# Using Wave Based Geometrical Acoustics (WBGA) to investigate room resonances

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1. Overview of methods and the software used for the simulation and measurement

2. Some theory behind the measurement system IRIS

3. Some theory behind Olive Tree Lab-Suite

4. Results

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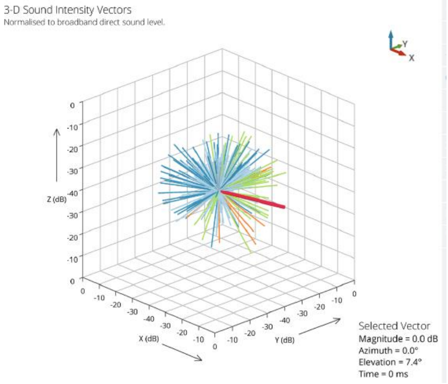
# Measurement system IRIS

The IRIS room acoustics measurement system, developed by Marshall Day Acoustics was used for capturing the impulse responses in 3D.

A compact tetrahedral microphone array is used to capture the sound data.

• The 3D impulse response data was converted from B-format to mono.

• Exported to WinMLS for further processing

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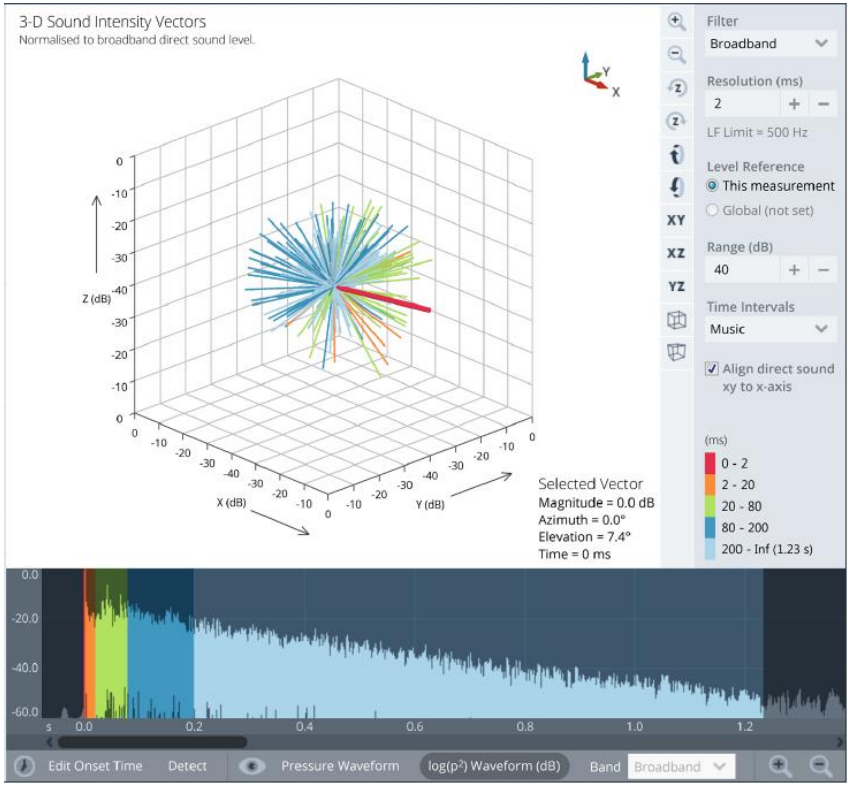
# Measurement System IRIS

**Omni-directional waveform view**
• Interaction between the IRIS plot and waveform view
• Automatic detection of onset time with manual adjustment

**Room acoustic parameters**
• Room acoustic parameters calculated in octave bands according to ISO 3382-1:2009
• Laboratory validated LF measurement
• Sound strength calibration and measurement
• Results are displayed in graphs and tables

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# Simulation software Olive Tree Lab-Suite

**WBGA**

- Wave Based Geometrical Acoustics.
- Spherical or plane wave propagation
- Complex pressure summation
- Impedance surfaces
- Image source method

**Accounting for**

- Reflection
- Diffraction
- Refraction
- Transmission

# Plane waves vs Spherical waves?

## Plane wave reflection coefficient

$$R_p = \frac{\cos\theta - 1/\beta}{\cos\theta + 1/\beta}$$

θ reflection angle

β Surface admittance

$\beta = \frac{1}{Z}$

When i this valid?

- Infinite plane

- Admittance constant over the whole surface

# Plane waves vs Spherical waves?

## Spherical wave reflection coefficient

$$Q = R_{\mathrm{p}} + (1 - R_{\mathrm{p}})F(w)$$

"Ground wave"

θ reflection angle

β Surface admittance

$$F(w) = 1 + jw\sqrt{\pi}e^{-w^2} erfc(-jw)$$

Boundary loss factor due to spherical wave front

$$w = \sqrt{jkR_2/2}(\beta + \cos\theta)$$

Numerical distance

$R_2$ Total path length

# Plane waves vs Spherical waves?

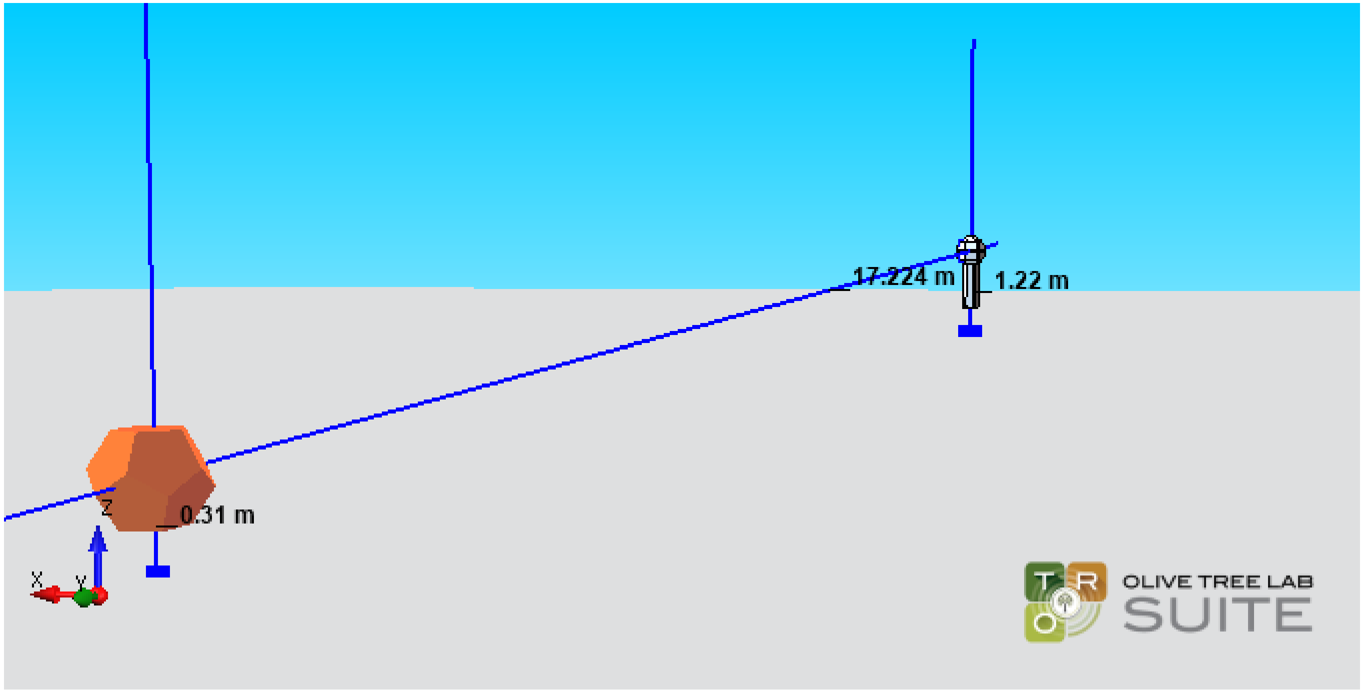
Plane waves are ok for hard surfaces at normal incidence

Not OK for gracing incidence

Not OK for high sound absorption

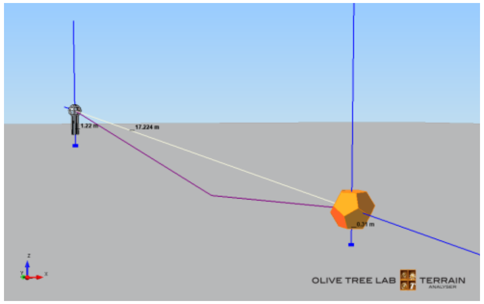
# Plane waves vs Spherical waves?

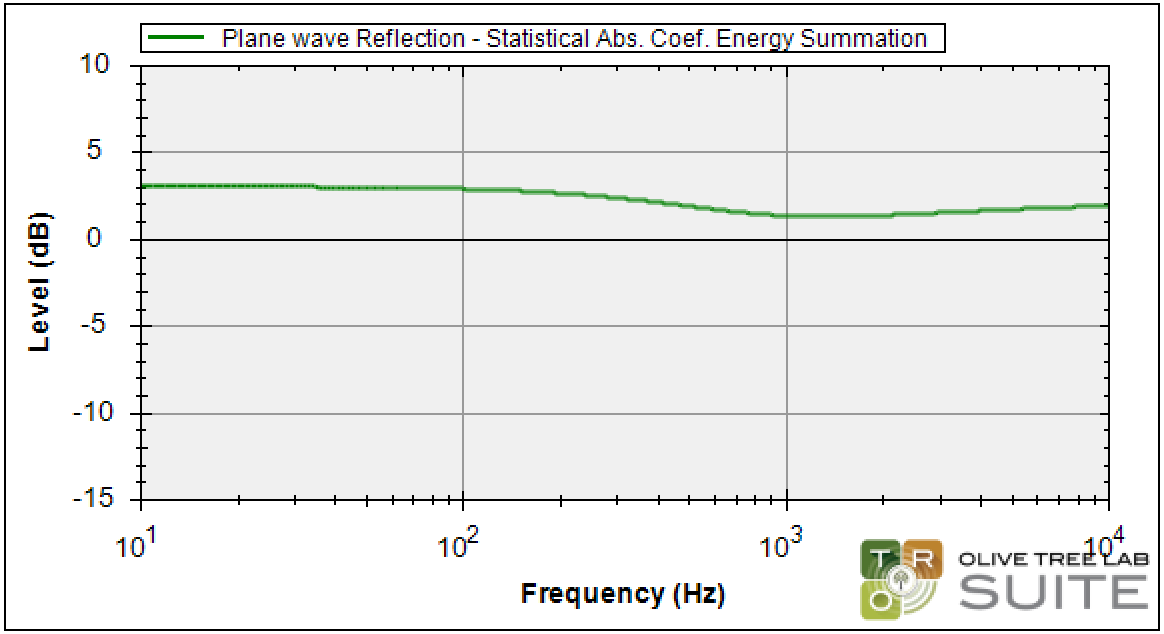
REFLECTION -
SOURCE – RECEIVER CLOSE TO A SURFACE
OF FINITE IMPEDANCE (flow resistivity of 300 kPa s m$^{-2}$)



# STATISTICAL REFLECTION COEFFICIENT
# Using equivalent abs. coeff. Energy Summation

$$\rho = 1 - \alpha$$

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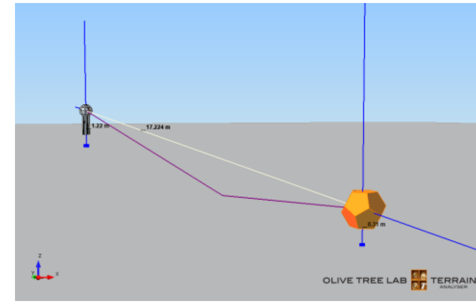
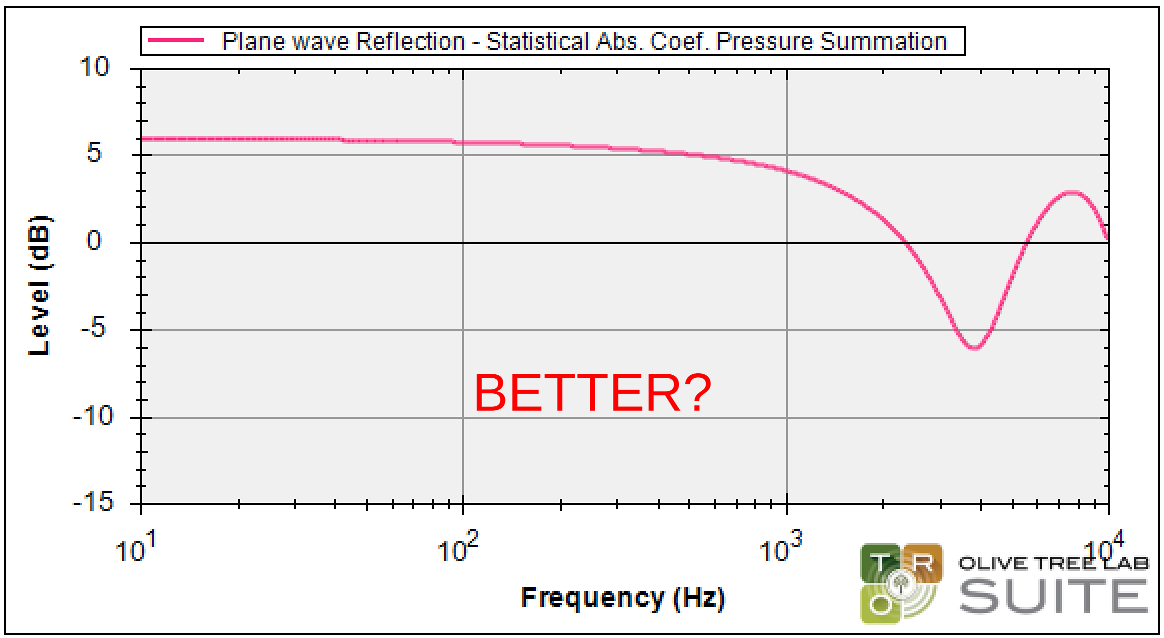
## PLANE WAVE REFLECTION COEFFICIENT
## Using equivalent abs. coeff. Pressure Summation




$$R_p = \frac{Z_m \cos\theta - \rho c}{Z_m \cos\theta + \rho c}$$

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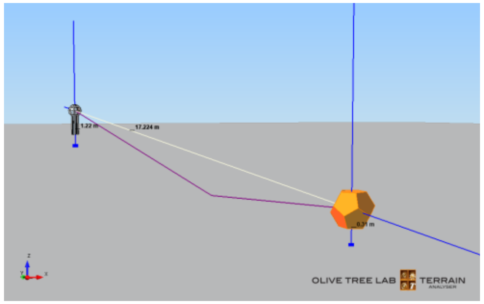
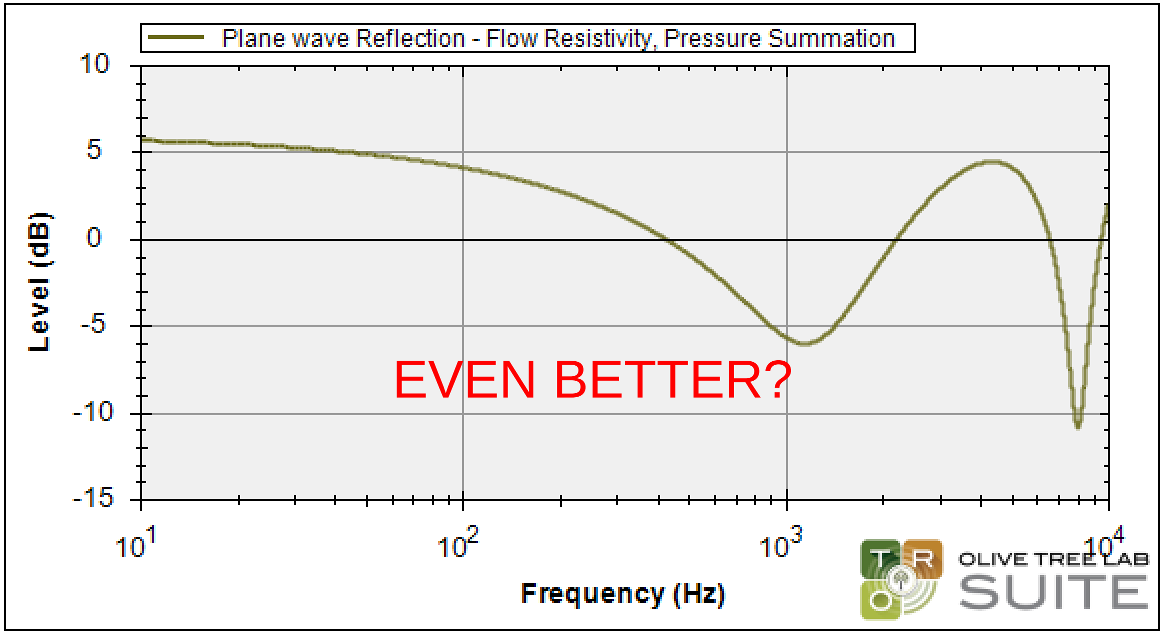
## PLANE WAVE REFLECTION COEFFICIENT
## Using flow resistivity, Pressure Summation

$$R_p = \frac{Z_m \cos\theta - \rho c}{Z_m \cos\theta + \rho c}$$

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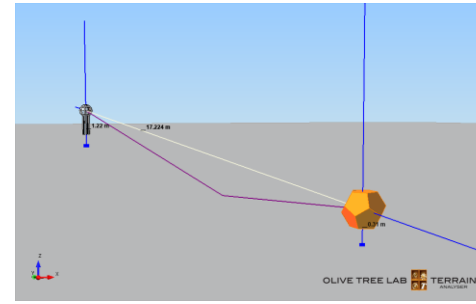
# SPHERICAL WAVE REFLECTION COEFFICIENT

## Using flow resistivity, Pressure summation

Credit, "Engineering Noise Control", By David A. Bies and Colin H. Hansen




$$R_s = R_p + BG(w)(1 - R_p) \qquad (5.146)$$

In Equation (5.146), $R_p$ is the plane wave complex amplitude reflection coefficient given by either Equation (5.142) or (5.144) as appropriate. For the general case that the reflecting interface is extensively reactive, $B$ is defined as follows:

$$B = \frac{B_1 B_2}{B_3 B_4 B_5} \qquad (5.147)$$

where

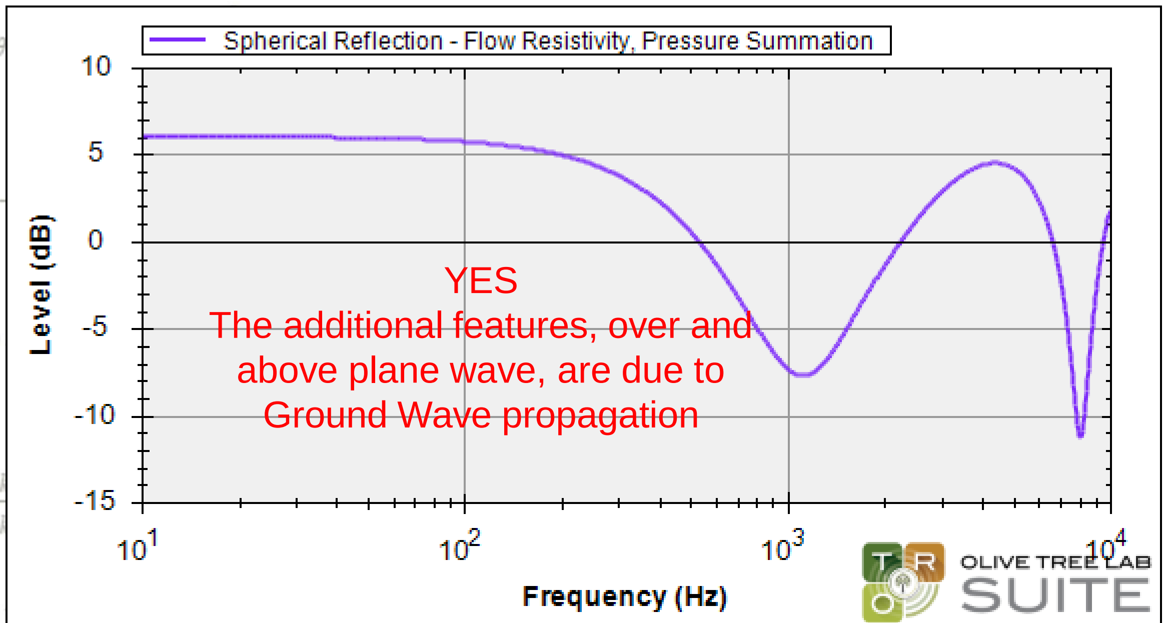
$B_1 = \left[\cos\theta \right.$

$B_2 = \left[\left(1 \right.\right.$

$B_3 = \cos\theta$

$B_4 = \left[1 - \right.$

$B_5 = \left[1 - \frac{}{\rho_m^2}\right]$




The argument, $w$, of $G(w)$ in Equation (5.146), is referred to as the numerical dist... and is calculated using the following equation, where $r_1$ and $r_2$ are defined in Fi... 5.14:

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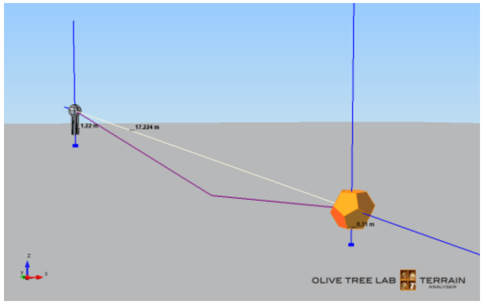
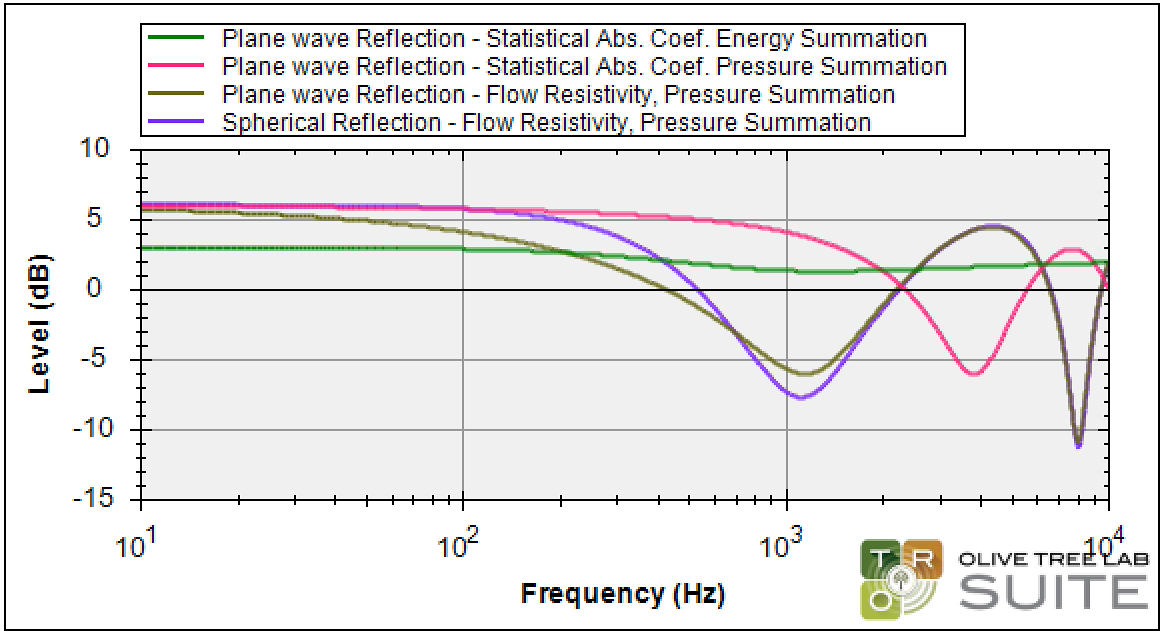
# ALL TOGETHER FOR COMPARISON

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# REFLECTION – PREDICTING GROUND WAVE

SOURCE – RECEIVER ON THE SURFACE

(of finite impedance, flow resistivity of 10 kPa s $m^{-2}$)

NO PLANE WAVE REFLECTION IS POSSIBLE


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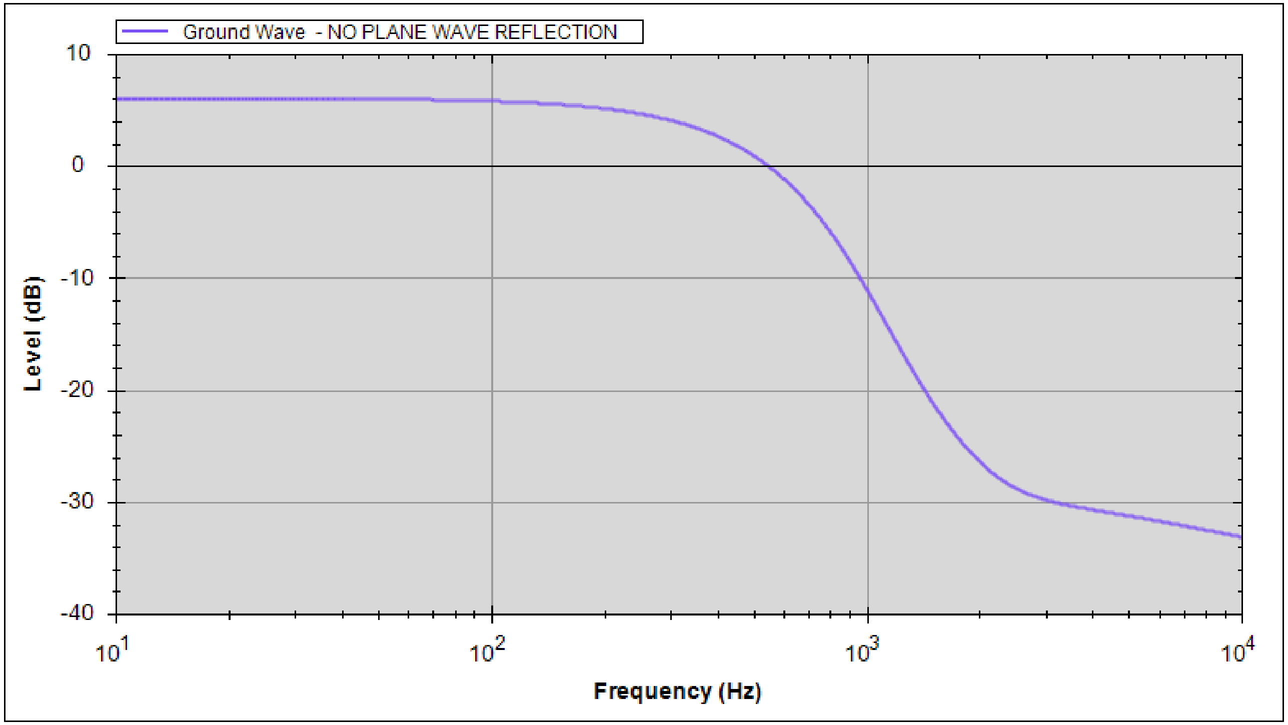
# SPHERICAL WAVE REFLECTION COEFFICIENT

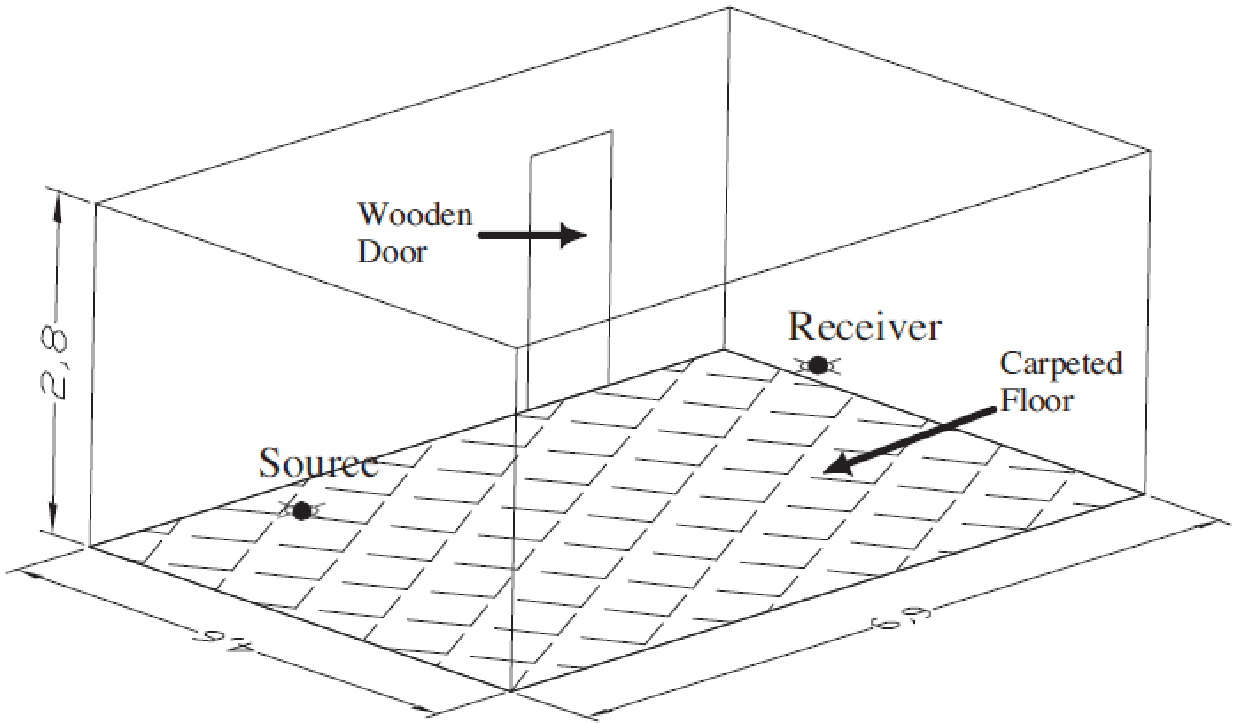
PREDICTS **GROUND WAVE**

WHEN PLANE WAVE REFLECTION IS NOT POSSIBLE

(finite impedance, flow resistivity of 10 kPa s m$^{-2}$)



# Example listening room from Lam's paper




*Acoust. Sci. & Tech.* **26**, 2 (2005)

**PAPER**

**Issues for computer modelling of room acoustics in non-concert hall settings**

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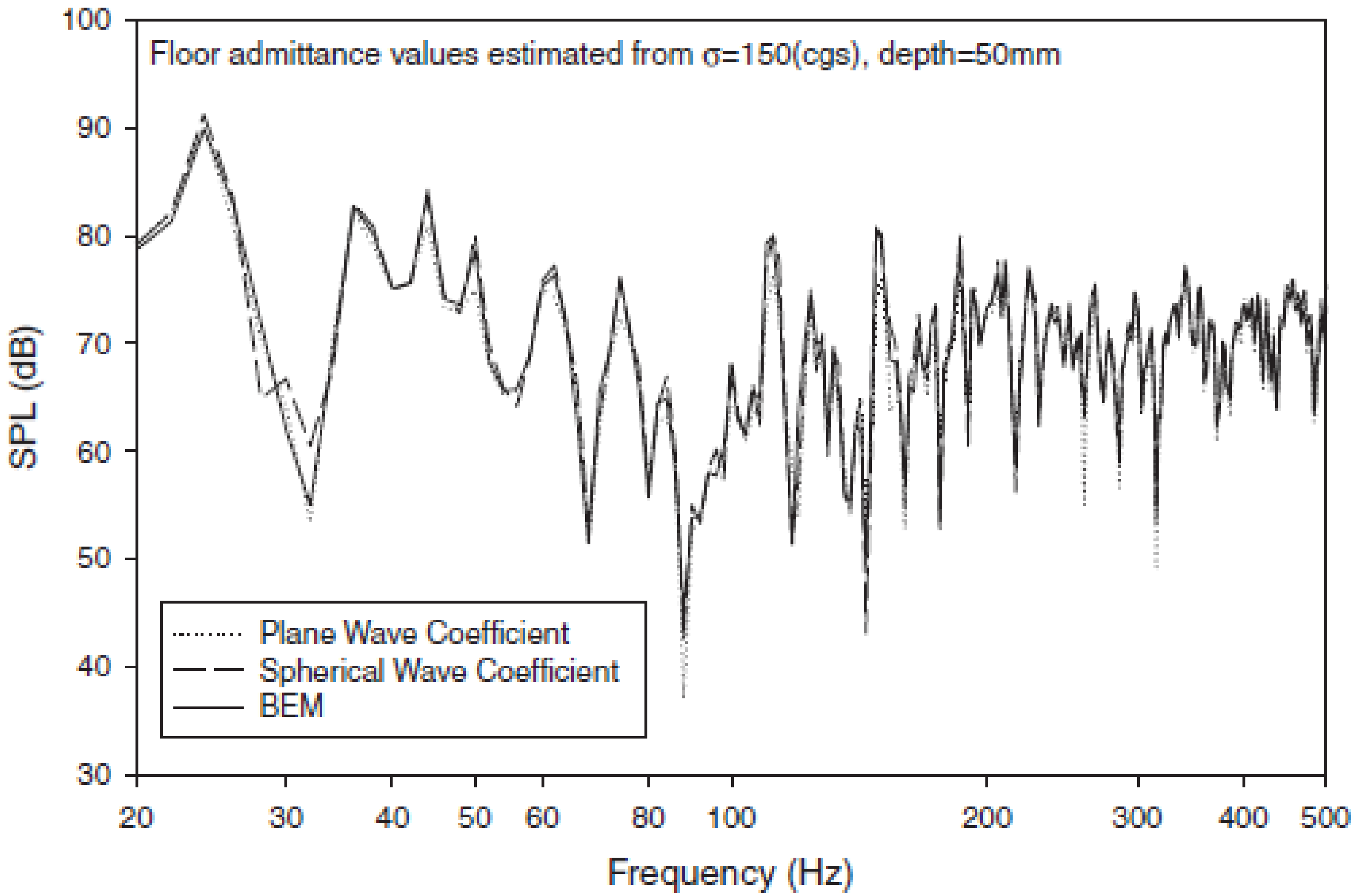
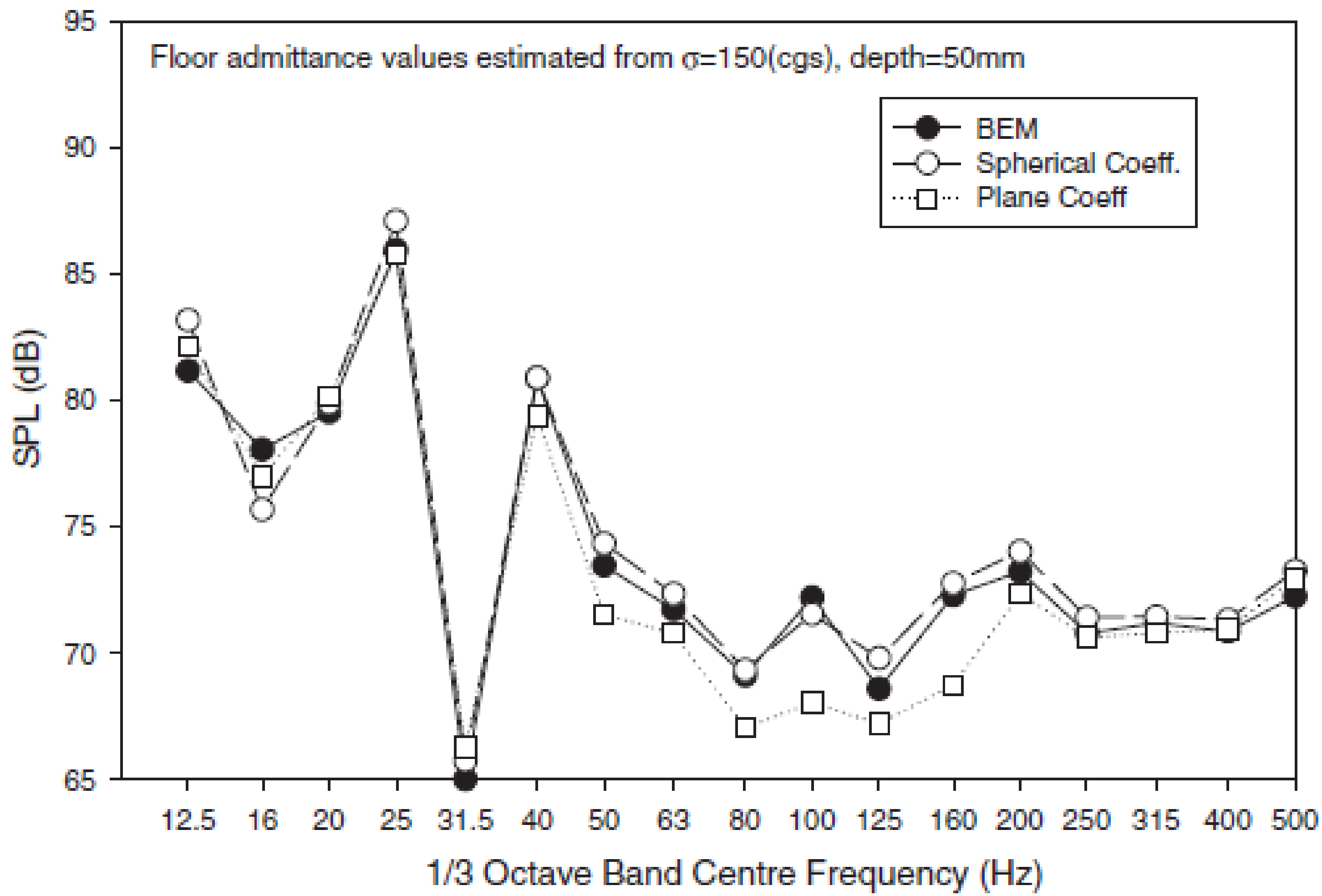
( *Received 7 July 2004, Accepted for publication 20 November 2004* )

# Example listening room from Lam's paper



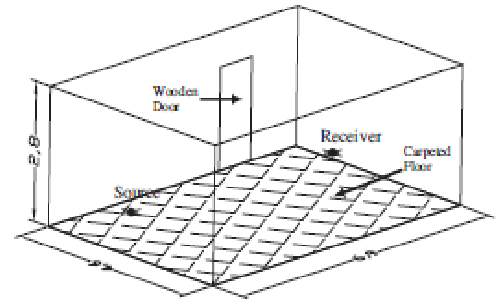
# Example listening room from Lam’s paper



# Validation of room resonances

From Lam's paper, where he proves that Spherical Reflection Coefficient matches BEM results.

- estimated reflection orders 80,
- our results with 23 orders (calc. time 19 hrs)




Y. W. LAM: COMPUTER MODELLING OF ROOM ACOUSTICS

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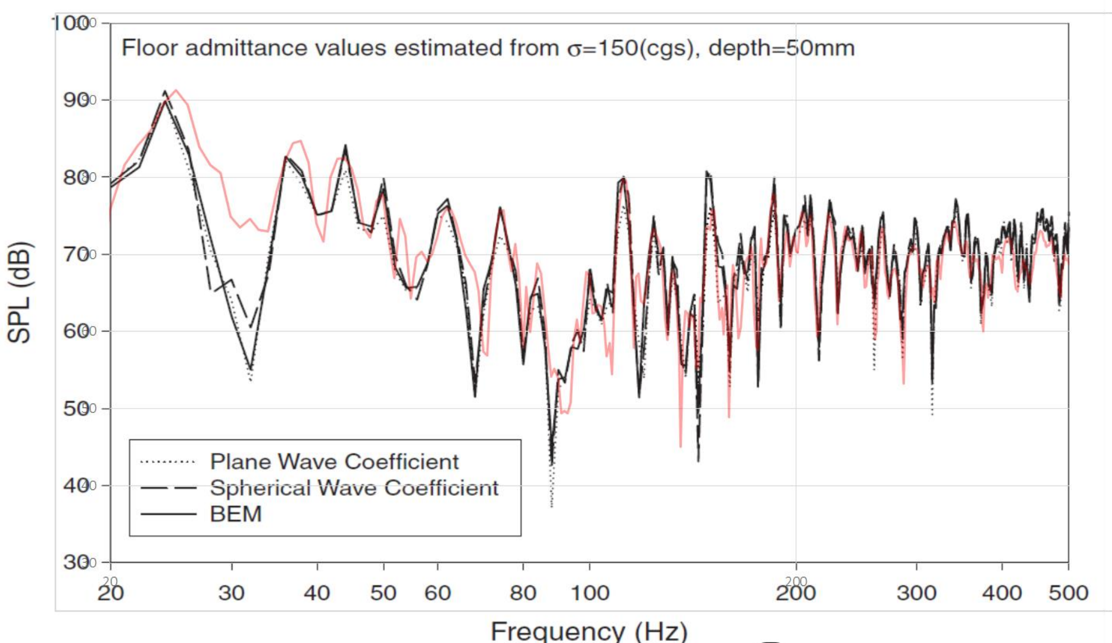


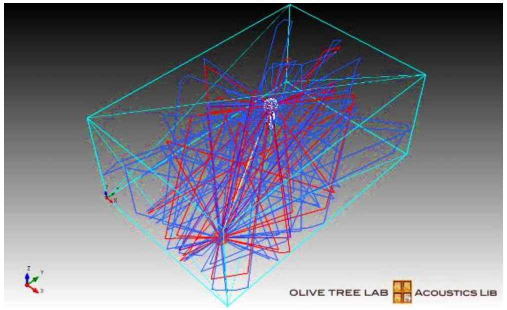


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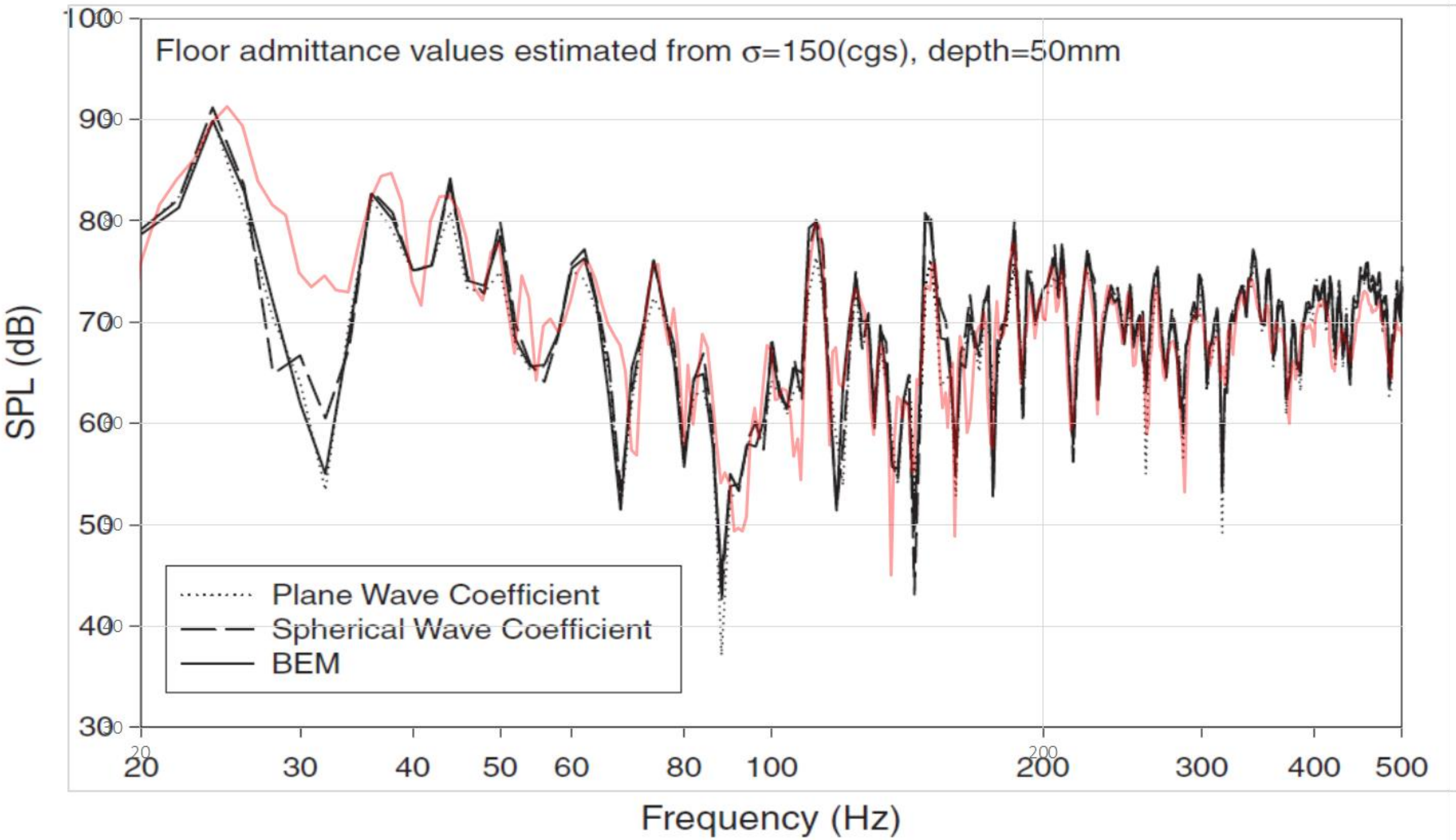
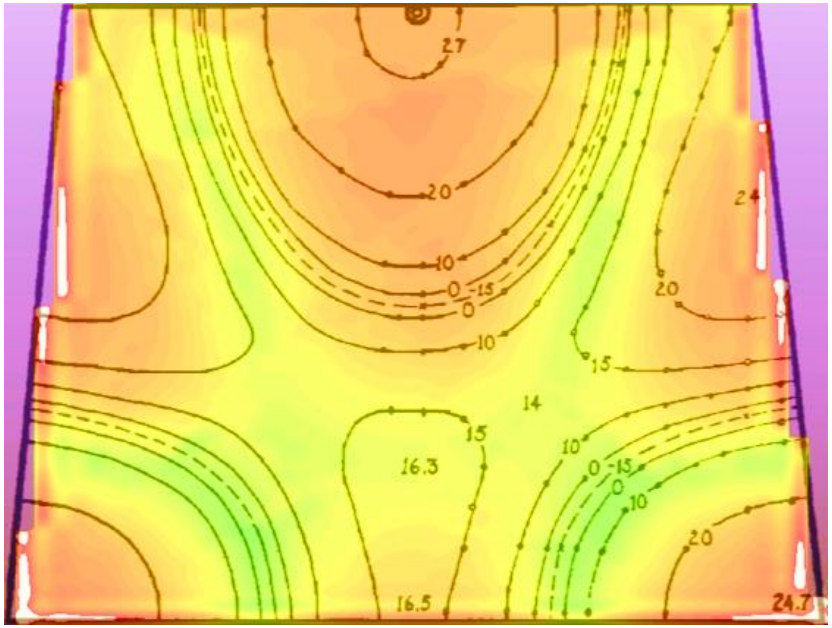
# Validation of room resonances



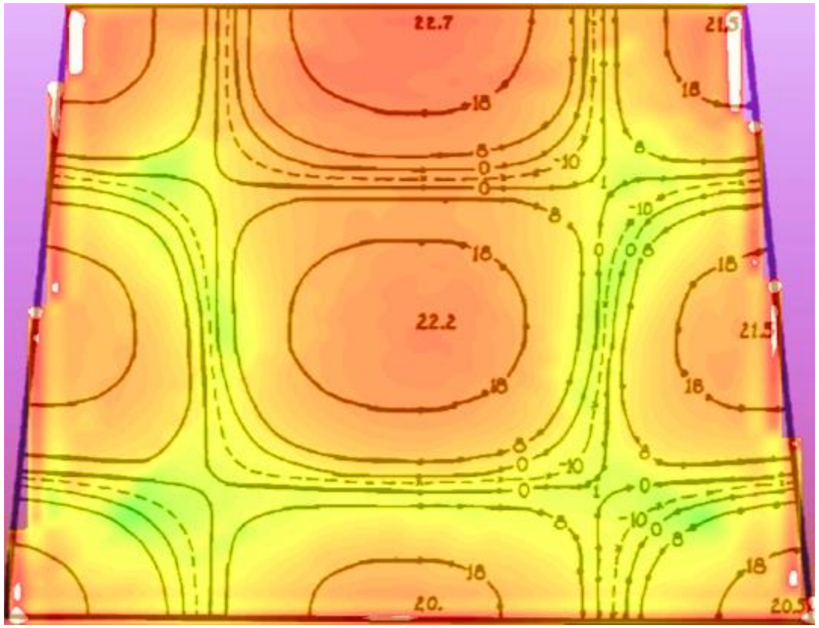
# Validation of room modes

Comparison to scale model (1:10) measurements of 2D room with non-parallell walls. Height small compared to sound wavelength. Figures in color is from OTL suite. From a paper by Bolt [5].

200 Hz

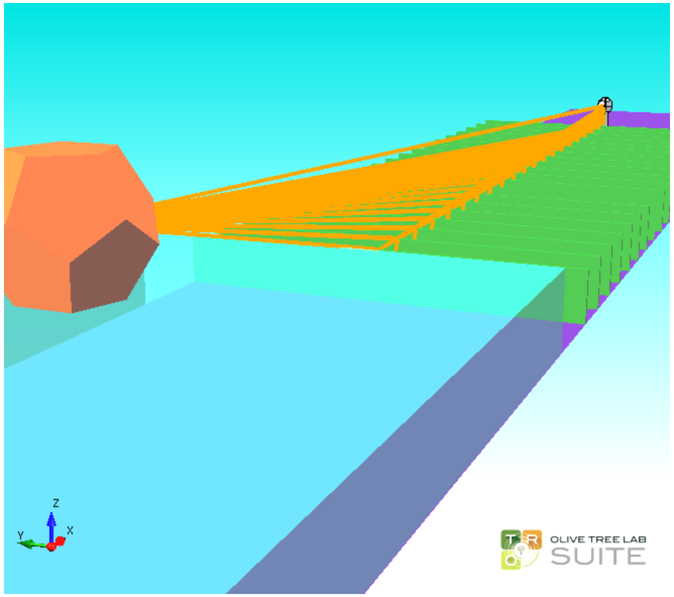



250 Hz



# Validations og the WBGA in simulating the Seat Dip Effect.

The Seat Dip Effect is a well-studied phenomenon of low frequency sound attenuation at grazing incidence over surfaces characterized by roughness, either of periodic or non-periodic in structure [10]. In effect, the total sound pressure is made up of the direct sound wave, scattered and reflected waves off seat rows and floor.



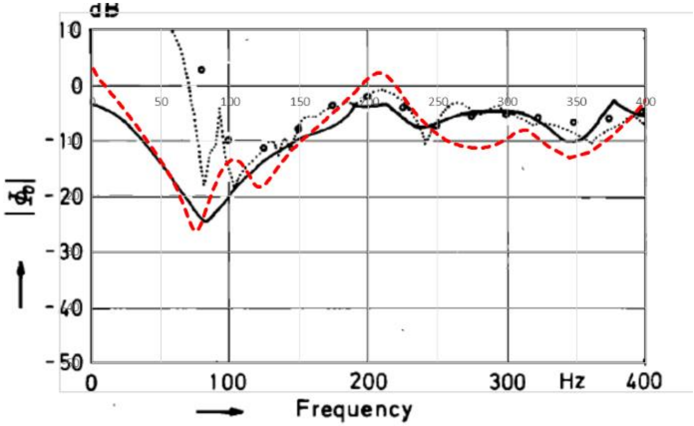




FIG. 2. Comparison between the sound pressures measured and those calculated, in reference to that of the direct sound. OOO: Tone-burst measurements with the 1/10 scale model (after Sessler and West[3]). .....: Continuous-wave measurements with the 1/10 scale model (after Sessler and West[3]). ——: Calculations with the boundary condition of the measurements, ($d_1 = 76$ cm).

# The Room

The room is a TV room with dimensions  3,78 x 3,72 x 2,55 m.
Gypsum walls, wooden floor on concrete and wooden ceiling.

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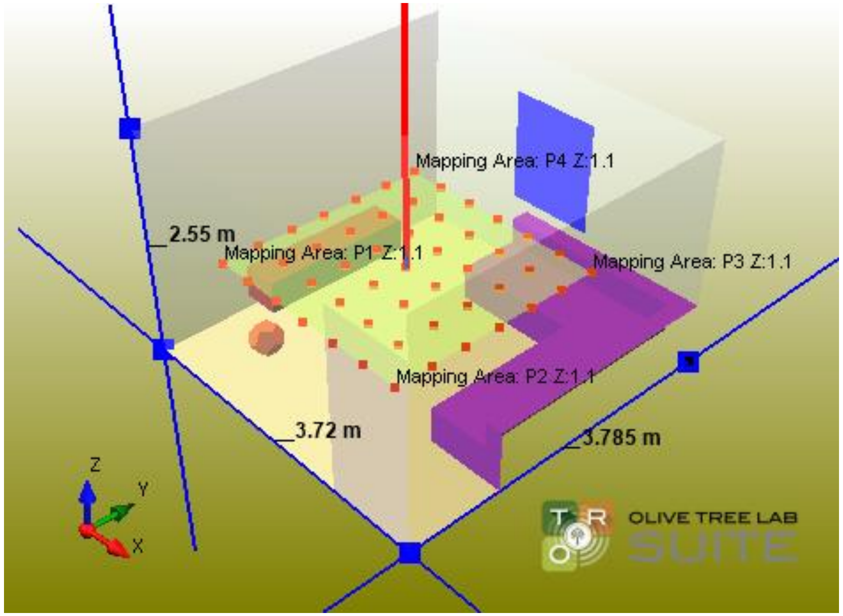
# The Room

Some furnitures are present, sofa, hifi cupboard, wall mounted TV.

No curtains, no carpet, mainly well defined surfaces

36 measurement positions at 1.2 m height above the floor.

Since the measurements and sound mapping grid was set at 0.5m, the maximum frequency which can be mapped without aliasing is of the order of 343 Hz

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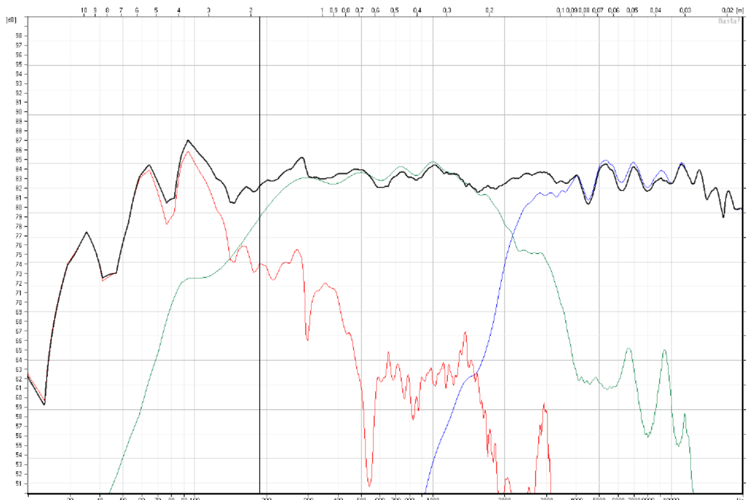
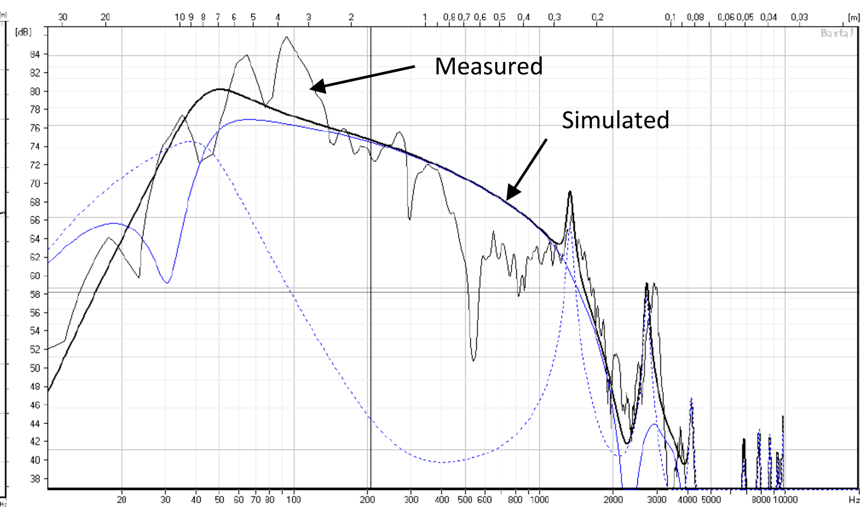
# The source

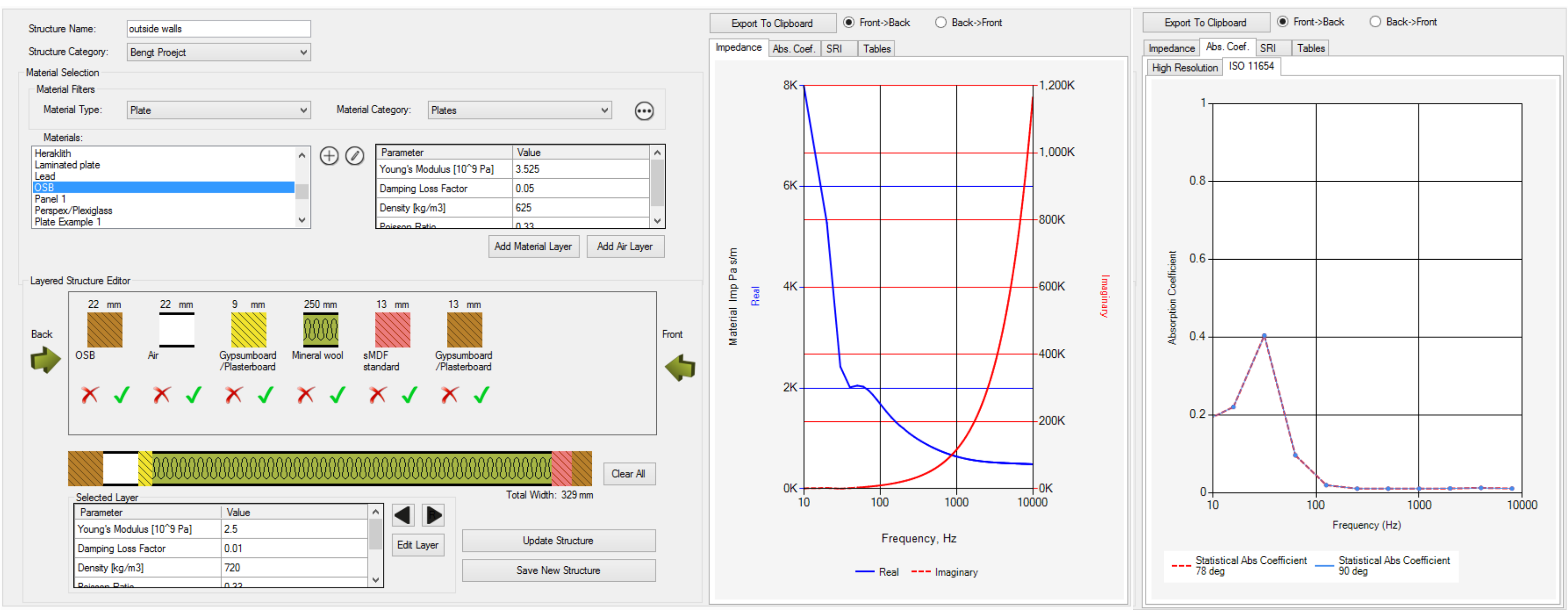
A custom made LF speaker was used for the excitation. The speaker has an 8-inch driver which is omnidirectional at frequencies up to about 500 Hz. The speaker's frequency response was measured and simulated, see figure below.



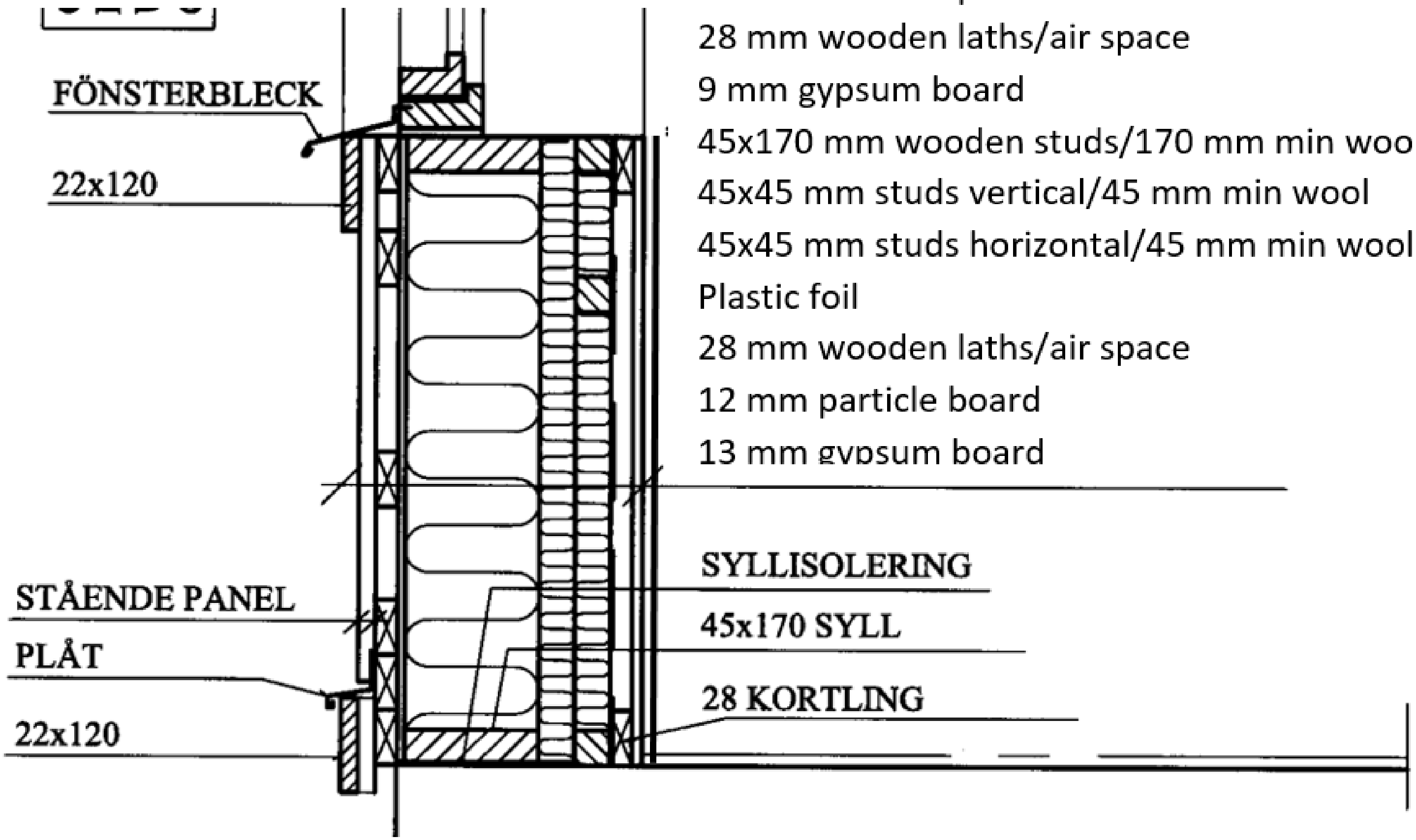


# The 3D computer model

The 3D model was made in SketchUp and exported to dxf/dwg and imported to  Olive Tree Lab-Suite. A built-in tool, Multilayer Structure Builder, was made to calculate the surface impedances.

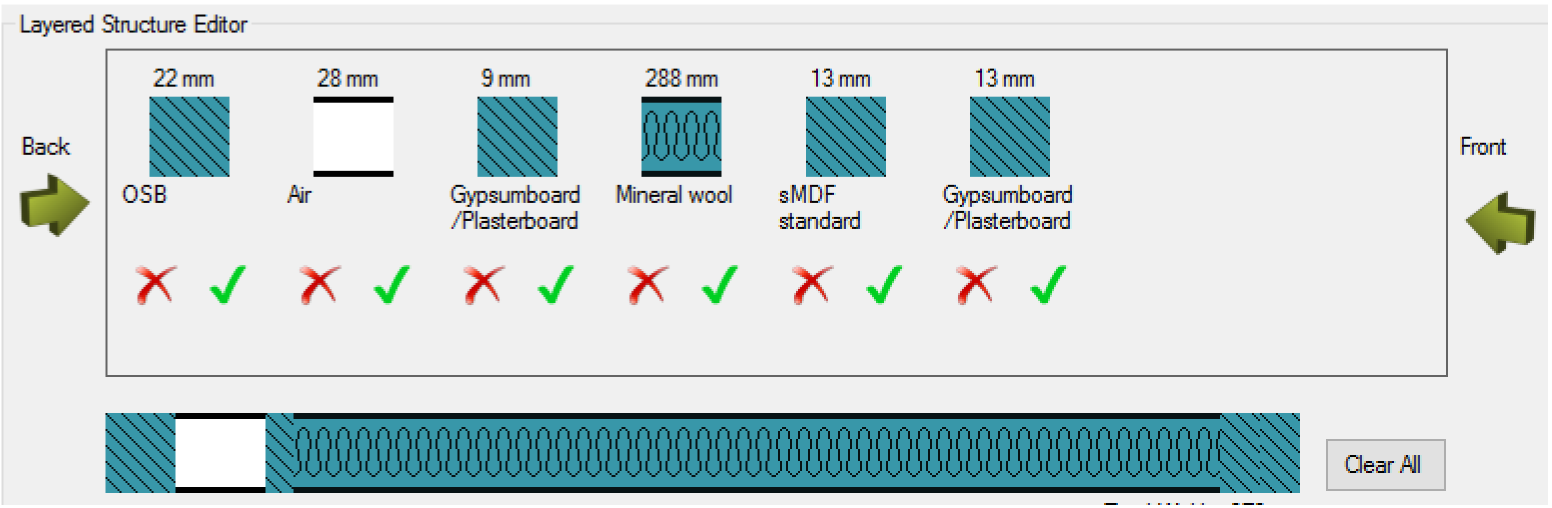


# The structures – wall example



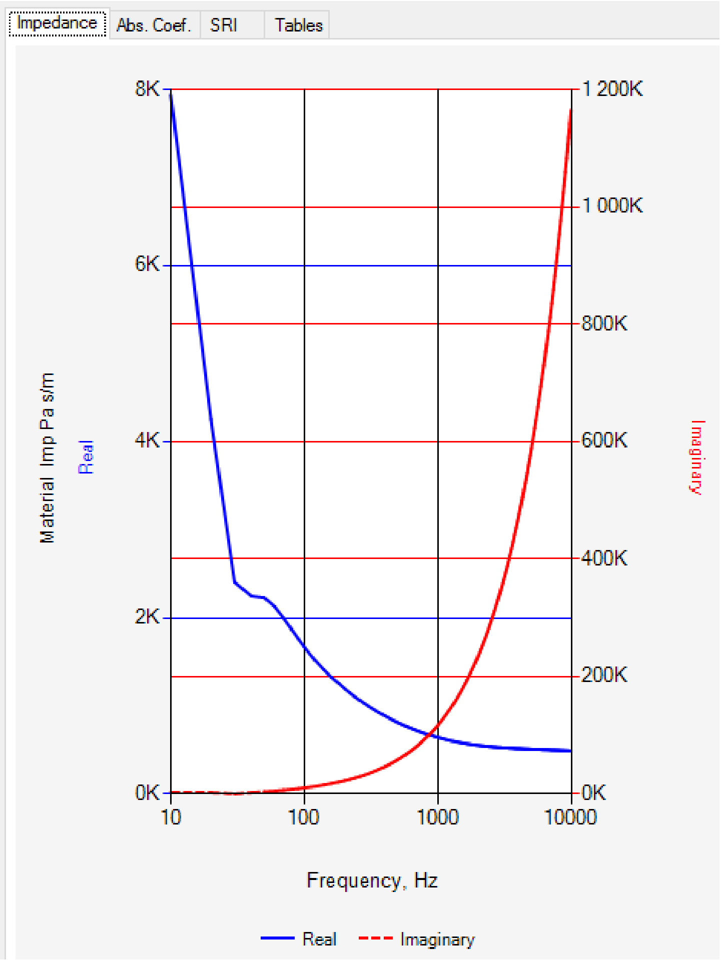

22 mm wooden panel
28 mm wooden laths/air space
9 mm gypsum board
45x170 mm wooden studs/170 mm min wool
45x45 mm studs vertical/45 mm min wool
45x45 mm studs horizontal/45 mm min wool
Plastic foil
28 mm wooden laths/air space
12 mm particle board
13 mm gypsum board

# The wall modeled in OTL Multi Layer Structure Builder

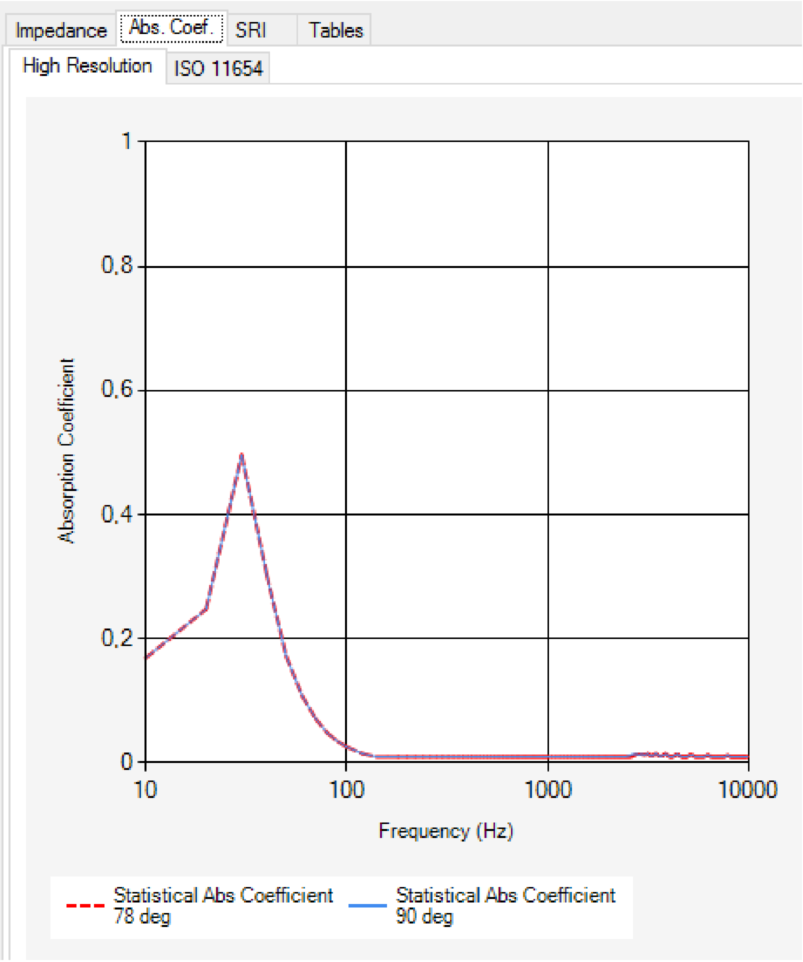


# The wall modeled in  OTL Multi Layer Structure Builder

## Impedance

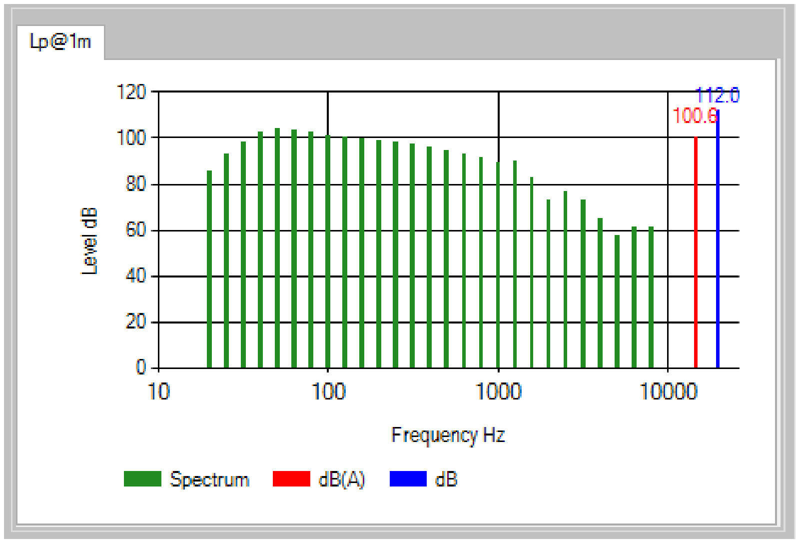



## Absorption coefficient



# The source model

The source spectrum used in modeling was taken from a narrow band simulated analysis which was transformed into 1/3rd octave bands in OTL-Suite. The spectrum and levels used are shown in the left figure below, while on the right, shows a picture of the loudspeaker used for the measurements.

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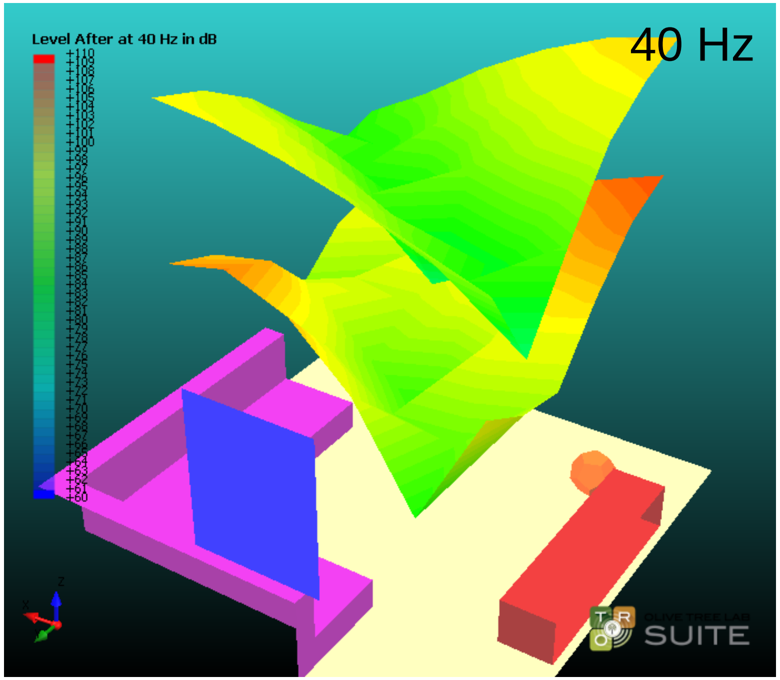
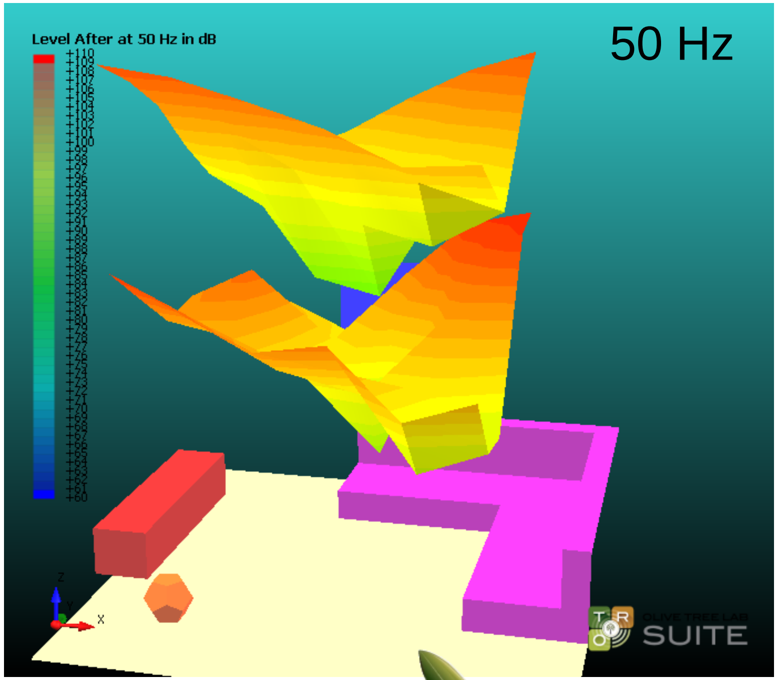
# Measurement vs Simulation – Spatial domain (1/5)

The 3D model has 21 surfaces. For mapping, the calculation time for a grid 6 x 6 (36 calculation positions) at a height of 1.2m, took about 5 minutes with a typical laptop when taking into account 5 orders of reflection, 1 order of diffraction. Measured data are shown as the top map, while calculated results as the bottom map.

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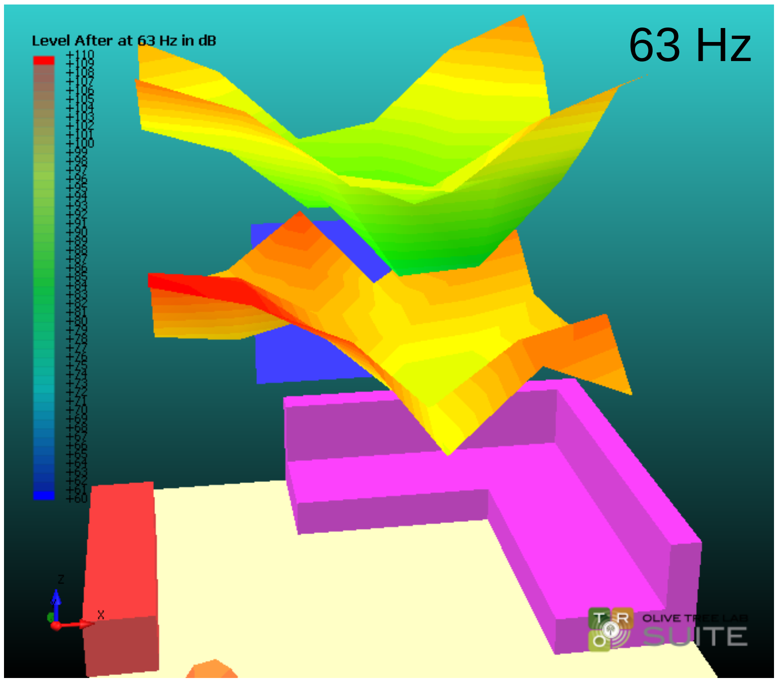
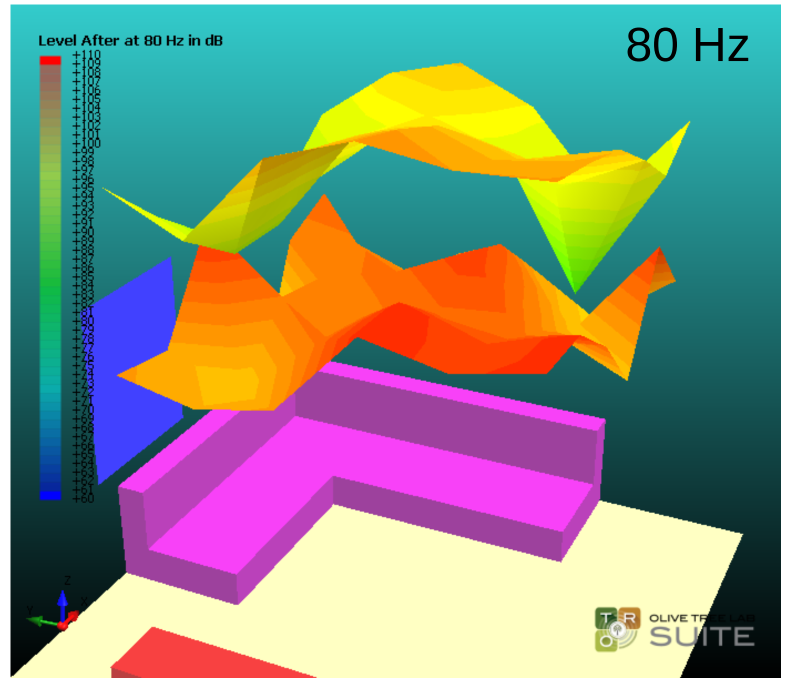
# Measurement vs Simulation – Spatial domain (2/5)

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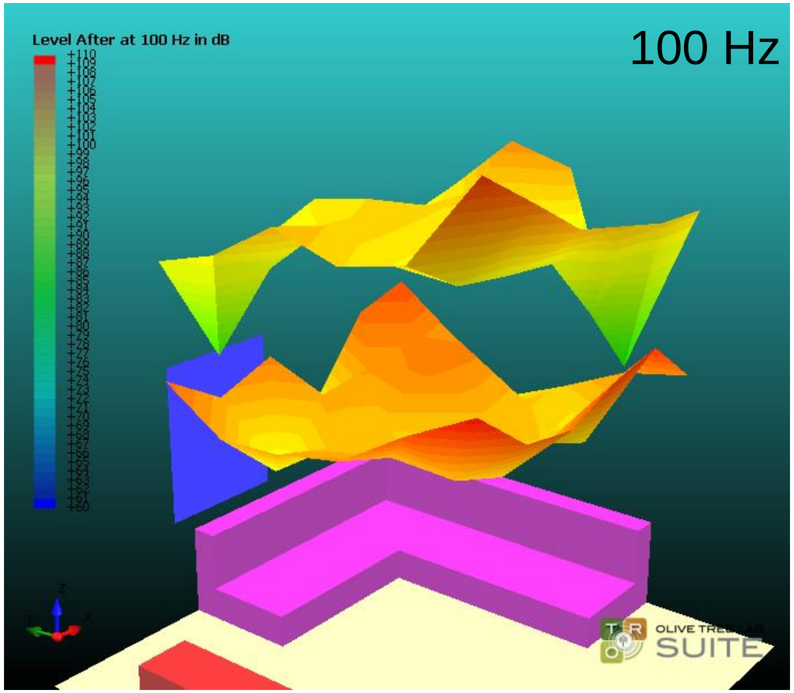
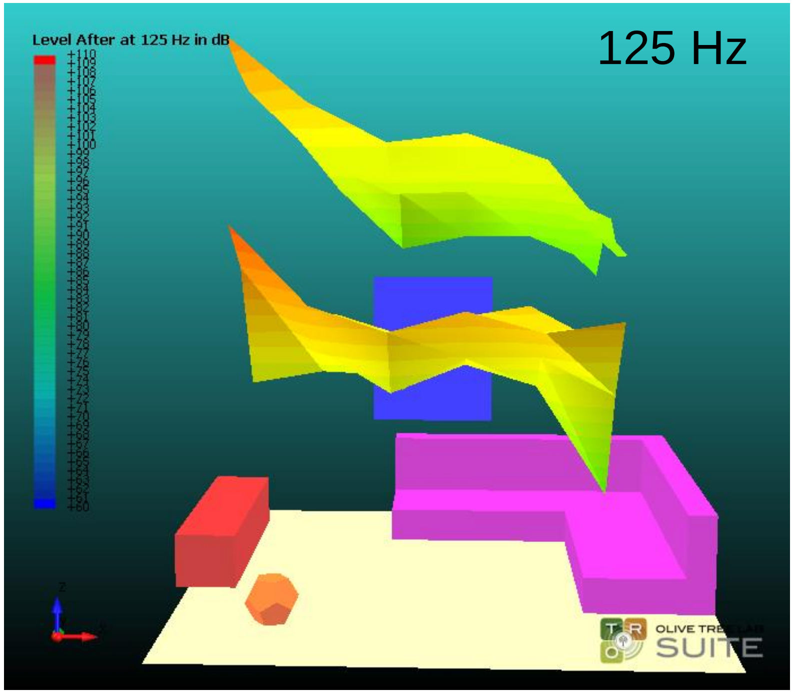
# Measurement vs Simulation – Spatial domain (3/5)

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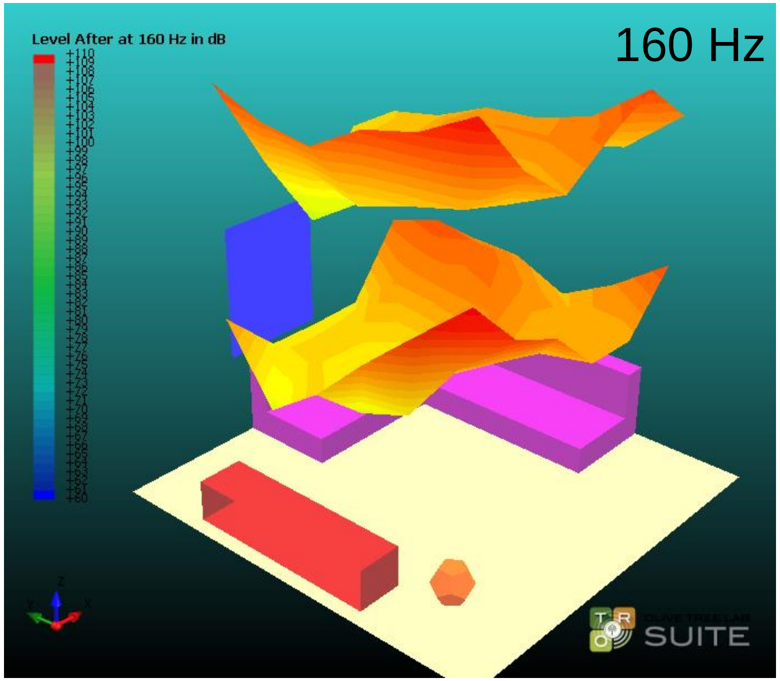
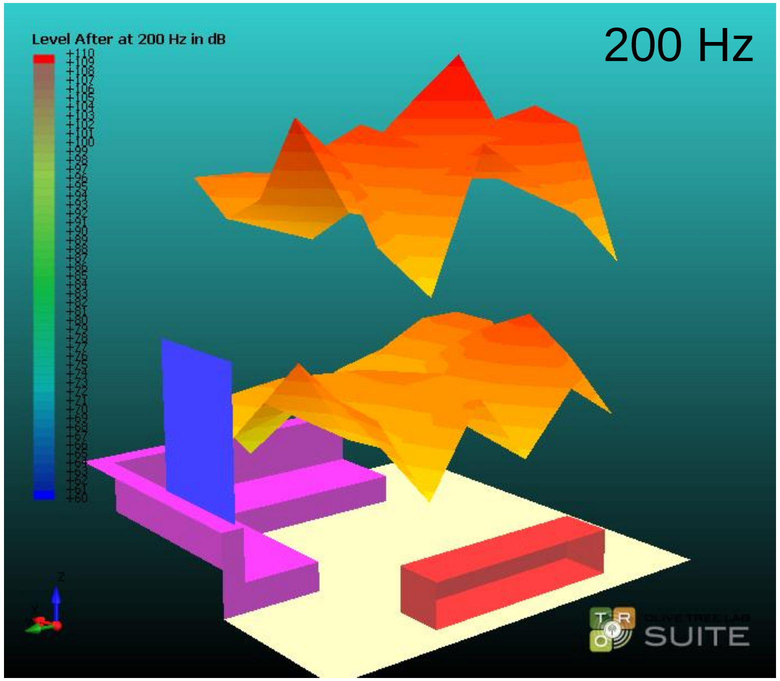
# Measurement vs Simulation – Spatial domain (4/5)

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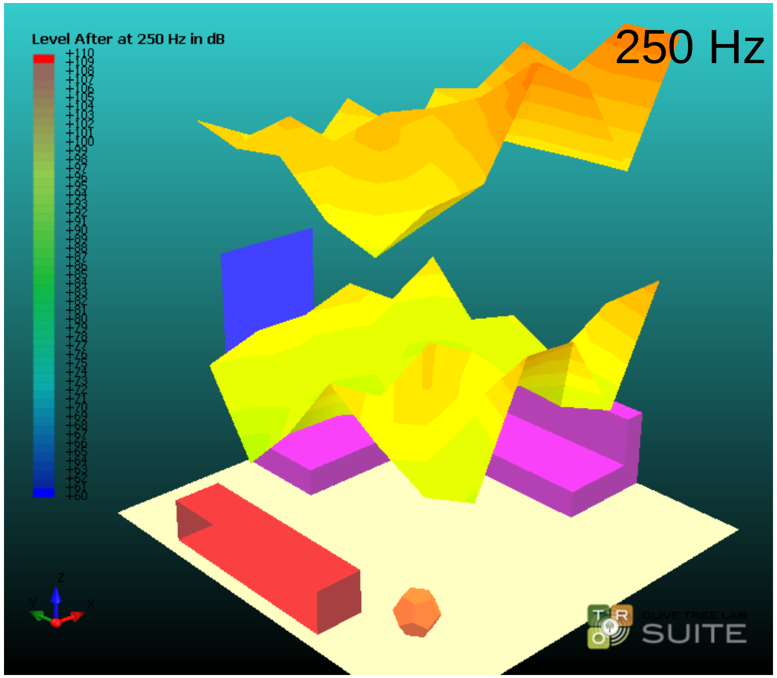
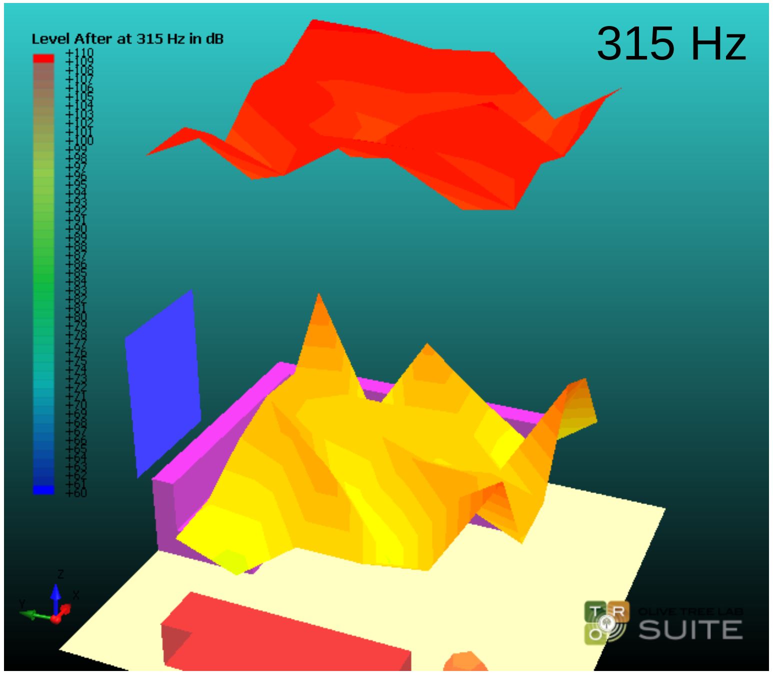
# Measurement vs Simulation – Spatial domain (5/5)

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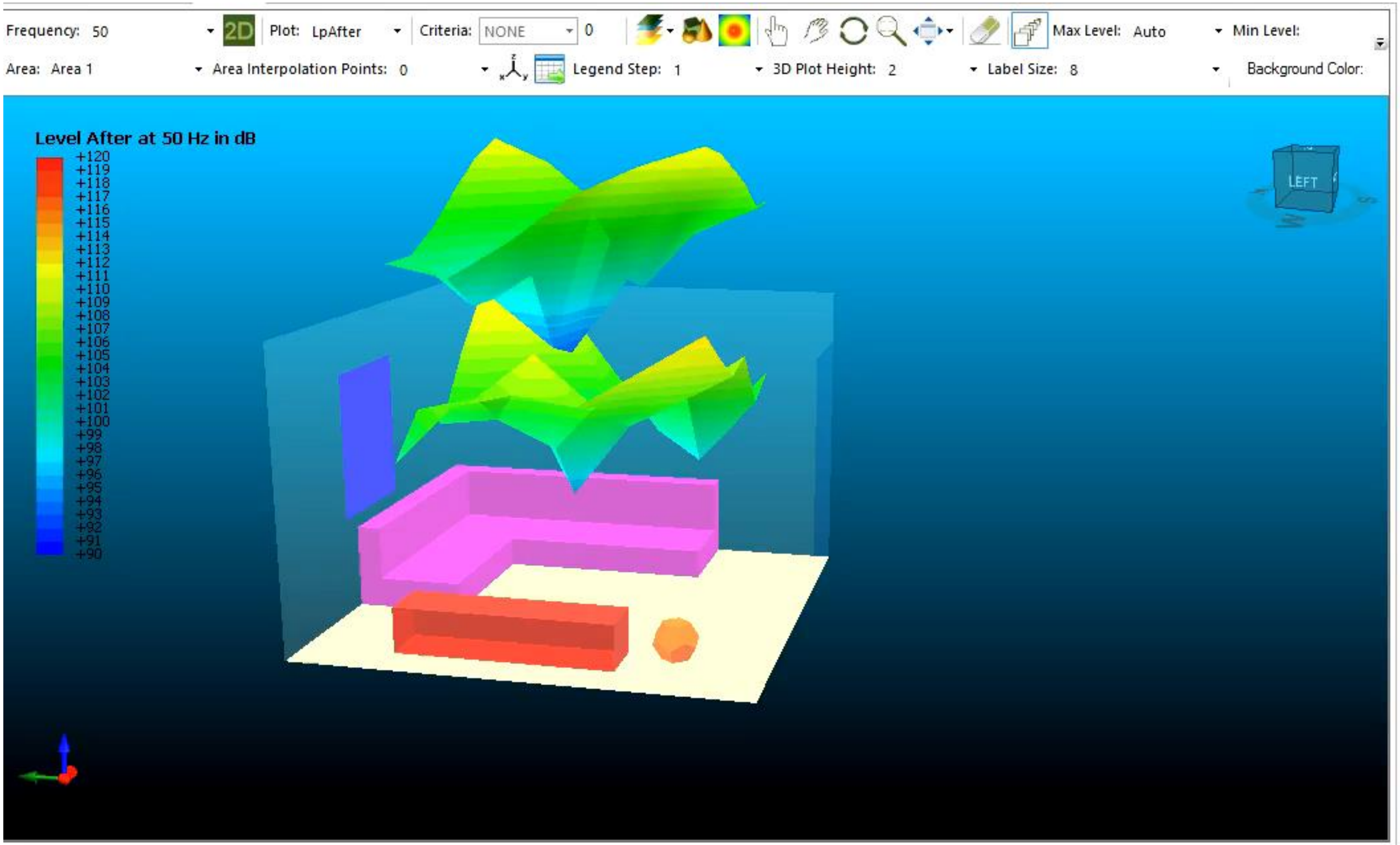
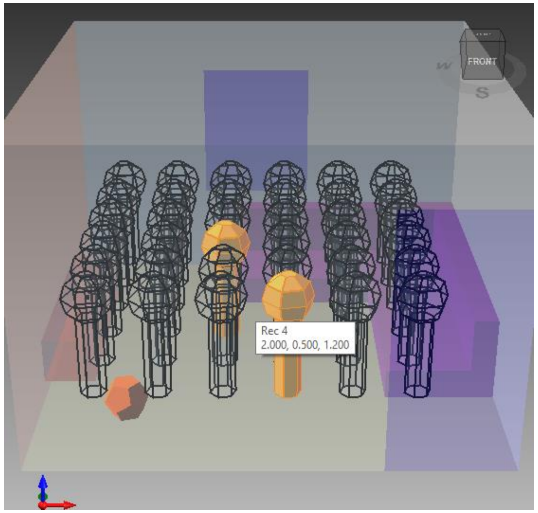
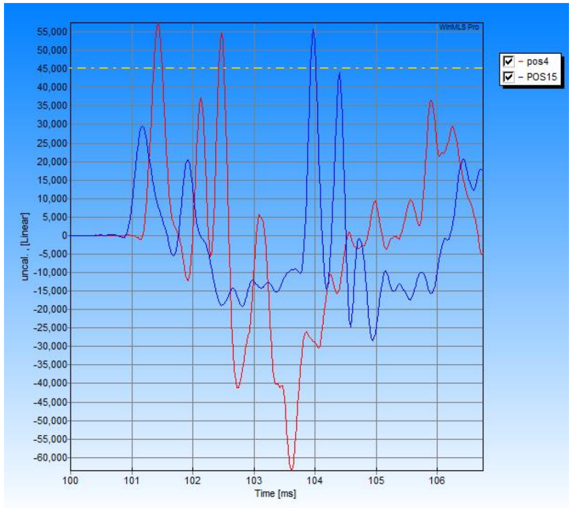
# Measurement vs Simulation – Spatial domain (5/5)



# Measurement vs Simulation – Frequency domain (1/2)

Rec.4 had direct sound from the loudspeaker driver while Rec. 15 had no direct sound but diffracted sound around the speaker cabinet. The speaker cabinet was not part of the 3D model.
This is demonstrated in the middle figure which shows the IR of the 2 receivers.

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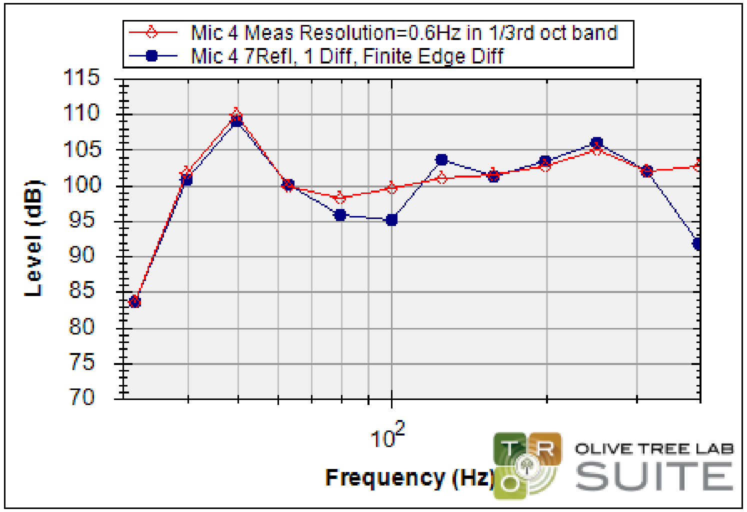
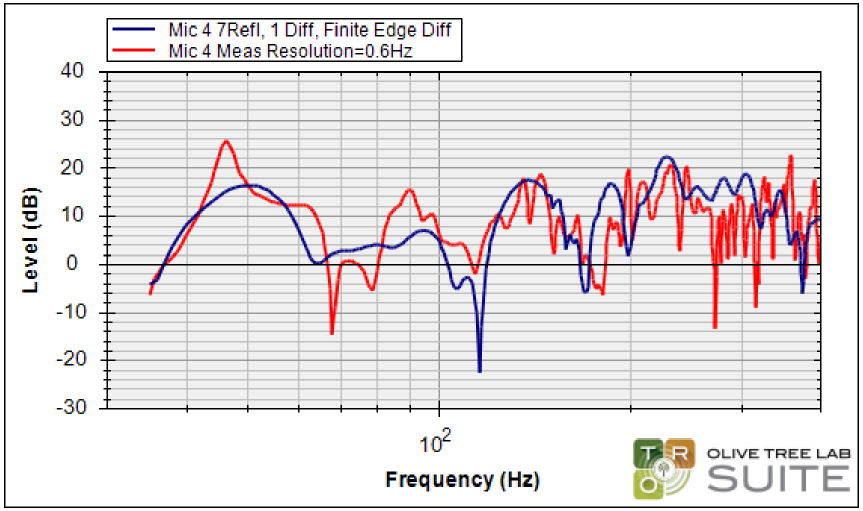
# Measurement vs Simulation – Frequency domain (1/2)

Rec.4 calculated with OTL with 7 orders of reflection and one order of diffraction using Finite edge diffraction. Calculation time was about 5 min.

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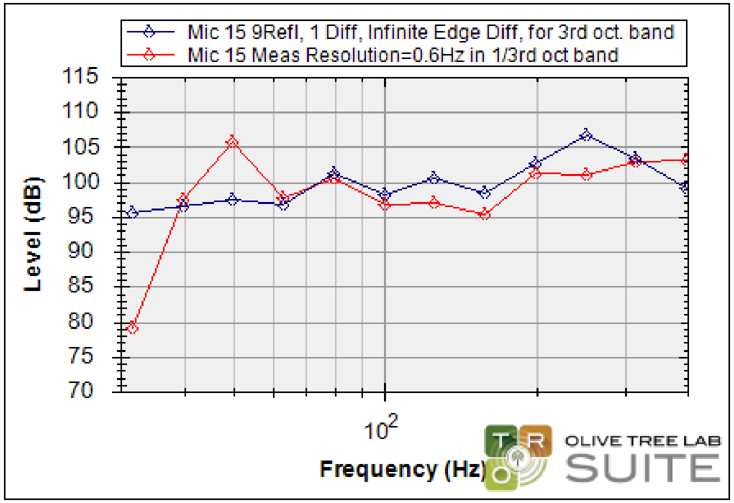
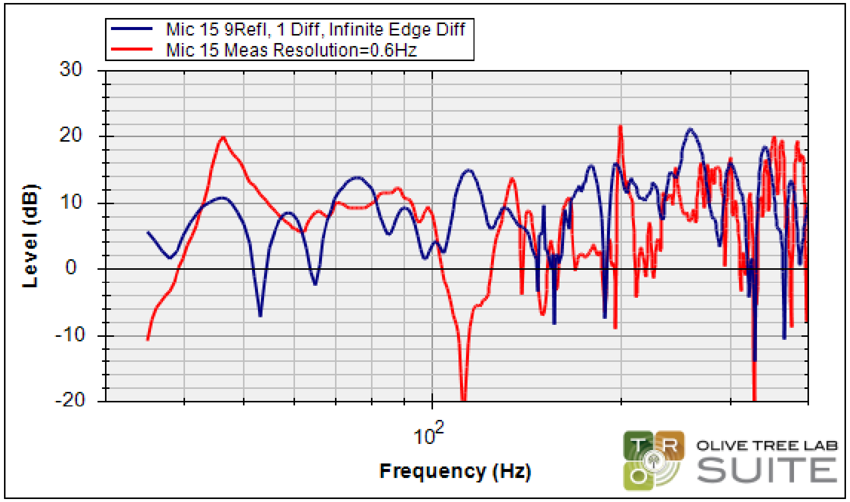
# Measurement vs simulation – Frequency domain

Rec.7 calculated with OTL with 9 orders of reflection, 1 order of diffraction and 1 order of reflection between diffraction edges. Infinite edge diffraction. Calculation time was about 4 hours.

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# Discussion

A real room has been studied for frequency response and room modes. IR Measurements were performed with IRIS and post-processed with WinMLS.

Simulations have been performed with Wave Based Geometrical Acoustics, WBGA, using the software Olive Tree Lab-Suite.

Spherical wave reflection coefficient has been used and surface impedance has been calculated with built-in tool Multi Layer Structure Builder MSB.

Results in third octave bands and mode shapes have good agreement with measurements.

Results in high freq resolution could have better agreement with higher orders of reflections and diffraction but also longer calculation time.

The room model is simplyfied. For practical reasons things are missing, the speaker cabinet, TV, open HiFi furniture etc

Uncertainties in microphone positions, wall construction etc

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