

## Building & Architectural Acoustics



Bruel & Kjaer  
Seminar Series  
November 2009

## Building & Architectural Acoustics

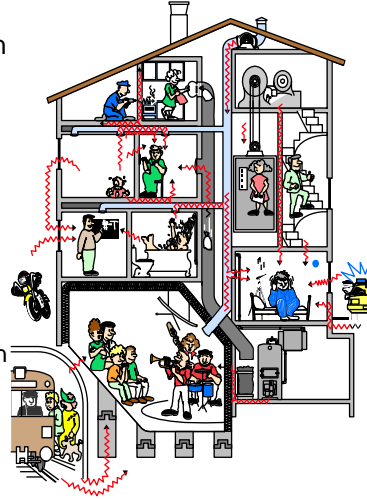
### Outline Programme

- Room Acoustics
  - Interior Sound Levels
  - Reverberation
  - Speech Intelligibility
  - Impulse Response Testing
  - Auralization
  - Modeling
- Isolation between Spaces
  - Transmission Loss of Building Components
  - Impact Isolation of floors and Ceilings



## What is Architectural Acoustics

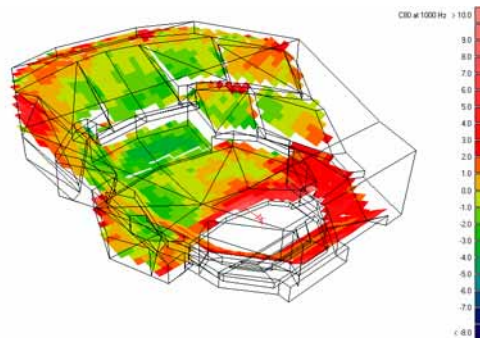
- Room Acoustics and Building Insulation
- Room acoustics relate to the place you are – and how sound is perceived
- Building Insulation is noise control to keep sound out of your room
- Things we won't talk about...
  - Machine Diagnostics
  - HVAC and mechanical system design
  - Only a little bit about building design



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## Room Acoustics: Measure or Model?



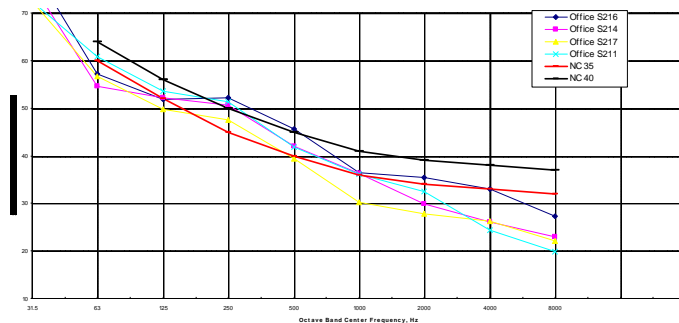
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## Interior Sound Levels

- A-weighted Sound Level
- Octave Band Sound Pressure Level
- NC, PNC, RC, NCB

Figure 2 - Octave Band Sound Pressure Level Spectra Measured at Ortho Open Plan Office Area. Data of 17 December 2001 .



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## Recommendations for acceptable Room Noise

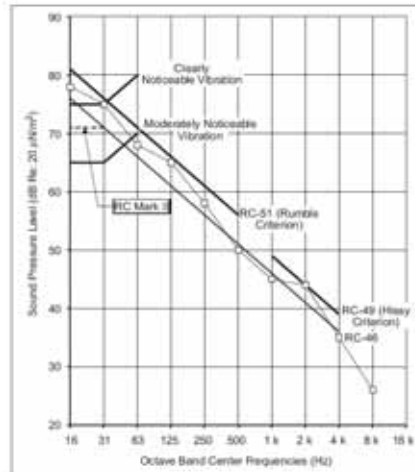
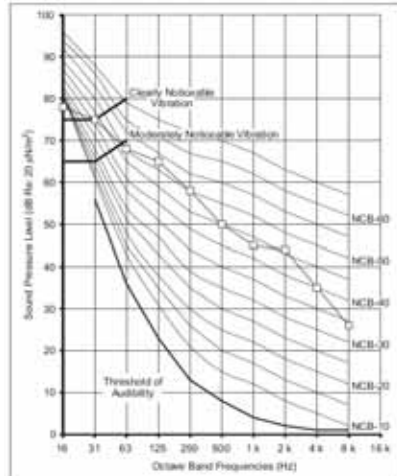
Type of Room - Occupancy		Noise Criterion - NC -	Noise Rating - NR	db(A)
Very quiet	Concert and opera halls, recording studios, theaters, etc.	10 - 20	20	25 - 30
	Private bedrooms, live theaters, television and radio studios, conference and lecture rooms, cathedrals and large churches, libraries, etc.	20 - 25	25	25 - 30
	Private living rooms, board rooms, conference and lecture rooms, hotel bedrooms	30 - 40	30	30 - 35
Quiet	Public rooms in hotels, small offices classrooms, courtrooms	30 - 40	35	40 - 45
Moderate noisy	Drawing offices, toilets, bathrooms, reception areas, lobbies, corridors, department stores, etc.	35 - 45	40	45 - 55
Noisy	Kitchens in hospitals and hotels, laundry rooms, computer rooms, canteens, supermarkets, office landscape, etc.	40 - 50	45	45 - 55

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## NCB and RC

Balanced Noise Criteria (NCB) SIL<sub>500,1K,2K,4K</sub> Room Criteria (RC) PSIL<sub>500,1K,2K</sub>

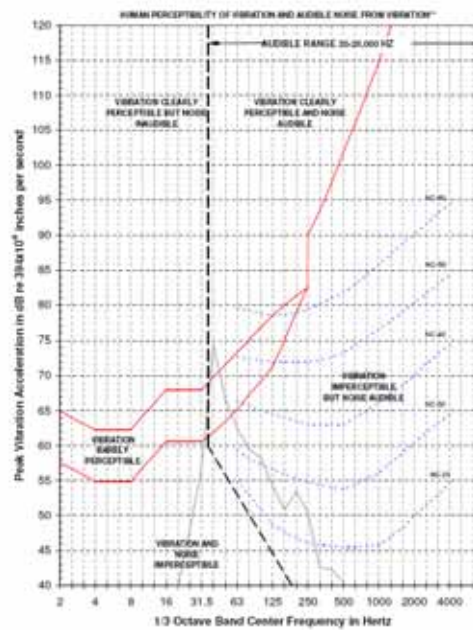


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## Building Vibration?

- Vibration Sensitivity of humans is at lower frequencies
- Velocity is the measured parameter of vibration
- Sometimes it's the sound produced by vibration that is audible.

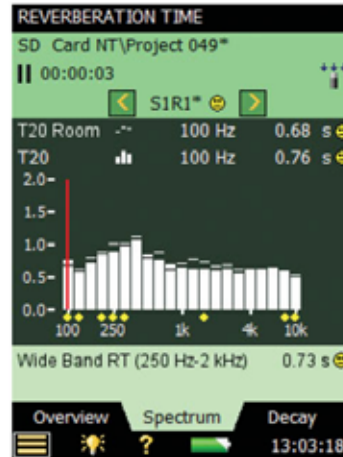


From ARCHITECTURAL RECORD, September, 1972

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Now ready, set, go!

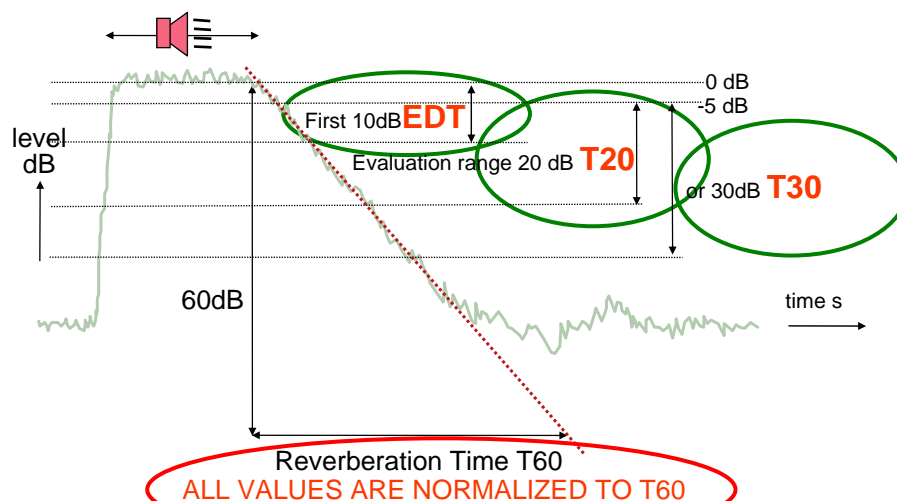


Reverberation!

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## Reverberation Parameters



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## Reverberation Time and Absorption

$$T = 0.161 \frac{V}{A}$$

$T$  is Reverberation Time  
- Sound decay in seconds to 1/1000 level (-60dB)

$V$  is the Volume of the Room ( $m^3$ )

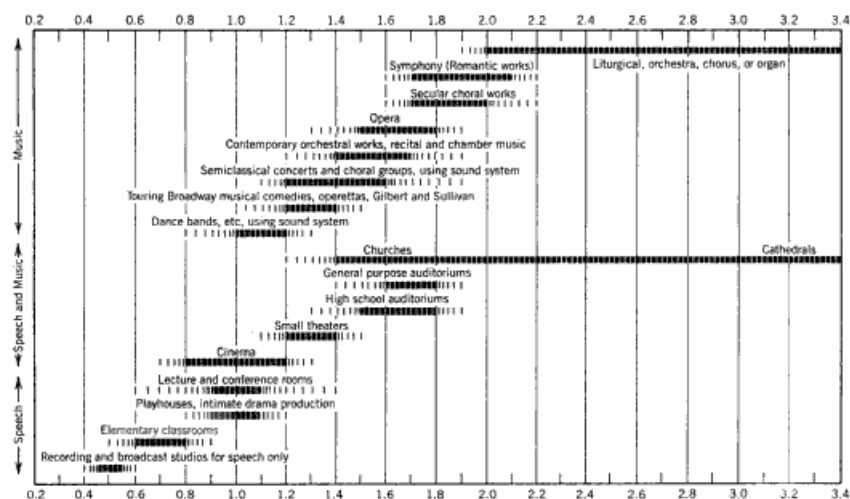
$A$  is the Total Absorption Area ( $m^2$ )

Wallace Clement Sabine ([June 13, 1868](#) - [January 10, 1919](#))

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## Optimum Reverberation Times

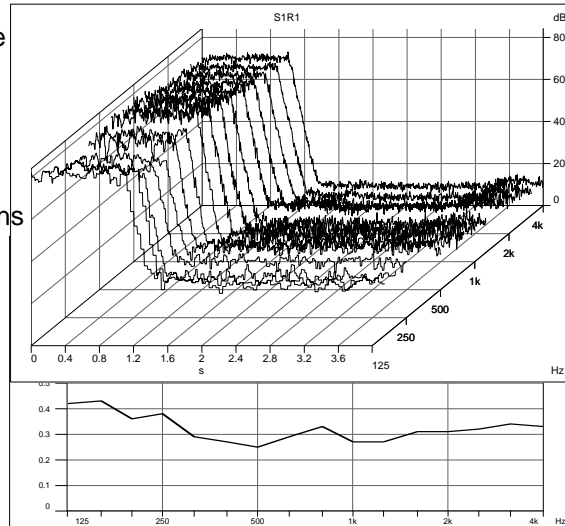


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## What makes a Good Listening Room

- Steep Early Decay Curve
  - Maintains clarity
- Early reflections
  - +/- 60 degree
  - Horizontal
- Minimize ceiling reflections
- Side Wall reflections
  - Discreet
  - Lateral
- Eliminate
  - Discrete echoes
  - Flutter
  - Standing Waves



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## Factors Influencing Speech Intelligibility

- Word Material and Presentation
- Character of the Speaker
- Quality of the Transmission System
- Character of the Acoustics
- Character of the Listener



"Can you speak in garbled, unintelligible, muffled tones? We're looking for someone to work the drive-thru window."

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- Articulation Index
- Speech Interference Level (SIL,PSIL,SIL3)
- Direct to Reverb ration (Weighted C50/C35)
- Speech Intelligibility Index
- Speech Transmission Index (STI)
- Rapid Speech Transmission Index (RASTI)
- %ALCONS

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The graph illustrates the relationship between the articulation index and the percentage of linguistic units understood. The y-axis represents the percentage of units understood (0 to 100%), and the x-axis represents the articulation index (0 to 1.0). Several curves are plotted, showing that understanding increases as the articulation index increases. The curves are labeled as follows:

- test intelligibility limited to 22 1/2 words
- sentences (not presented as isolated)
- sentences (not presented as isolated)
- 1000 different words
- 1000 different syllables
- single words
- test intelligibility limited to 225 1/2 words



**Let's try a simple measurement with a 2250**

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## **The model 2250 from Bruel & Kjaer**

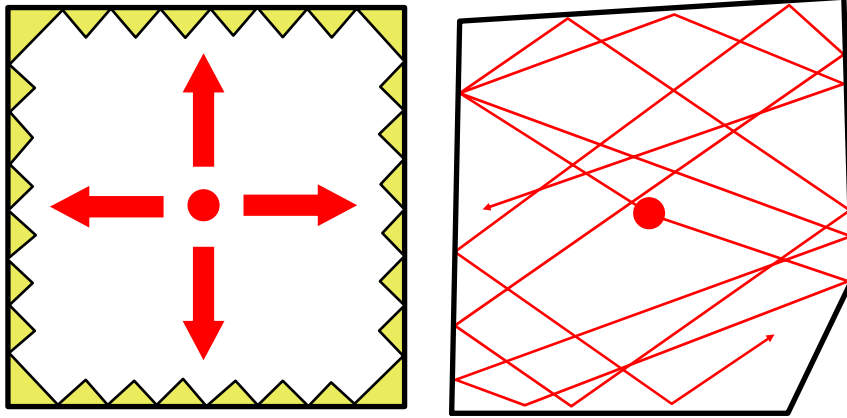


- Sound Level Meter Functions
- Real-Time Frequency Analysis
- Detailed Noise Level Analysis
- High Quality Sound Recording
- Reverberation Time Measurement

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## Anechoic and Reverberant Enclosures



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## Typical reverberation times at 500Hz in seconds

	Minimum	Maximum
Speech	0.4	1.0
Music (Average)	1.0	1.6
Churches (Average)	1.2	1.6
Organ music	1.5	2.4

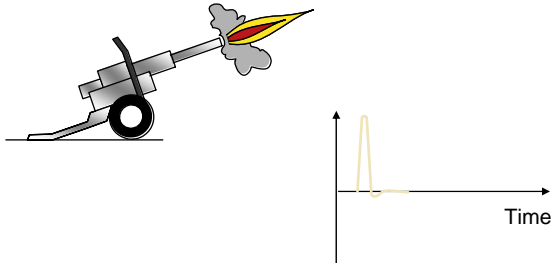


Speech Intelligibility poor in reverberant environment



Suitable environment

## Impulse - Pistol Shot



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## Speech Clarity Measurement – then and now



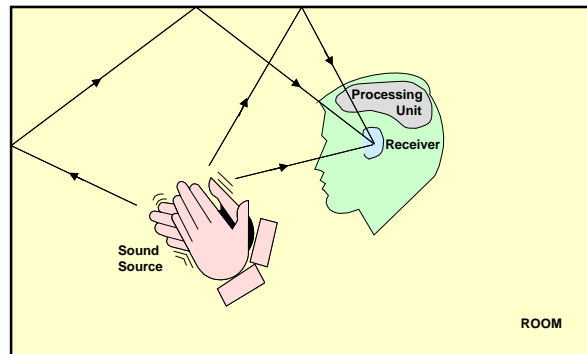
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Let's try a simple measurement with a 2250  
And a balloon .....

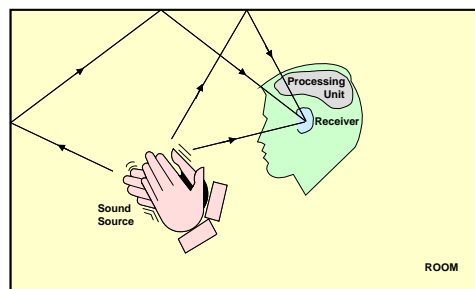


## Impulse Response the natural way



What can be improved ?

## Impulse Response - Improvements



What can be improved ?

- Source/receiver locations
- Source specifications
- Receiver specifications
- Measured parameters

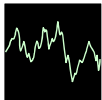
## Source Signals for Impulse Response



- Ideal Impulse (Dirac function)  
+ No postprocessing - Only theoretical



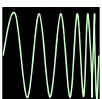
- Approximated Impulse  
+ Simple, No postprocessing - Directivity, repeatability



- Random Signal  
+ Simple - Postprocessing, Residual noise



- MLS Signal  
+ SPL measurement - Postprocessing



- Sine Sweep Signal  
+ High power - Postprocessing

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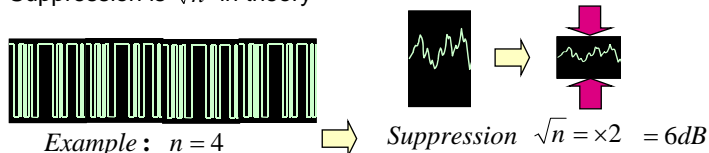
## MLS - Why?



- MLS means Maximum Length Sequence  
It's a pseudorandom binary sequence, widely used for "white noise" generation



- The crest factor (Peak/RMS) is low, an advantage for a loudspeaker sound source
- Convolve with microphone signal to get room impulse response
- Suppress uncorrelated background noise by increasing sequence length (or repeating sequence)  $n$  times  
Suppression is  $\sqrt{n}$  in theory



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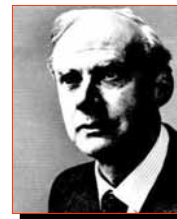


## What is DIRAC ?

- Dual Input Room Acoustics Calculator
- PC software
- Single or dual channel measurements
- Calculates room acoustical parameters
- Follows ISO 3382 and IEC 60268-16



**Paul Adrien Maurice Dirac (1902-1984)**  
The *singular delta function* was invented by Dirac, and is used in many different areas of mathematics, physics and acoustics.



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## DIRAC Measurement (1)



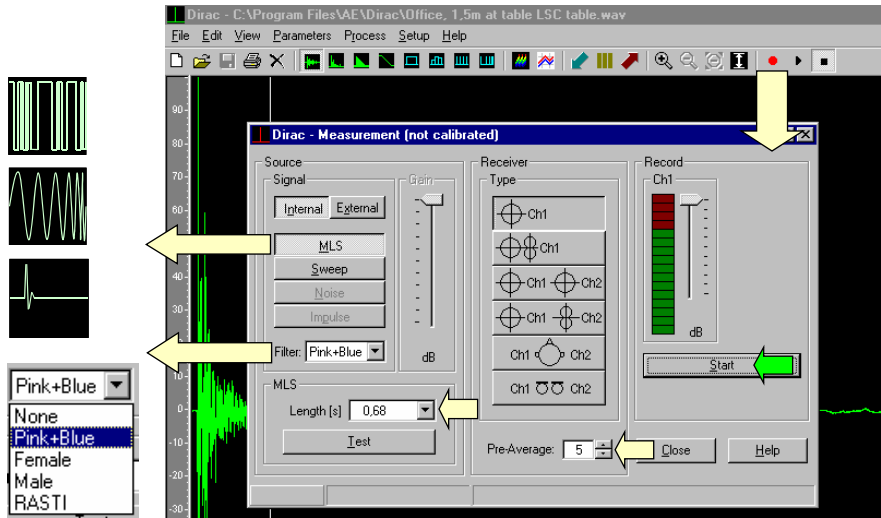
Sound Card Calibration

- Connect Line Out to Line In
- Start automatic calibration
- Sound card control and specifications are tested and improved
- Save calibration data for use in measurements
- Measure loop-back response ("Dirac" impulse)

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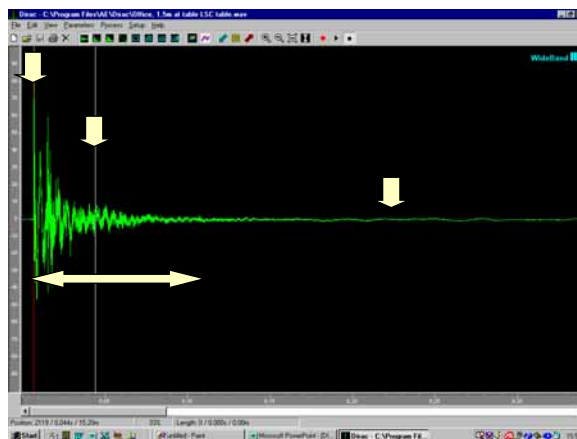
## DIRAC Measurement (2)



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## DIRAC Measurement (3)



Parameters

Levels - C:\Program Files\VAE\Dirac		
63	125	250
INR [dB]	10	>39 50

**Measurement Result:**  
Impulse Response .wav file

**Postprocessing:**  
Parameters are calculated  
from the .wav file

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## Room Acoustic Standards

- Room Parameters ISO 3382  
EDT, T20, T30, C80, D50, Ts, LF, LFC, IACC, G
- Stage Parameters Gade  
STearly, STlate, STtotal
- Speech ISO 60268-16  
STI, STIPA, STImale, STIfemale, STITEL, RASTI, ALC



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## Room Acoustic Parameters - Value examples

Recommended values for symphonic music in concert halls

- Reverberation Time T30 1,7 - 2,3 s
- Clarity C80 -1 to -3 dB
- Strength G > 3 dB
- Early Support STearly > -13 dB
- Total Support STtotal > -12 dB

Limit values for dwellings, public spaces and workspaces

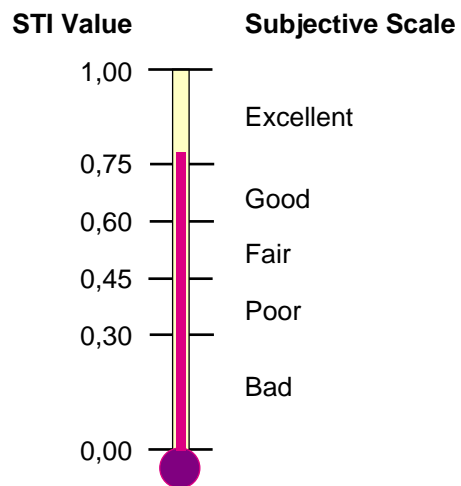
- Reverberation Time T30 See building regulations
- Speech Intelligibility RASTI See contract

The values are from the ODEON user manual section 7

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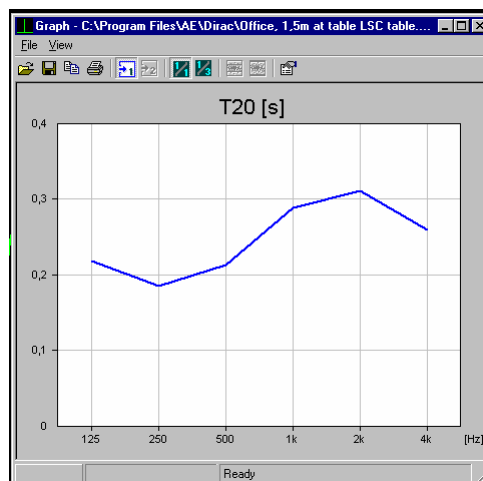
## Parameters - Speech STI scale



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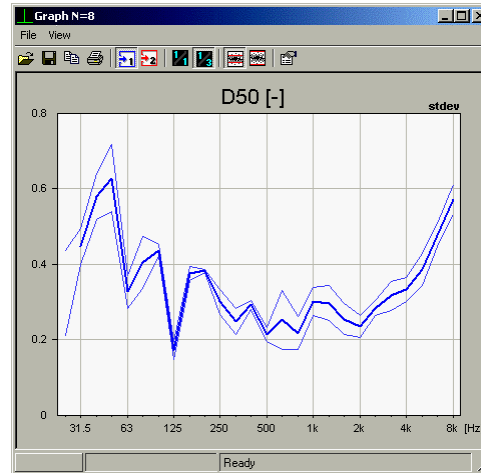
## Room Acoustic Parameters - Graphs (single)



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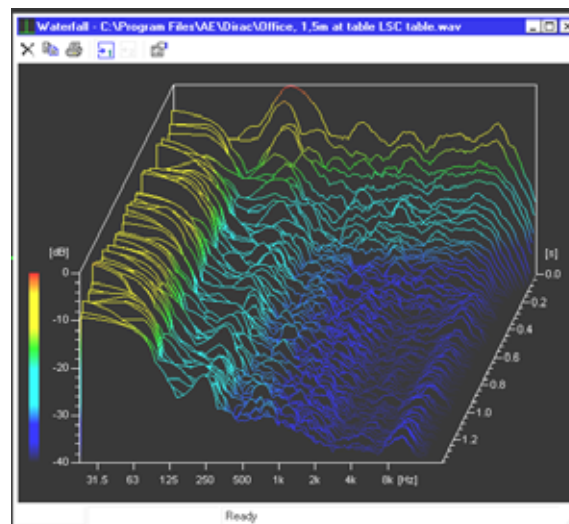
## Room Acoustic Parameters - Graphs (multiple)



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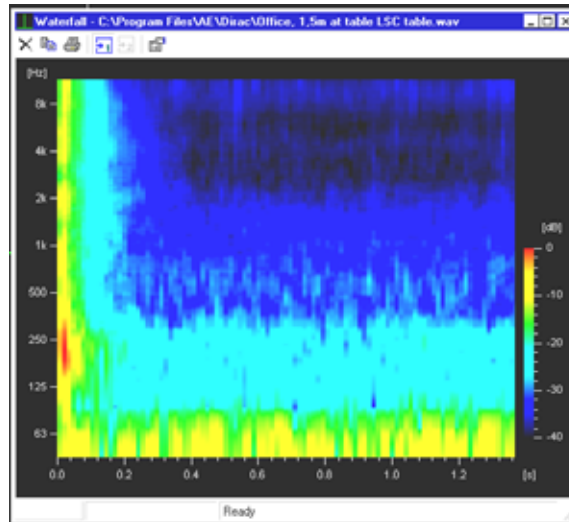
## 3D Graphs - TSS Waterfall (Time Shifted Spectra)



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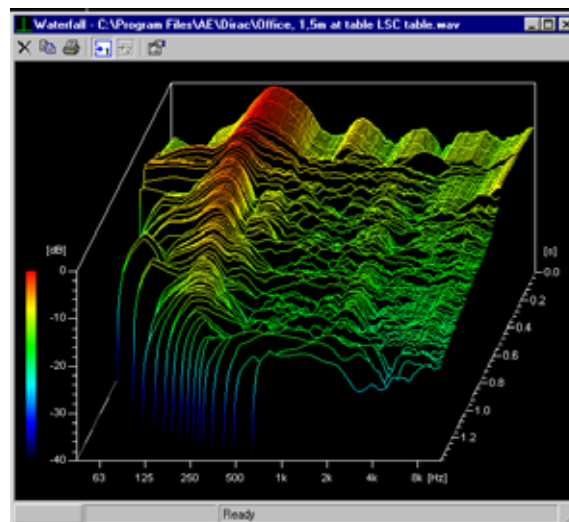
### 3D Graphs - TTS Spectrogram (Time Shifted Spectra)



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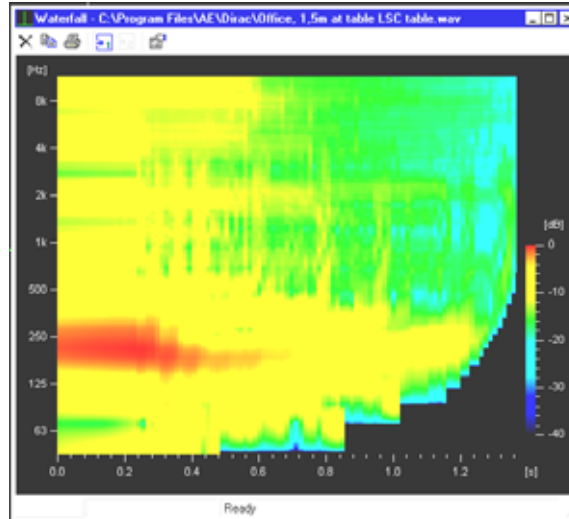
### 3D Graphs - CSD Waterfall (Cumulative Spectra Decay)



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## 3D Graphs - CSD Spectrogram (Time Shifted Spectra)



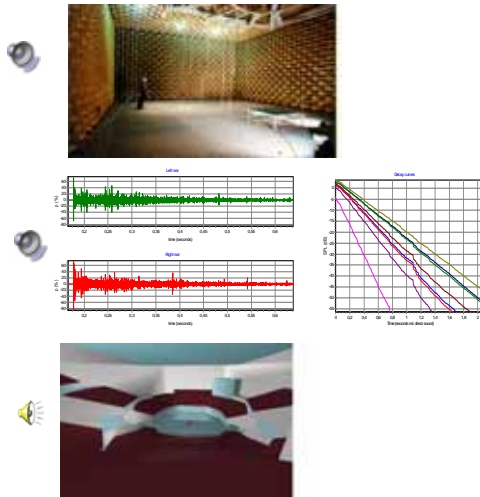
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## Only 1 more thing to do with Impulse Response

### Auralization

- Anechoic input signal
- is convolved with BRIR  
Binaural Room Impulse Response
- to give sound at receiver  
Listen using headphones
- Use for analysis and demonstration

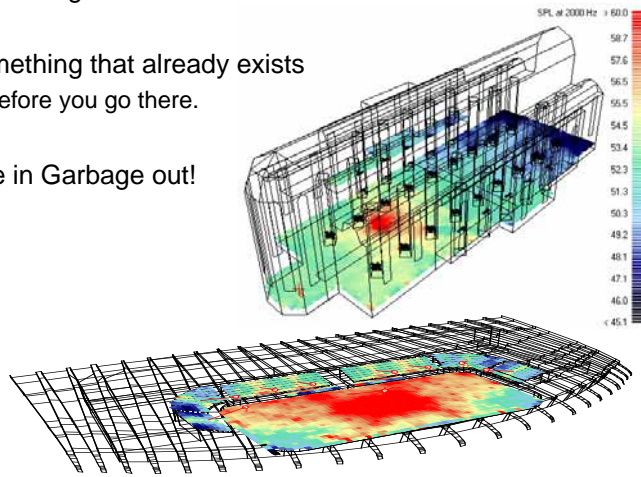
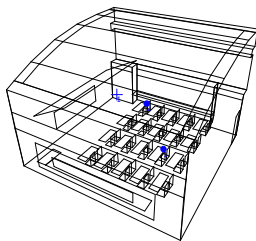


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## Modeling

- You can model something that doesn't exist!
- You can model something that already exists
  - and “measure” before you go there.
- Important: Garbage in Garbage out!

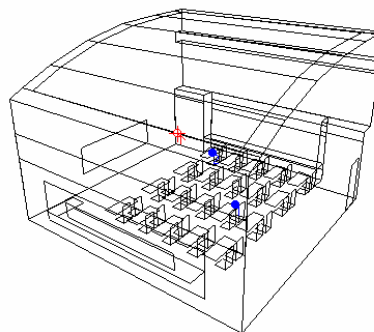


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## Modeling Applications

- Concert halls
- Opera halls
- Foyers
- Auditoria
- Classrooms
- Open plan offices
- Stadiums (incl. open air)
- Gymnasiums
- Airport terminals
- Train stations
- Factory halls



Room Dimension

greater than

3 Wavelengths



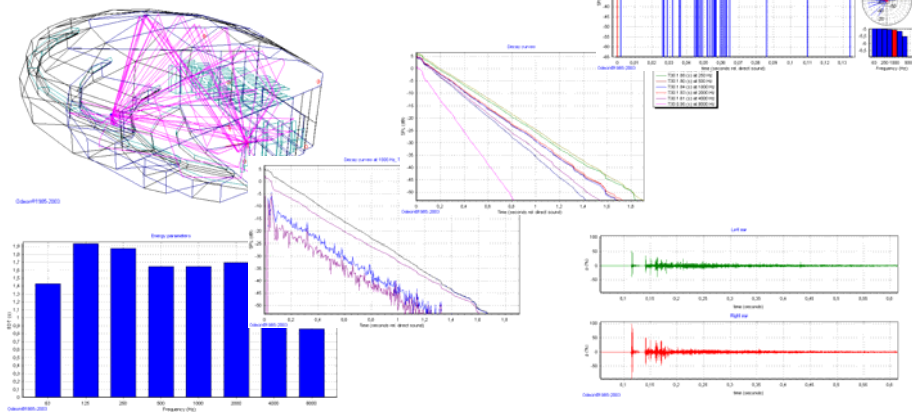
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## Calculated Results –

### Measurement Parameters and more

- Analysis at selected Receiver
- Auralization



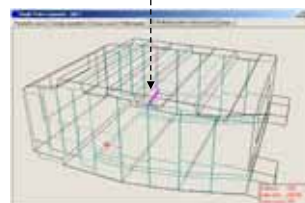
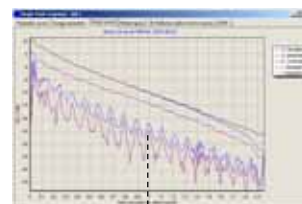
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## Modelling Advantage: Tracking down Echoes

### Directional Decay

- Directional part of decay shown  
Activate by using the A shortcut
- Click on reflection in decay to see its origin
- Diffuse field  
if directional decay is 6 dB below energy decay and parallel
- Non-diffuse field  
if less than 6 dB difference and narrowing



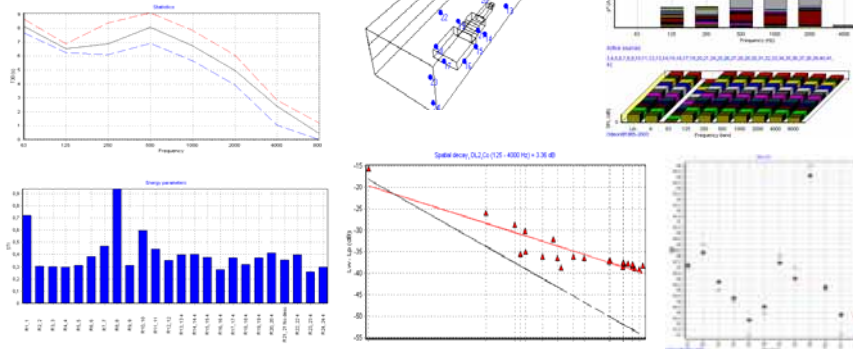
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## Easy to do comparisons

### Multi Point Response

- Analysis at selected Receivers
- Comparisons and correlations
- Noise Control assessment



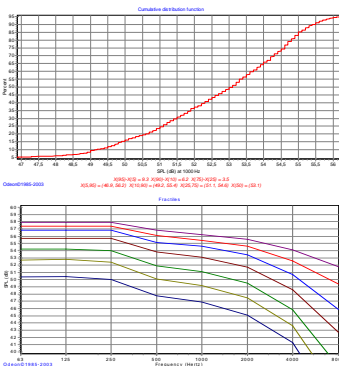
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## Area graphs

### Grid Response

- Mapping of Receivers
- Cumulative statistics
- Fractile graph



### You define a Receiver grid by

- Room surface(s)
- Receiver height above surface
- Receiver spacing

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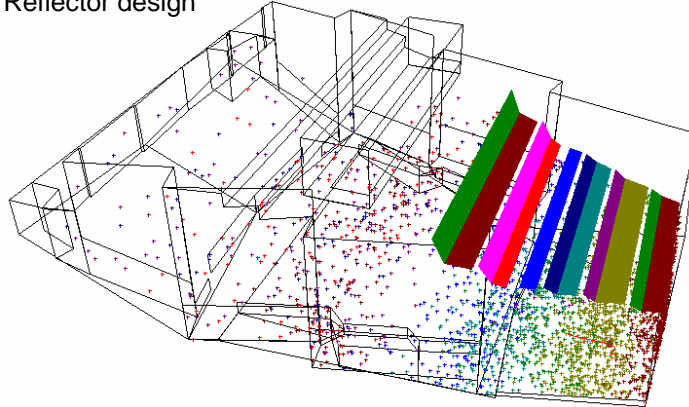
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## Tools to improve your room acoustics

### Reflector Coverage

- Shows Reflector coverage
- Validates Reflector design



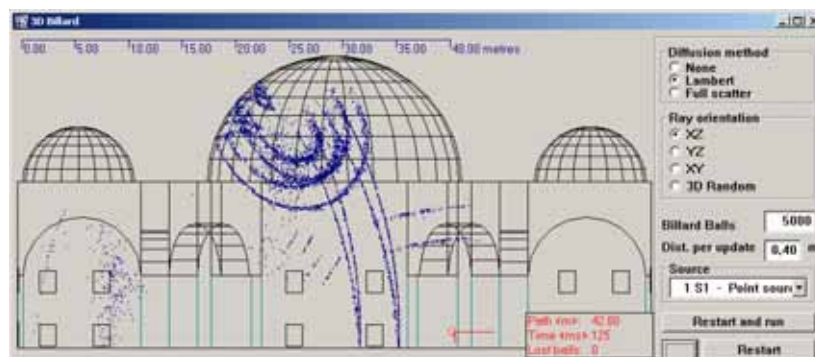
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## Animation Tools

### 3D Billard

- Visualize wave-fronts
- Investigate scattering effects
- Investigate possible echo problems



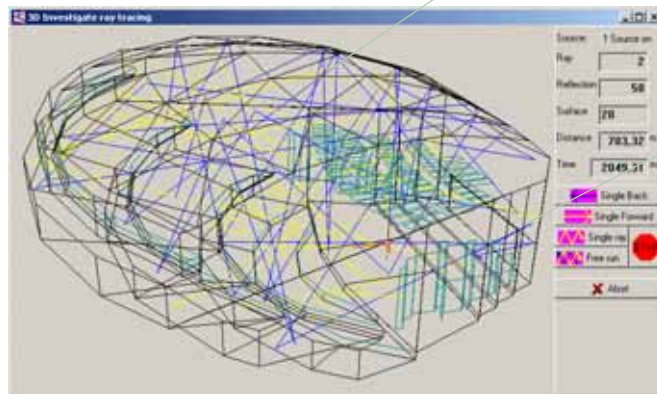
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## ODEON Animations, Cont.

### 3D Investigate ray-tracing

- Verify water tightness of geometry
- Investigate scattering effects



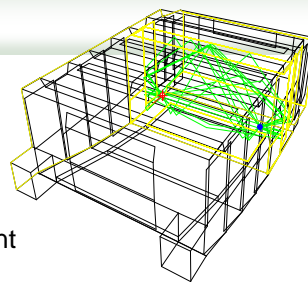
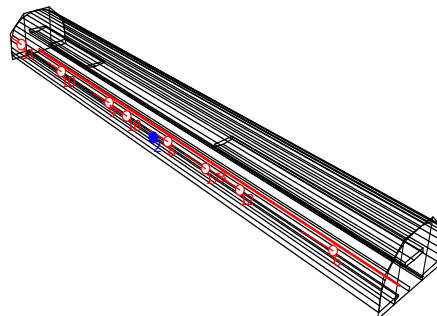
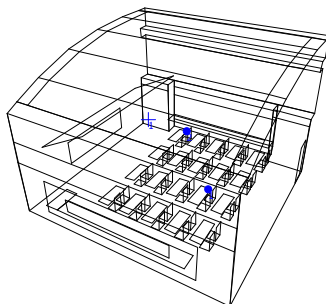
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## ODEON Results - Auralization

### Examples of Auralization

- Flutter echo - before and after treatment
- Underground train station with PA system
- Classroom with and without acoustic treatment



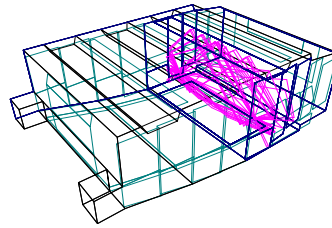
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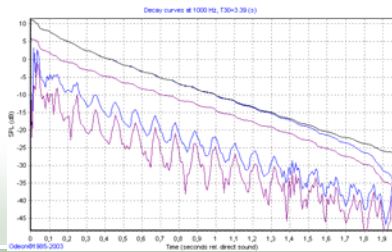
## ODEON Results - Auralization

### Flutter Echo in Concert Hall

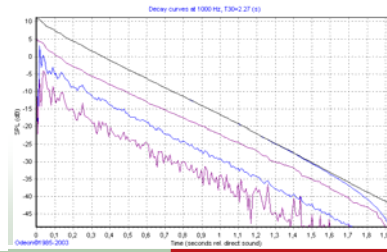
- Without diffusing panel
- Diffusing panel removes echo



Without diffusor

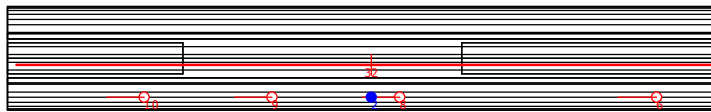


With diffusor



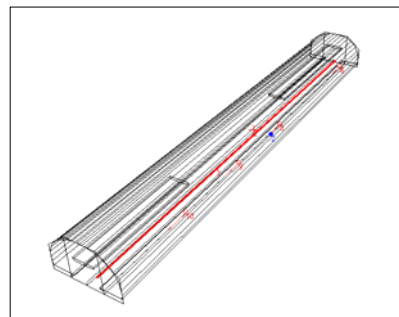
## ODEON Results - Auralization

0.00 20.00 40.00 60.00 80.00 100.00 metres



### Underground Station

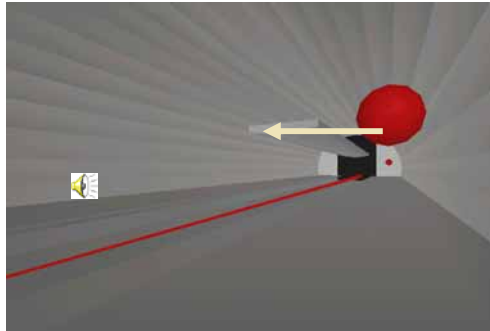
- Train noise from line source
- Speech from four loudspeakers



## ODEON Underground Station

### Train stopping

- Loudspeaker message
- Noise from passing train
- Reverberation time 8 s



Train anechoic recording



Speech anechoic recording

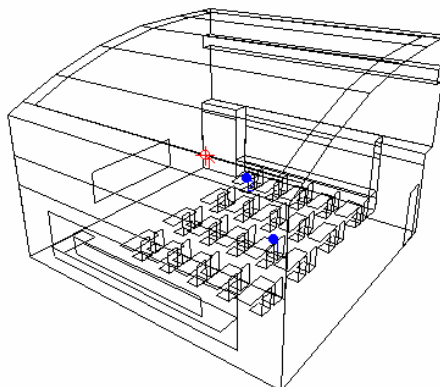


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## ODEON School Project

### Classroom Model



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## ODEON School Project

### Original Acoustics



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## ODEON School Project

### Absorption Added

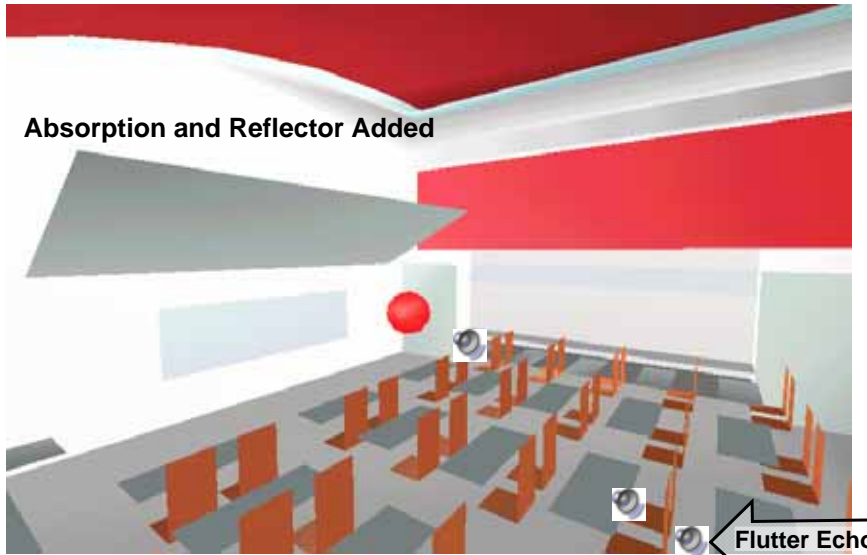


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## ODEON School Project

### Absorption and Reflector Added

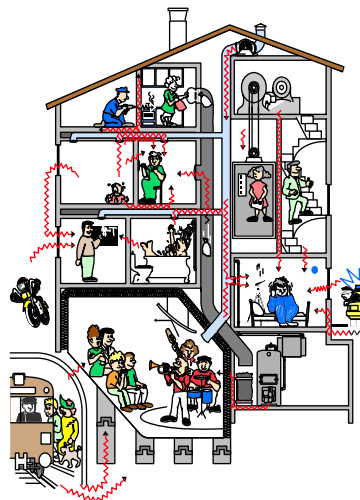


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## What are Building Acoustics

- A part of the Community Comfort Market (B&K's definition)
- A part of the Architectural Acoustics applications and interior noise and noise control.
- Concerned with building quality and community noise annoyance
- Which is a big part of the consulting work done by acoustical consultants

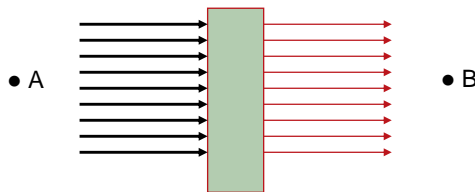


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## A bit of terminology

- Noise reduction is the difference between the sound level at point A and point B
- Transmission Loss is the reduction in sound power as it is transmitted between point A and point B
  - $TL = L_{wincident} - L_{wtransmitted}$
- Insertion loss is the difference in sound level before and after a “modification”

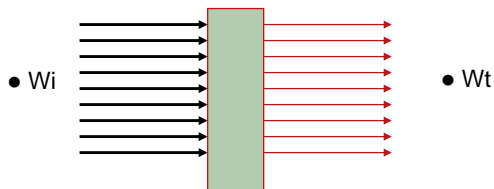


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## Sound Power Transmission

- Sound Transmission Coefficient =  $\tau = W_t/W_i$
- Transmission Loss =  $TL = 10 \cdot \log(1/\tau)$



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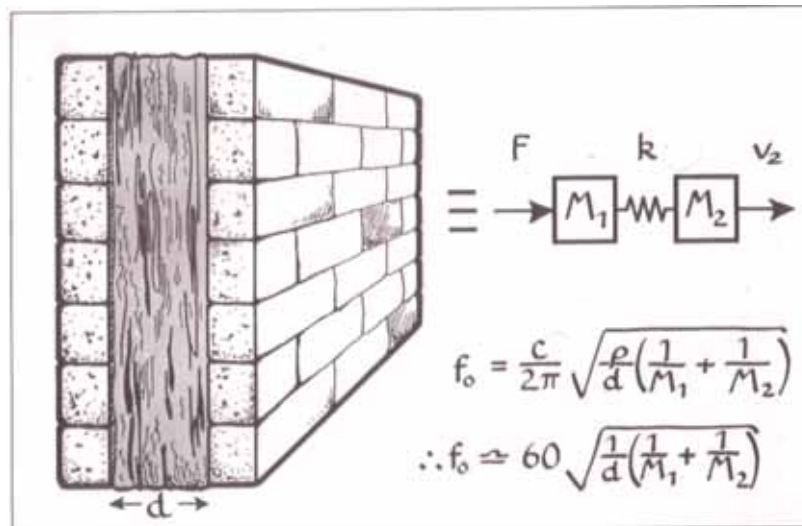
## Multiple Layer Walls increase Transmission Loss

- $TL \sim 20\log(f) + 20\log(M) - 47$
- $TL \sim 20 \cdot \log(Md) + 34$  (at 500 Hz)
- At 500 Hz
  - Solid with  $M=10\text{kg/sq.m.}$ 
    - » 27 dB
  - Two layers together
    - » 34 dB
  - Two layers and separate by 10 cm
    - » 40 dB

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## Multiple layers introduce new “resonances

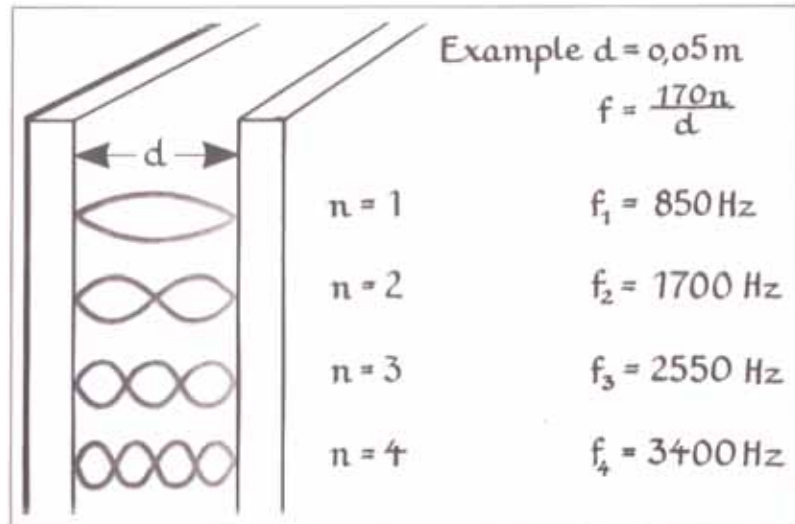


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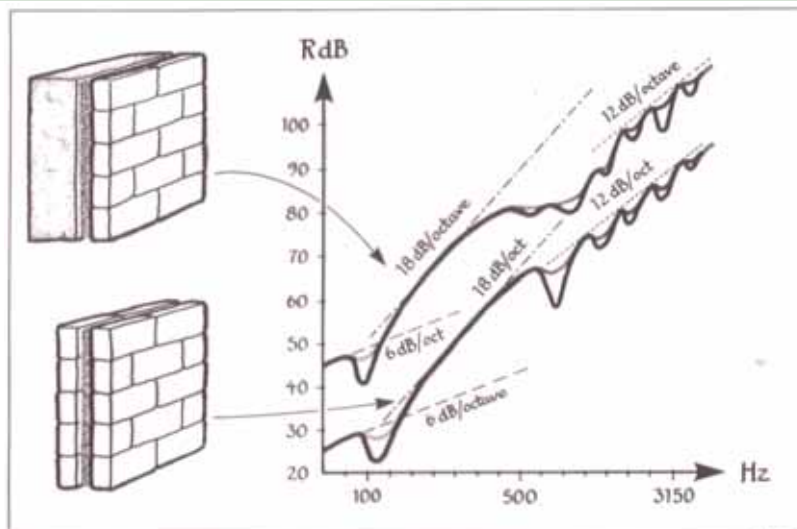
## Cavity Resonances



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## Complex Walls



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## Sweating the Details

edge detail		lab STC performance on experimental perimeter		
	Unsealed	19		Two beads of caulk each side 51
	Single bead of caulking under track	30		Two beads of caulk each side and one under track 52
	Single bead of caulking under inner layer of gypsum board	48		Six rows of caulk bead, two at each side and two under track 54

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## Standard Ratings of Isolation

- STC- Standard Transmission Class

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## Isolation Between Spaces

- Regulations
  - Unified Building Code – STC 45
- Use Driven
  - Speech Isolation

STC	Hearing Quality
25	Normal speech understood
30	Normal speech heard/ Loud speech understood
35	Loud speech heard
42	Loud speech audible
45	Loud speech not audible
50	Stereo just heard

## Isolation Between Spaces (cont.)

- NC Goal (or hearing protection) for other than speech isolation
  - »  $L_p(\text{in source room}) - NC = NR$
  - »  $NR = TL + 10 \log(Sw/A)$
- Select wall construction meeting TL goal from literature
  - » Get manufacturer test data
  - » Don't try to calculate yourself
  - » Add 5 dB for safety factor
  - » Remember STC is for speech!!! What are you isolating??

## Building Acoustic Measurement Tasks...

### Tasks

There are three kinds of BA measurement (Tasks), depending on the purpose:

- **Airborne sound insulation** is the sound insulation from one room (the source room) to another (the receiving room).  
It is calculated from the Leq spectrum for the average source room level L1, average receiving room level L2, receiving room background noise level B2 and average reverberation time T2.
- **Facade sound insulation** is airborne sound insulation with the "source room" being the space outside a building, and the receiving room being inside the building
- **Impact Sound Level** is the sound level in the receiving room from a standardized tapping machine in the source room.

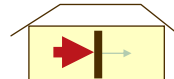
Sound insulation refers to a specific part of a building, e.g. a wall, floor or window. *Partition* is the common term used in all tasks. For each task, a result spectrum and single-number result is calculated and reported. The report format must follow international and national standards.

*But also... troubleshooting noise problems (FFT – sound and vibration), assessing noise levels relative to the purpose of the room (Noise Criteria, EDT, Speech Intelligibility, etc.) and occasionally using sound-intensity to identify leaks and noise sources.*

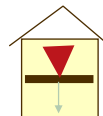
## Types of Measurement

A  
S  
T  
M  
  
S  
T  
D

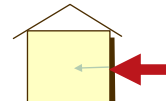
- Airborne sound insulation .....



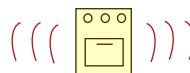
- Impact sound level .....



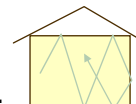
- Facade insulation .....



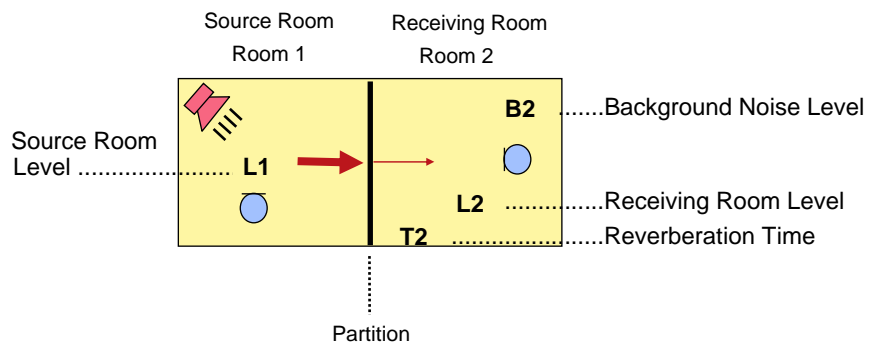
- Installation noise .....



- Reverberation time .....



## Airborne Sound Insulation - Measurements

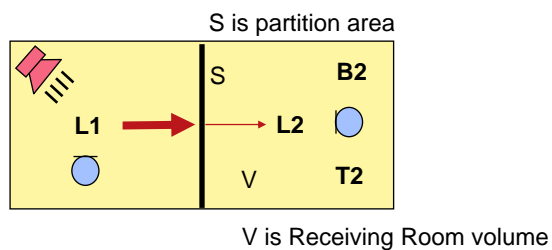


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## Calculating sound insulation

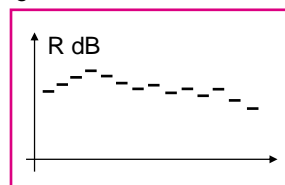
Example: Sound Transmission Loss



Sound Transmission Loss  

$$R = L1 - L2(B2) + 10 \log(ST/0.16V)$$

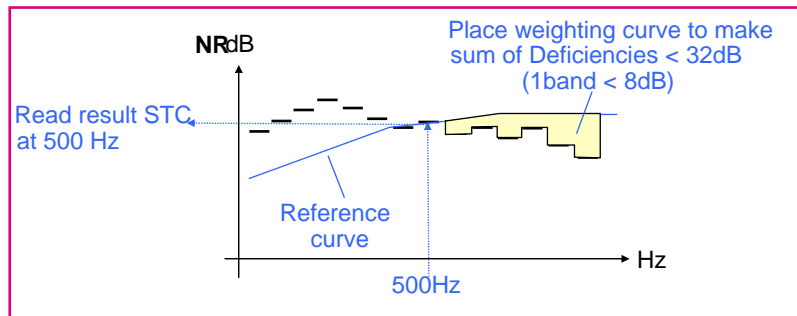
... this is a 1/3 octave Transmission Loss (TL) spectrum  
 (without the Absorption correction it is called a  
 Noise Reduction (NR) Spectrum)



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## Calculating sound insulation: weighting



**STC: Weighted Sound Transmission Class**

- single number, e.g. 52 dB

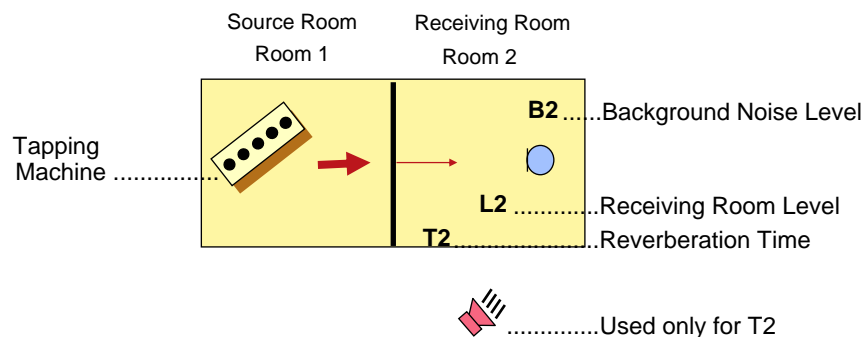
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## Impact Sound Level - Measurements

Similar to Airborne, except:

- L1 is not measured
- Tapping machine is used



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## Instrument Requirements



Investigator™  
Type 2260D



Building  
Acoustics  
Software  
BZ7204

- **Pink and white noise generator**
- **Measure**
  - 1/3 and 1/1 octave bands (depending on standard)
  - level and reverberation time spectra
- **Calculation and display of.....**
  - Average of positions
  - Sound reduction spectra (R', DnT, **NR**, **FTL**....)
  - Weighted indices (R'w, DnTw, **NIC**, **FSTC**.....)
  - Reverberation Time and Decay Curves
- **....according to the following standards**
  - ISO, SS, DIN, ÖNORM, BS, Sia, UNI, NF, UNE, NEN, **ASTM**

*The 2260 Investigator has it all*

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## Now the 2250 and 2270 have it all, too!

- Single (BZ7228) or Dual Channel Applications available (BZ7229)
- Single Channel on 2250 or 2270; Dual Channel on Type 2270 ONLY
- Systems and kits (add-ins) available
- Same accessory and cables as Type 2260D building acoustics systems
- With a few advantages...

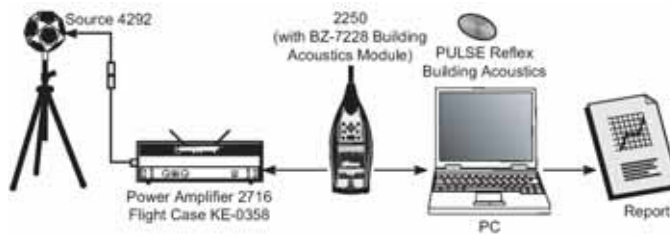


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## Type 2250

- Single-channel measurements
- Sound recording
- Possibility to add spoken or written comments to measurements



Optional software: BZ5503 and Qualifier type 7830. Software for reporting and post processing of results from Type 2260D (Building Acoustics Application)



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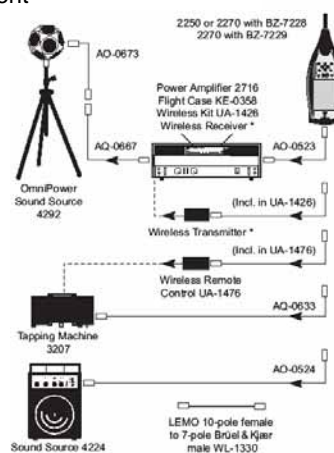
## Type 2270 & 2250

2270 only :

- Camera option to document the test environment
- Up to two-channels

2270 and 2250 :

- Built-in pink and white noise generator
- Equalisation of sound source spectra
- Position management and sound recording



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## New for Euronoise 2009

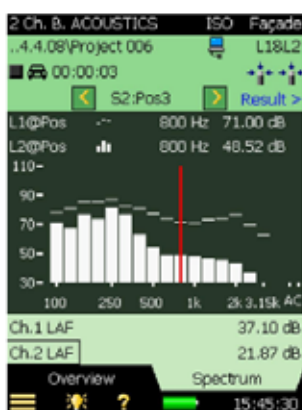
- Introducing the new Type 2734 light-weight, high power amplifier
  - 7Kg Mass
  - Built-in pink & white noise generator
  - Class D 500 W specification
  - Wireless remote control
  - Wireless source signal transmission



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## The Advanced Building Acoustics Analyzer



Dual parameter display of L1, L2, B2 or L1-L2 or L2-B2 as well as the current position measurement of a live LZF spectrum

Broadband level measurements

Simple touch screen navigation between displays.

Source and Receiving  
room measurement

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## Results Overview Screen

An easy to see overview of the many measurements in a Building Acoustics Project

We can now keep track of measurements when we move the source to a second position

BUILDING ACOUSTICS				ISO	AIR
CF-CardJob1VProject001				RESULT	
L1	L2	D2	T2		
S1: 1	S1: 1	1	1	1	
2	2	2	2	2	
3	3	3	3	3	Warning
4	4				
5	5				
S2: 1	S2: 1				
2	2				
3	3				
4	4				
5	5				

Touch a warning for its description.

Check or uncheck measurements to be included in the calculated results..

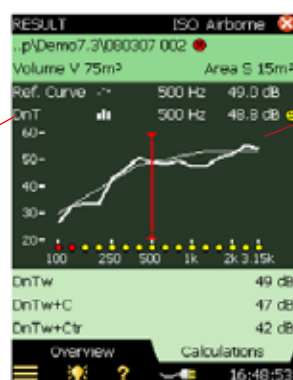
Real-time integrity checks & Planned measurements

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## Results Calculations Screen

Select the Calculated spectrum here



Show the result with or without the reference curve.

See the one number calculated NIC or STC Here

Results on the spot !

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## BZ5503 – Archive results as normal

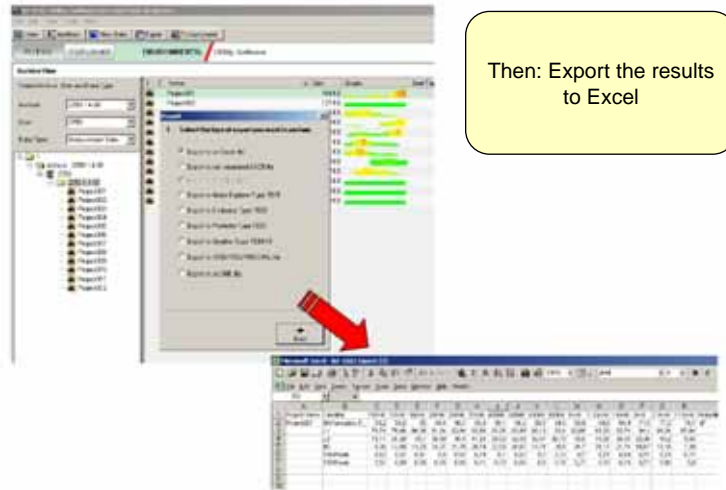
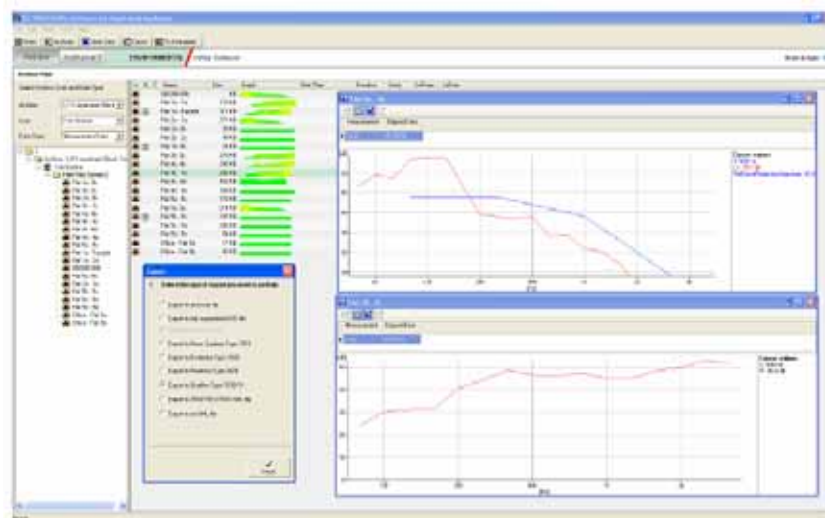


Fig 6. BZ 5503 utility software showing export to Microsoft Excel.

## Use BZ5503 to view calculated results



## PULSE Reflex Building Acoustics Reporting

**PULSE REFLEX™**  
The Product of Intuition



- Store, analyse, report – quickly
- Combine, compare, conclude
- Comply with standards

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## Pulse Reflex – Versatile, Powerful, Intuitive Post Processing

Type 2250



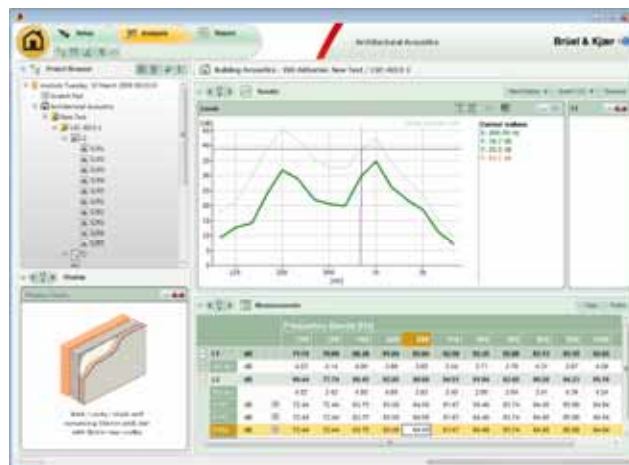
Type 2270



Type 2260



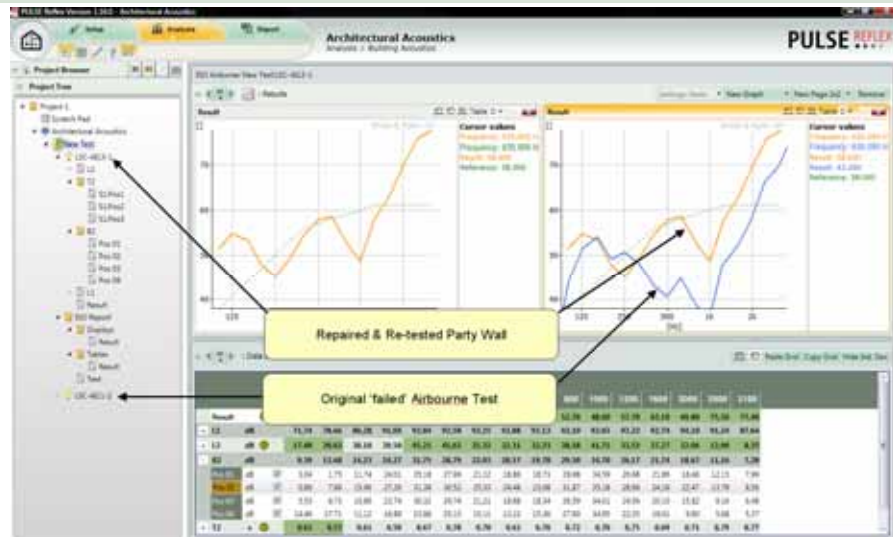
Microsoft Office Excel



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## Combine Results



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## Export to Qualifier

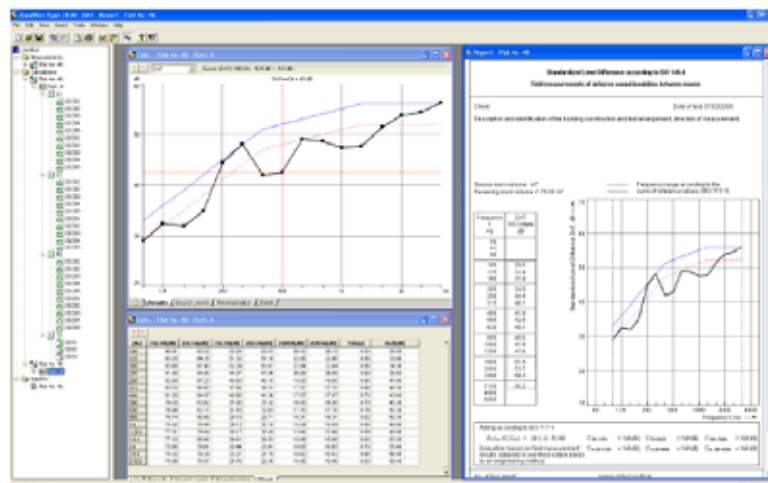
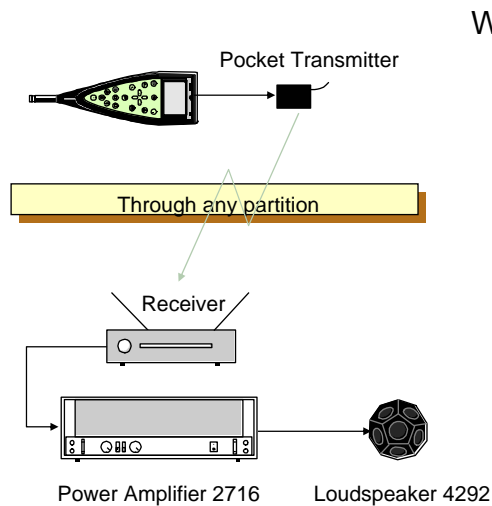


Fig 8 Qualifier PC software for analysis and report generation of building acoustic data

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## Freedom to move - Wireless Control



### Wireless Transmission Kit



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## Sound Sources



Omni-Source		Omni-Power
1	Speakers	12
3.5 kg	Weight	14 kg
105 dB	Lw	122 dB



OmniSource is for room acoustics

OmniPower is for sound insulation

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## Let's take a tour...

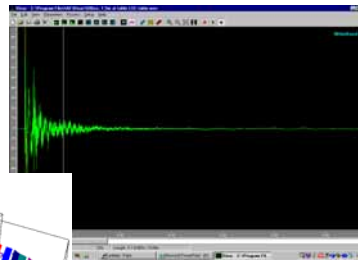
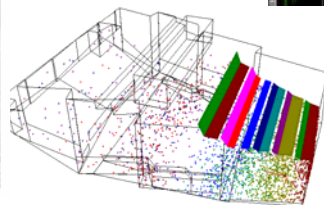


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## Summing up

Today we've looked at measuring and modeling Architectural Acoustical behavior. Brüel & Kjær offers a range of tools to assist the acoustician in assessing a condition and offering solutions



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## 25 Years Providing High Quality Building Acoustics Measurement Solutions



1980



1989



1996



2009