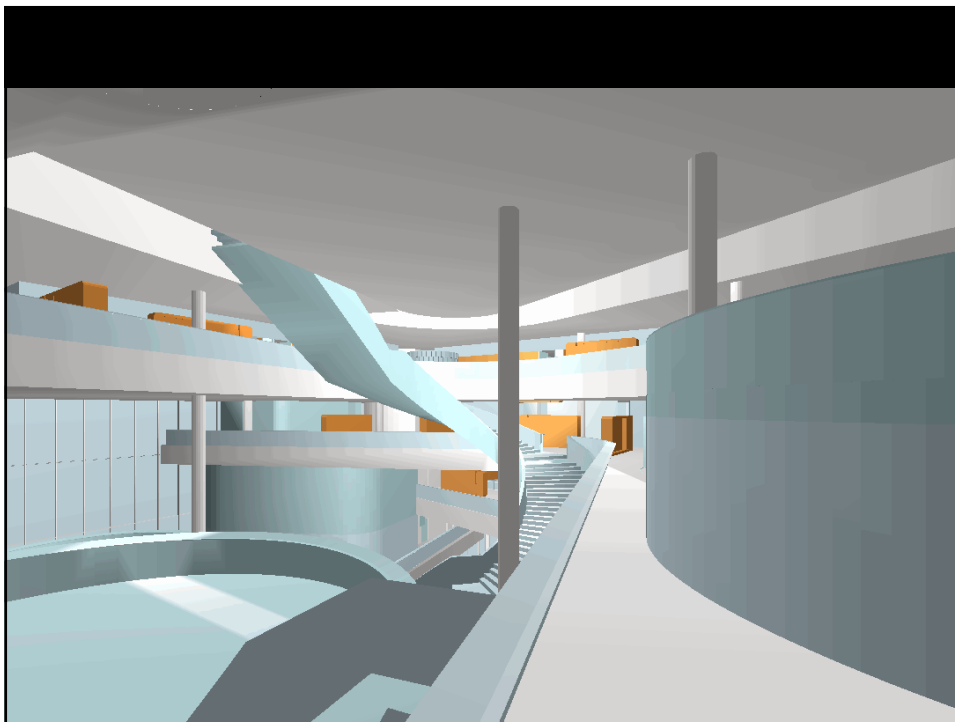
Assigning materials

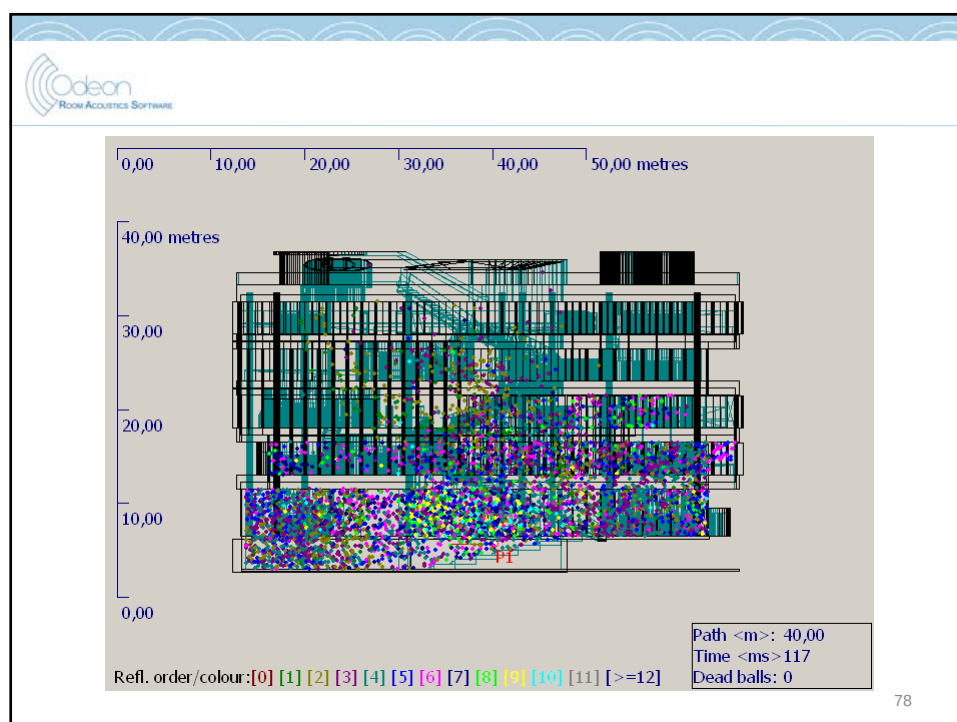
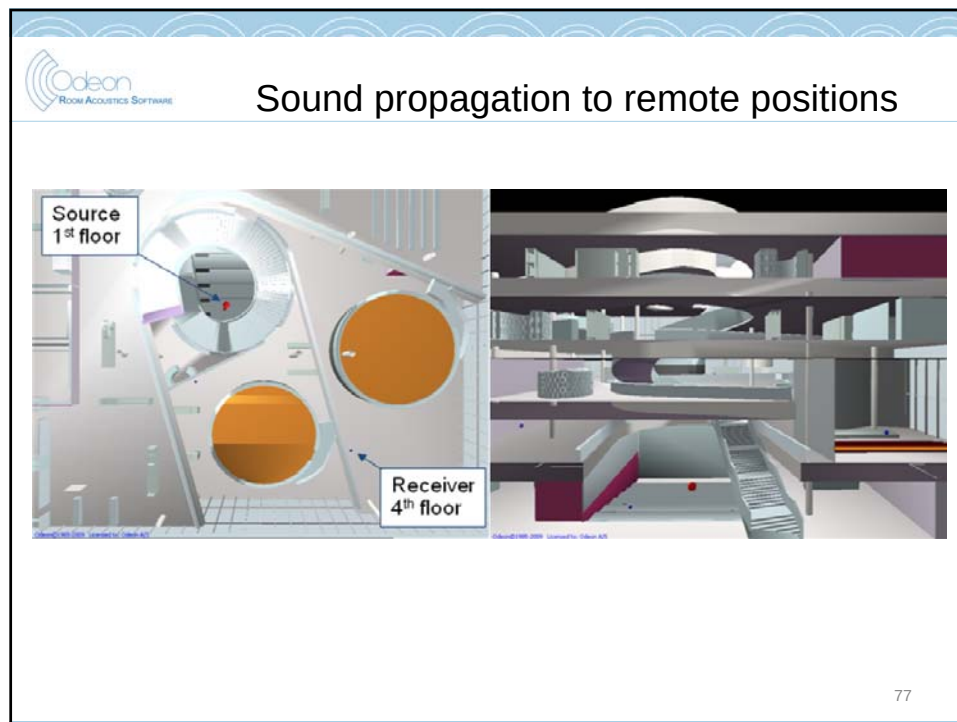


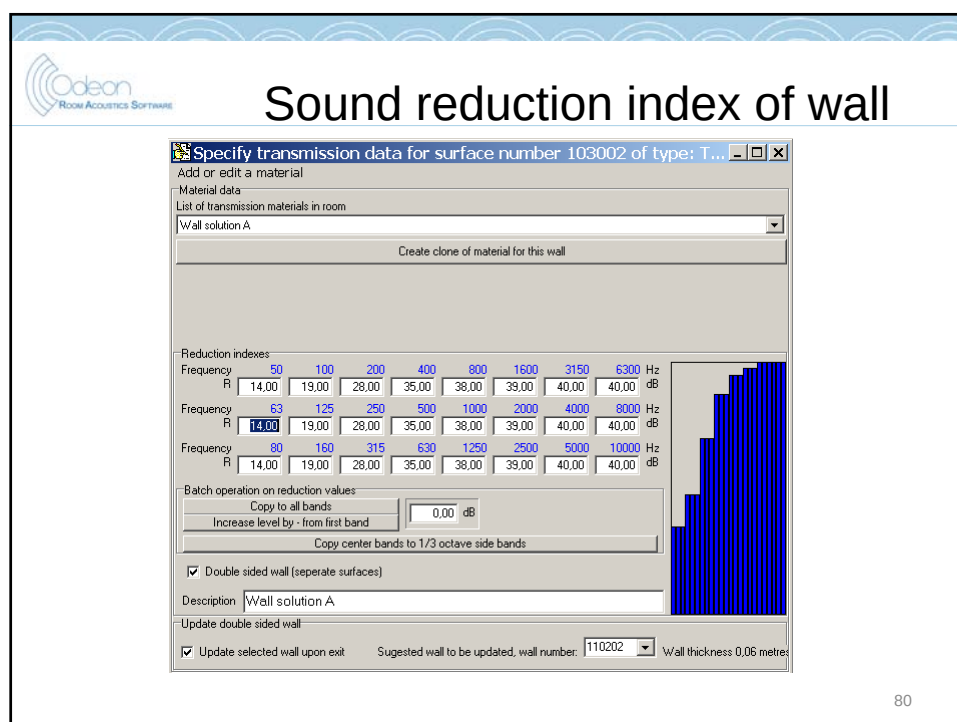
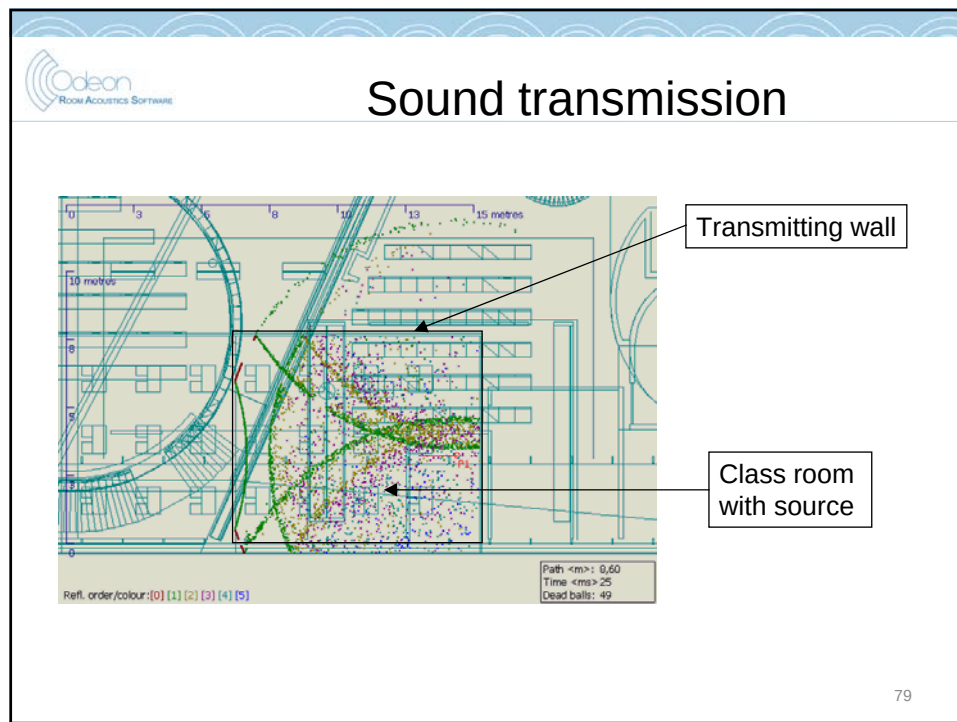
- The use of layers for the various building constructions is very helpful
- Each layer can be assigned material data in one single stroke

Exterior – interior – all surfaces – all layers –
concrete – gypsum – glass – furniture – absorption –
all layers

75



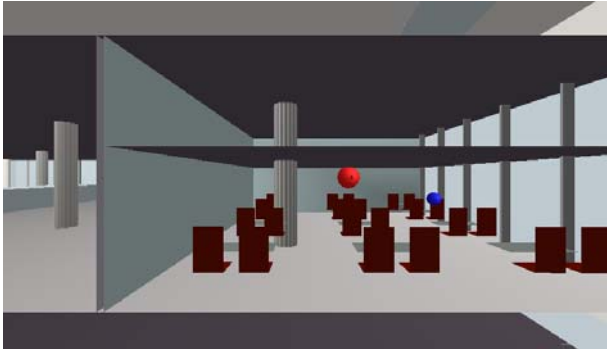






Auralisation

- Sound from music in class room (-10 dB)



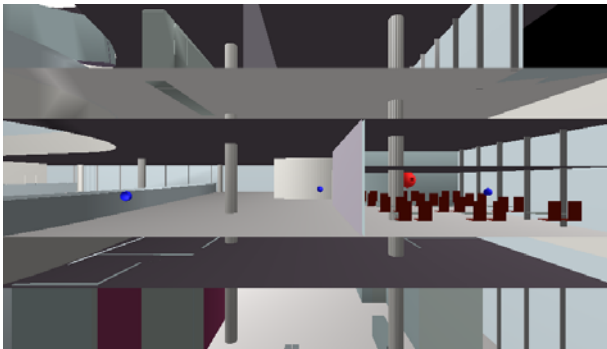


81



Auralisation

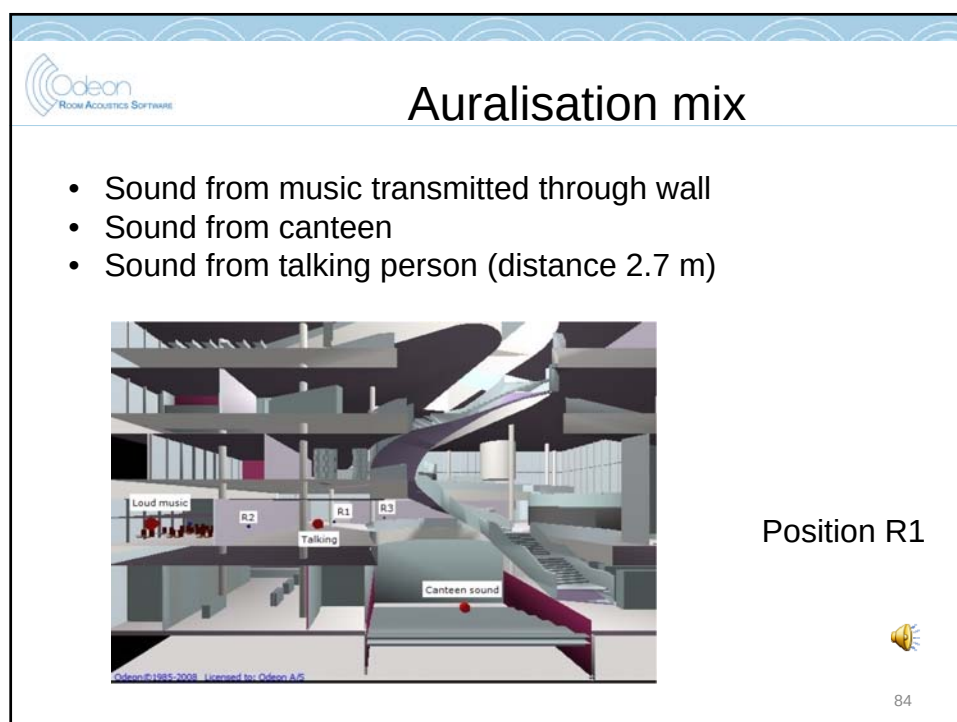
- Sound from music transmitted through wall



Position R1



82





Conclusion

- The hybrid room acoustic modelling methods have proven to be very accurate in auditoria and similar large rooms
- Room acoustic modelling has been extended to cover entire buildings
- The option of sound transmission between rooms opens for new applications
- Using multi-source auralisation it is possible to create full orchestra simulations and soundscape scenarios
- Auralisation has become a useful tool in the evaluation of the acoustics of building design

85