From Practice to Theory:
Wave based methods applied in
Olive Tree Lab – Terrain

a presentation at

«PROVIAMO A PENSARE DIVERSAMENTE
AL CONTROLLO DEL RUMORE AMBIENTALE»
Padova 3 Luglio 2014

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CYPRUS

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PART 1

INTRODUCTION

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- The characteristic of our époque is lack of time. It seems that today, time must have acquired its highest price ever.

- It's only natural that acoustical software ought to offer fast calculations.

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Introduction

- Even though efficiency is a function of time, fast calculations do not preclude high efficiency.
- Rather fast and accurate calculations determine high efficiency.

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PRACTICE

- So far, we were using simplified and empirical methods to apply engineering solutions.
- This does not need to be the case anymore.

THEORY

- The advent of technology and computers allows us to implement
- complicated mathematics
- in a user friendly environment
- which allows engineers to perform their tasks
  - accurately and
  - efficiently.

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PART 2

BASIC EQUATIONS USED IN PRACTICE
VS
ADVANCED METHODS

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Basic Equations & Approach in Practice

$$L_p = L_w - A_E$$

L_p= SPL at receiver

L_w=Source power

A_E=Excess Attenuation

A_E = Distance Atten. +

Air Abs. +

Ground Refl. +

Barriers +

Meteo. +

Miscellaneous

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Basic Equations & Approach

- The above approach is more or less correct and clearly distinguishes the various phenomena which take place between source and receiver
- However, if we have a closer look at the various components of the equation of A_E, and compare them to what theory dictates we'll discover discrepancies.

- Due to limited time and since all of us are well acquainted with **Sound Reflection at a receiver,** we will examine it a bit in detail.

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SOUND REFLECTION AT A RECEIVER

PRACTICE

Standard methodologies use

- ***Plane*** wave propagation and
- usually ***sound energy*** summation

$$p^2_{receiver} = p^2_{direct} + p^2_{refl}$$

In addition, based on:

- sound absorption coefficient

or at best

- surface impedance

THEORY

Advanced methodologies use

- ***Spherical*** wave propagation
- ***Surface impedance*** and
- Sound ***pressure addition***

$$p_{receiver} = p_{direct} + p_{refl}$$

They predict

- Plane wave Reflection
- Ground wave propagation and
- Surface wave propagation

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- We all know that there is "no free lunch", therefore,
- What are the consequences of applying approximate equations?

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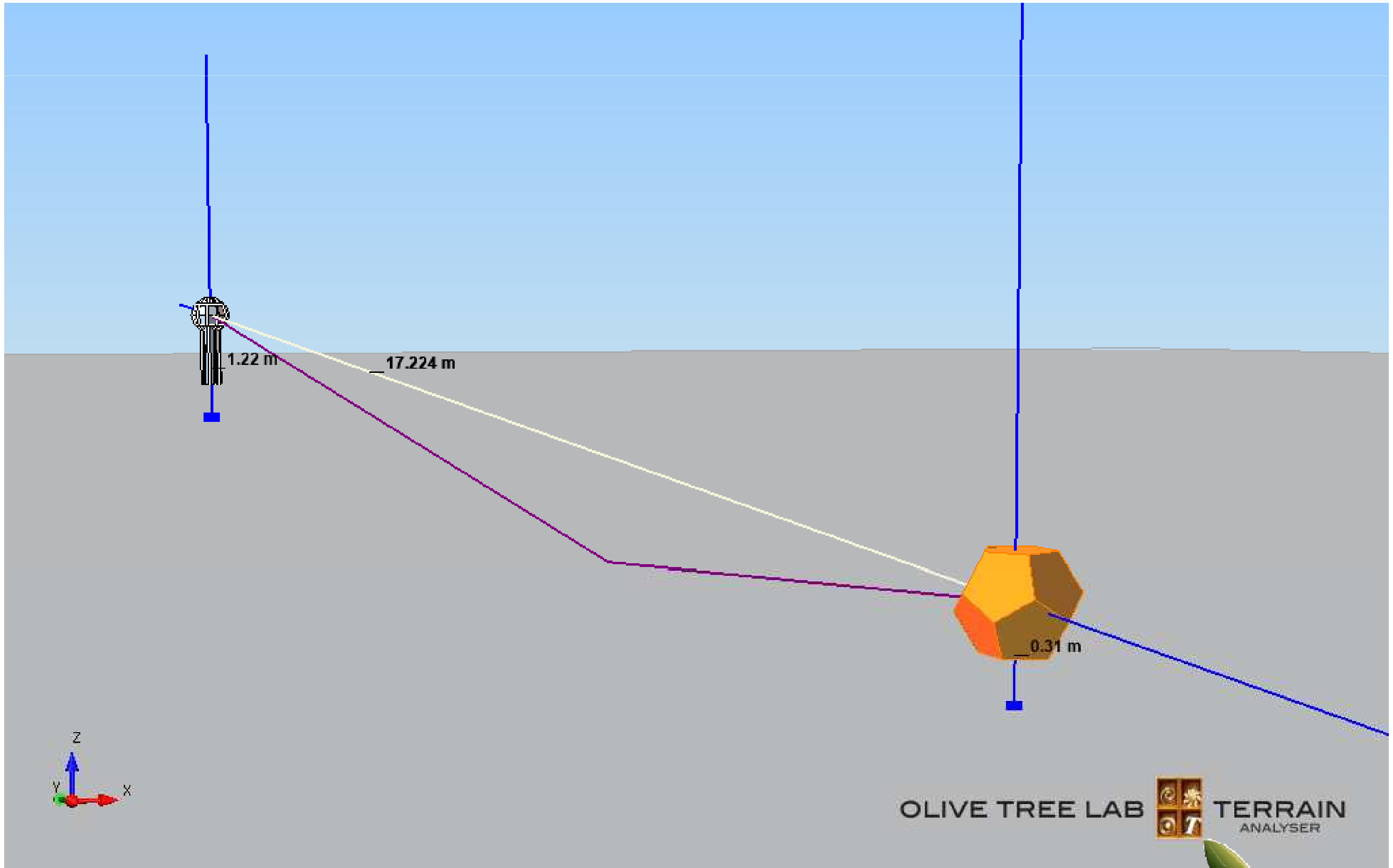
REFLECTION - SOURCE – RECEIVER CLOSE TO A SURFACE OF FINITE IMPEDANCE



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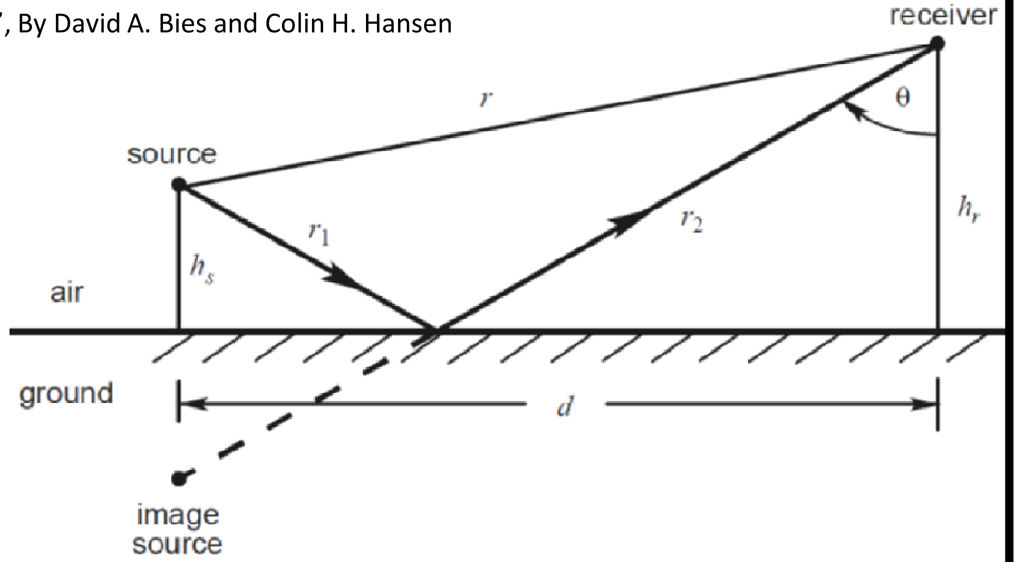
$$\rho = 1 - \alpha$$

α= statistical abs. coeff.

Not angle dependent

SIMPLE & MANAGABLE



STATISTICAL REFLECTION COEFFICIENT

- It is a function of absorption coefficient
- It is an energy based coefficient (p^2)
- **It does not provide** Interference effects due path differences
- **It does not provide** Interference effects due the material properties of the reflecting surface.

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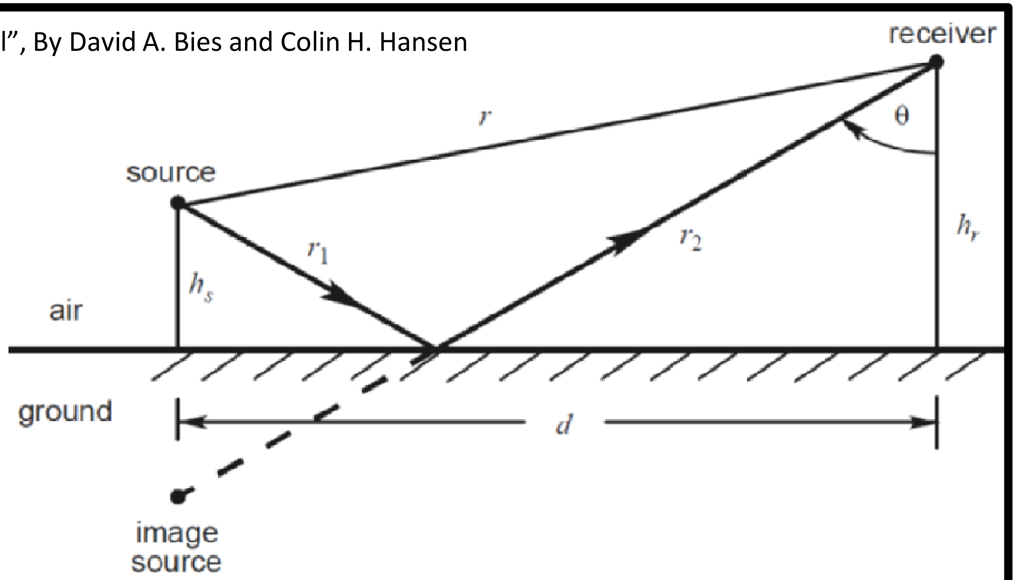
$$R_p = \frac{Z_m \cos\theta - \rho c}{Z_m \cos\theta + \rho c}$$

Zm=surface impedance
ρc= characteristic impedance
Angle dependent

SIMPLE & MANAGABLE



PLANE WAVE REFLECTION COEFFICIENT

- Function of surface impedance and angle of incidence.
- When pressures are added (not energy), they provide, interference effects due path differences.

- Interference ignores the additional effect of phase change due to the properties of the reflecting material
- **This can only be handled by the spherical wave reflection coefficient.**

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SPHERICAL WAVE REFLECTION COEFFICIENT - 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

$$B_1 = \left[\cos\theta + \frac{\rho c}{Z_m}\left(1 - \frac{k^2}{k_m^2}\sin^2\theta\right)^{1/2}\right]\left[1 - \frac{k^2}{k_m^2}\right]^{1/2} \qquad (5.148)$$

$$B_2 = \left[\left(1 - \frac{1}{\rho_m^2}\right)^{1/2} + \frac{\rho c}{Z_m}\left(1 - \frac{k^2}{k_m^2}\right)^{1/2}\cos\theta + \left(1 - \left(\frac{\rho c}{Z_m}\right)^2\right)^{1/2}\sin\theta\right] \qquad (5.149)$$

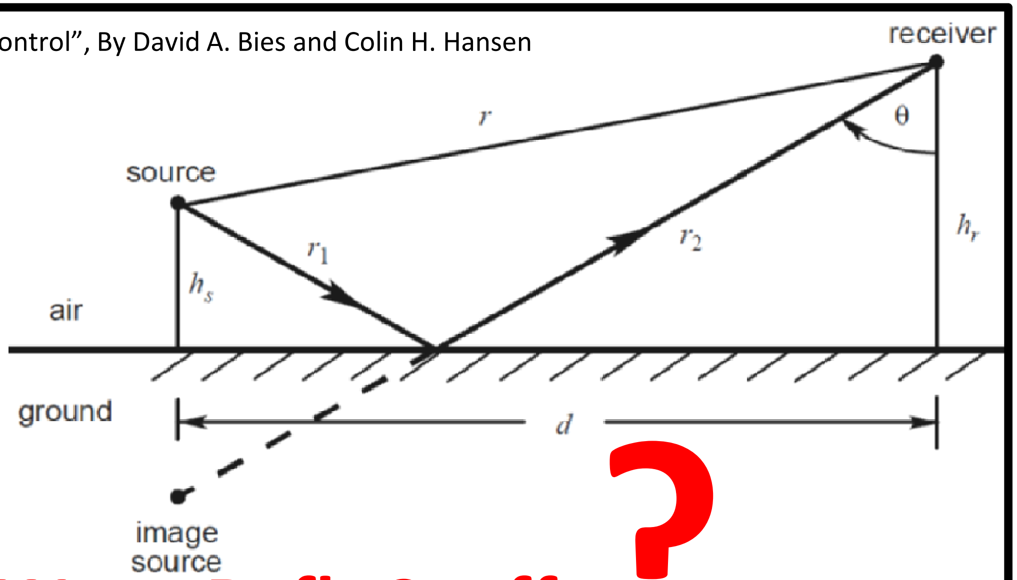
$$B_3 = \cos\theta + \frac{\rho c}{Z_m}\left(1 - \frac{k^2}{k_m^2}\right)^{1/2}\left[1 - \frac{1}{\rho_m^2}\right]^{-1/2} \qquad (5.150)$$

$$B_4 = \left[1 - \frac{k^2}{k_m^2}\sin\theta\right]^{1/2} \qquad (5.151)$$

$$B_5 = \left[1 - \frac{1}{\rho_m^2}\right]^{3/2}[2\sin\theta]^{1/2}\left[1 - \left(\frac{\rho c}{Z_m}\right)^2\right]^{1/2} \qquad (5.152)$$

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

$$w = \frac{1}{2}(1 - j)[2k_1(r_1 + r_2)]^{1/2}\frac{B_3}{B_6^{1/2}} \qquad (5.153)$$



All this for Spherical Wave Refl. Coeff. ?

$$B_6 = 1 + \left[\frac{\rho c}{Z_m}\left(1 - \frac{k^2}{k_m^2}\right)^{1/2}\cos\theta + \left(1 - \frac{\rho c}{Z_m}\right)^{1/2}\sin\theta\right]\left[1 - \frac{1}{\rho_m^2}\right]^{-1/2} \qquad (5.154)$$

The term $G(w)$ in Equation (5.146) is defined as follows:

$$G(w) = 1 - j\sqrt{\pi}\, w\, g(w) \qquad (5.155)$$

$Q = R_p + (1-R_p)F(w)$

the so called Weyl-Van der Pol formula

where

$$g(w) = e^{-w^2}\operatorname{erfc}(jw) \qquad (5.156)$$

and "erfc( )" is the error function (Abramowitz and Stegun, 1965).

For small w ($|w| < 3$):

$(1-R_p)F(w)$ = Ground Wave component, named so, from Electromagnetism

$$g(w) = e^{-w^2} - \left[\frac{2jw}{\pi^{1/2}}\right]\left[\sum_{n=0}\frac{(-2w^2)^n}{1 \times 3 \times \ldots \times (2n+1)}\right] \qquad (5.157)$$

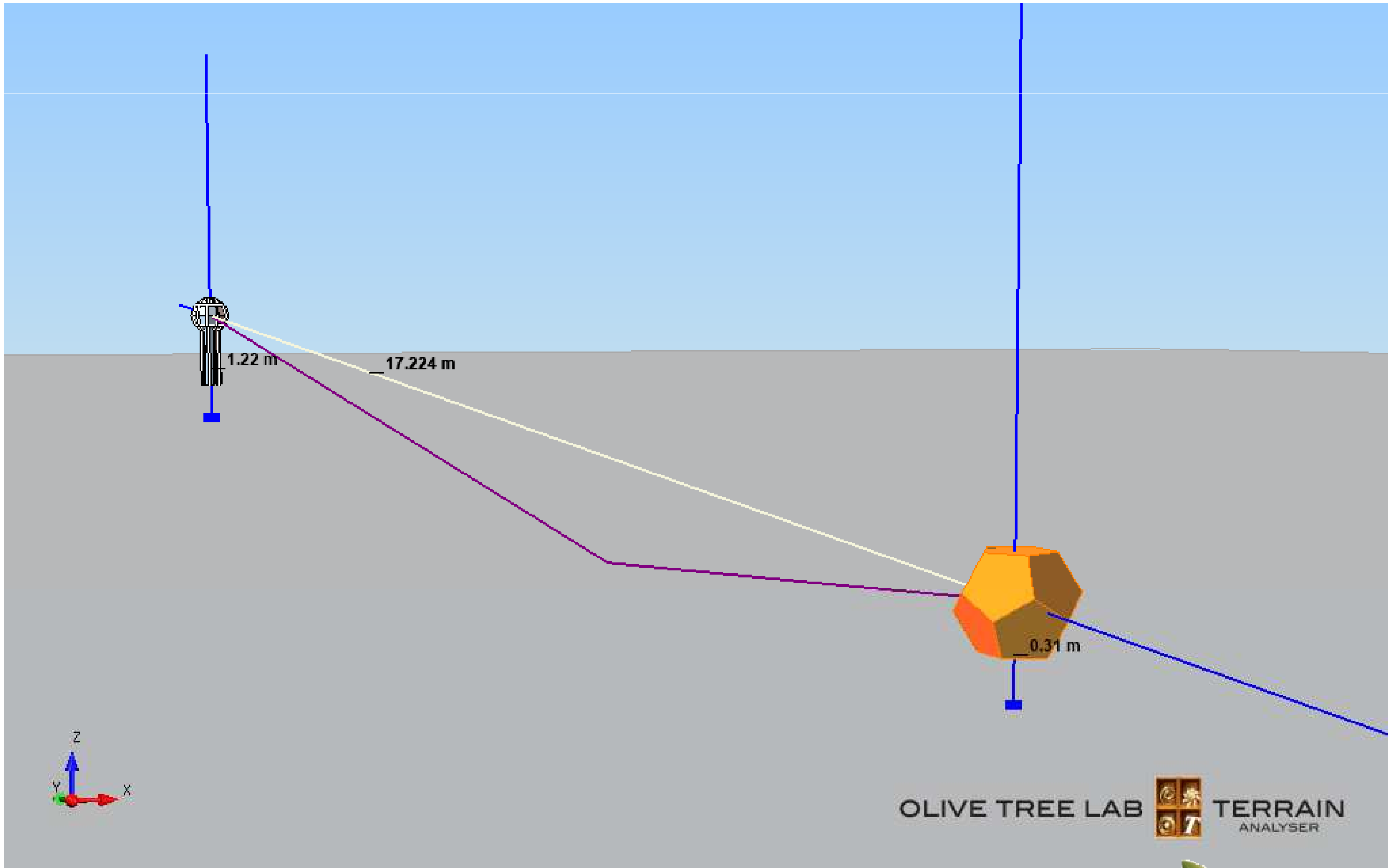
For values of w where the real part is greater than 3 or the imaginary part is greater than 2 and either is less than 6:

$$g(w) = -jw\left[\frac{0.4613135}{w^2 - 0.1901635} + \frac{0.09999216}{w^2 - 1.7844927} + \frac{0.002883894}{w^2 - 5.5253437}\right] \qquad (5.158)$$

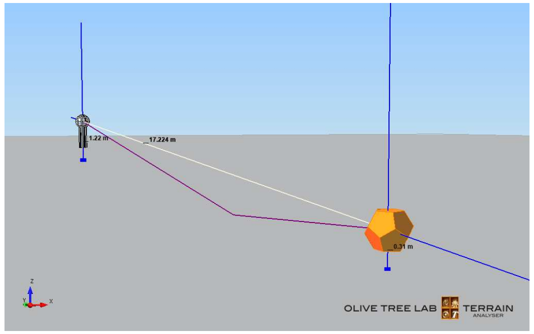
For real or imaginary parts of w greater than 6:

$$g(w) = -jw\left[\frac{0.5124242}{w^2 - 0.275255} + \frac{0.05176536}{w^2 - 2.724745}\right] \qquad (5.159)$$

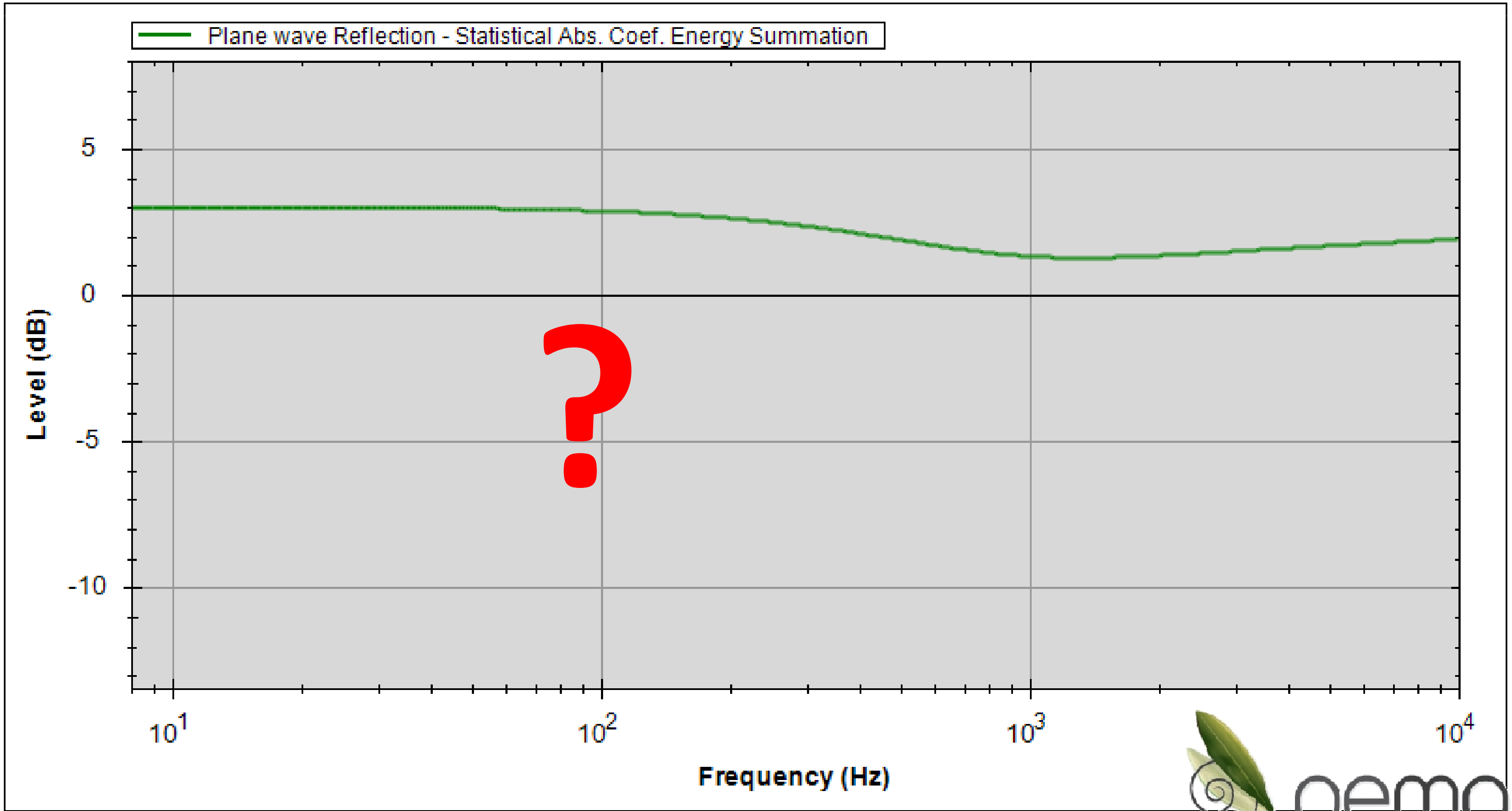
REFLECTION - SOURCE – RECEIVER CLOSE TO A SURFACE OF FINITE IMPEDANCE (flow resistivity of 200 kPa s m^{-2})



STATISTICAL REFLECTION COEFFICIENT
Using equivalent abs. coeff.



$$\rho=1-\alpha$$



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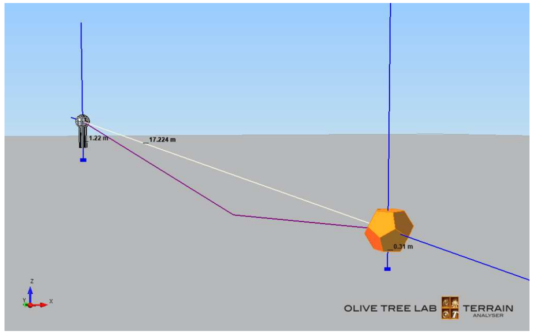
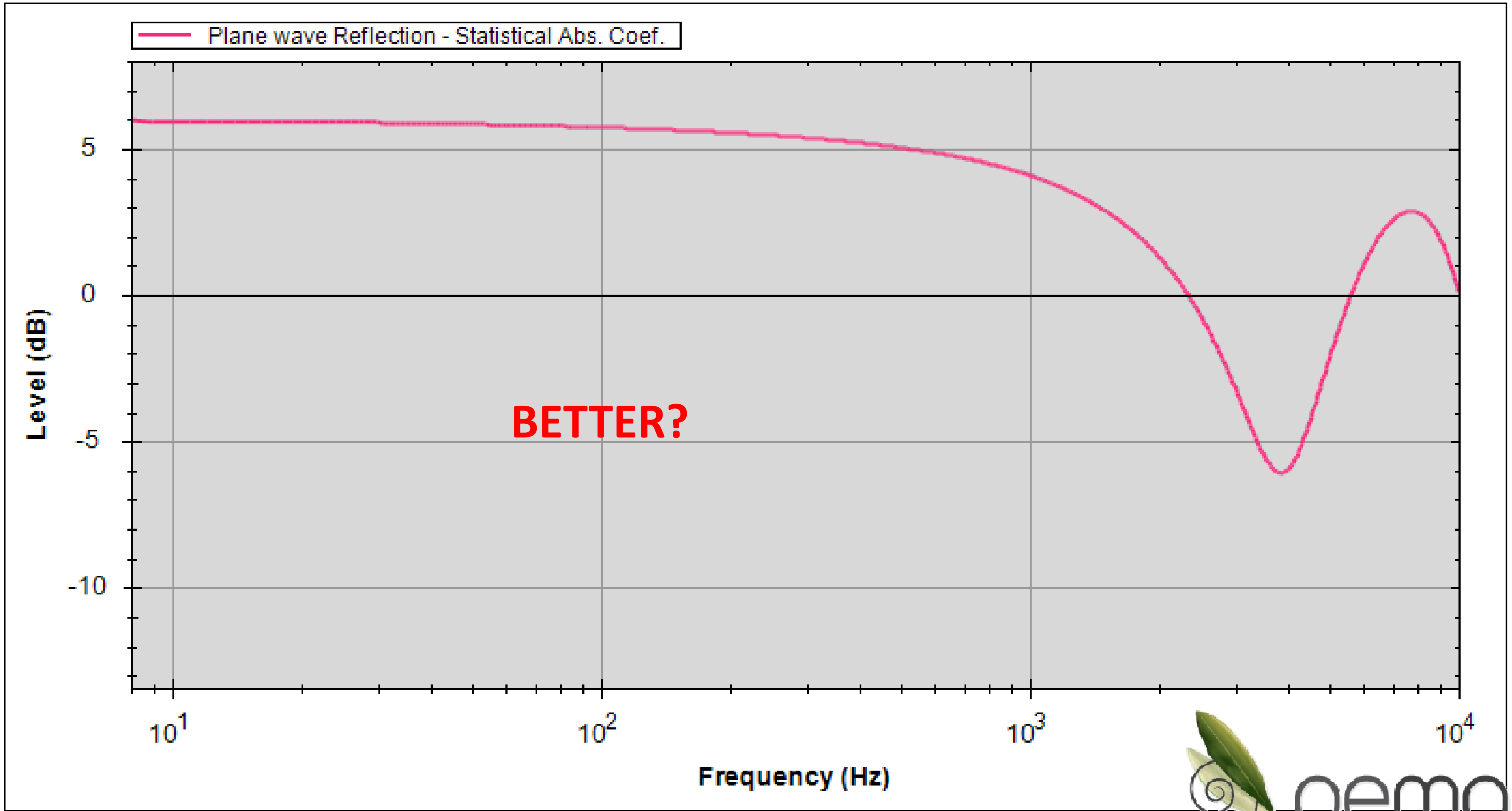
PLANE WAVE REFLECTION COEFFICIENT
Using equivalent abs. coeff.

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





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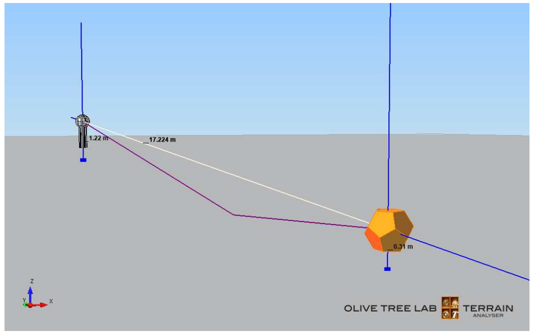
SPHERICAL WAVE REFLECTION COEFFICIENT

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



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$$B = \frac{B_1 B_2}{B_3 B_4 B_5} \tag{5.147}$$

where

$B_1 =$ (5.154)

(5.155)

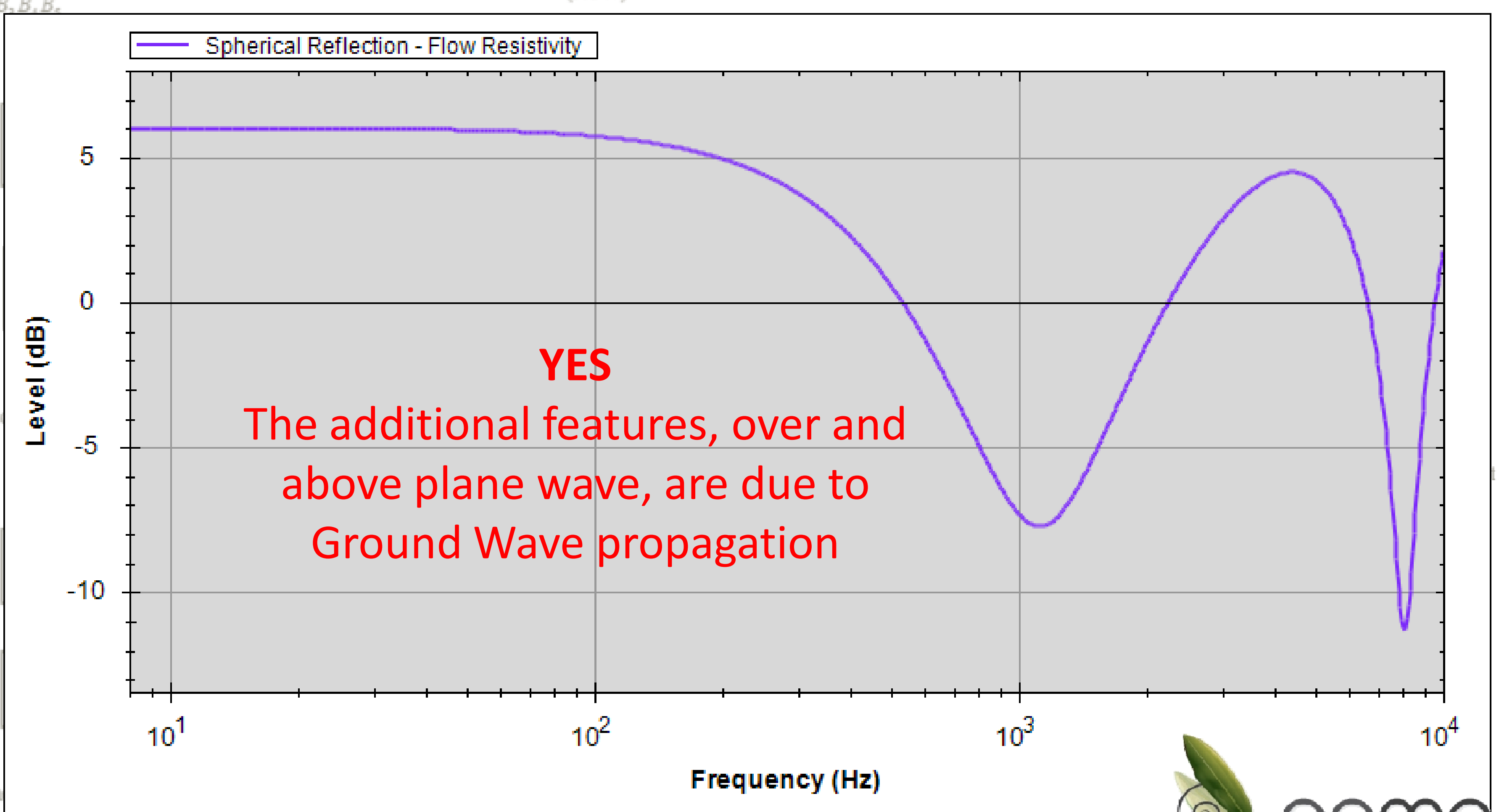
$B_2 =$ (5.156)

$B_3 =$ (5.157)

t is greater

$B_4 =$ (5.158)

$B_5 =$ (5.159)



YES

The additional features, over and above plane wave, are due to Ground Wave propagation

The argum... and is calculated using the following equation, where r_1 and r_2 are defined in Figure 5.14:

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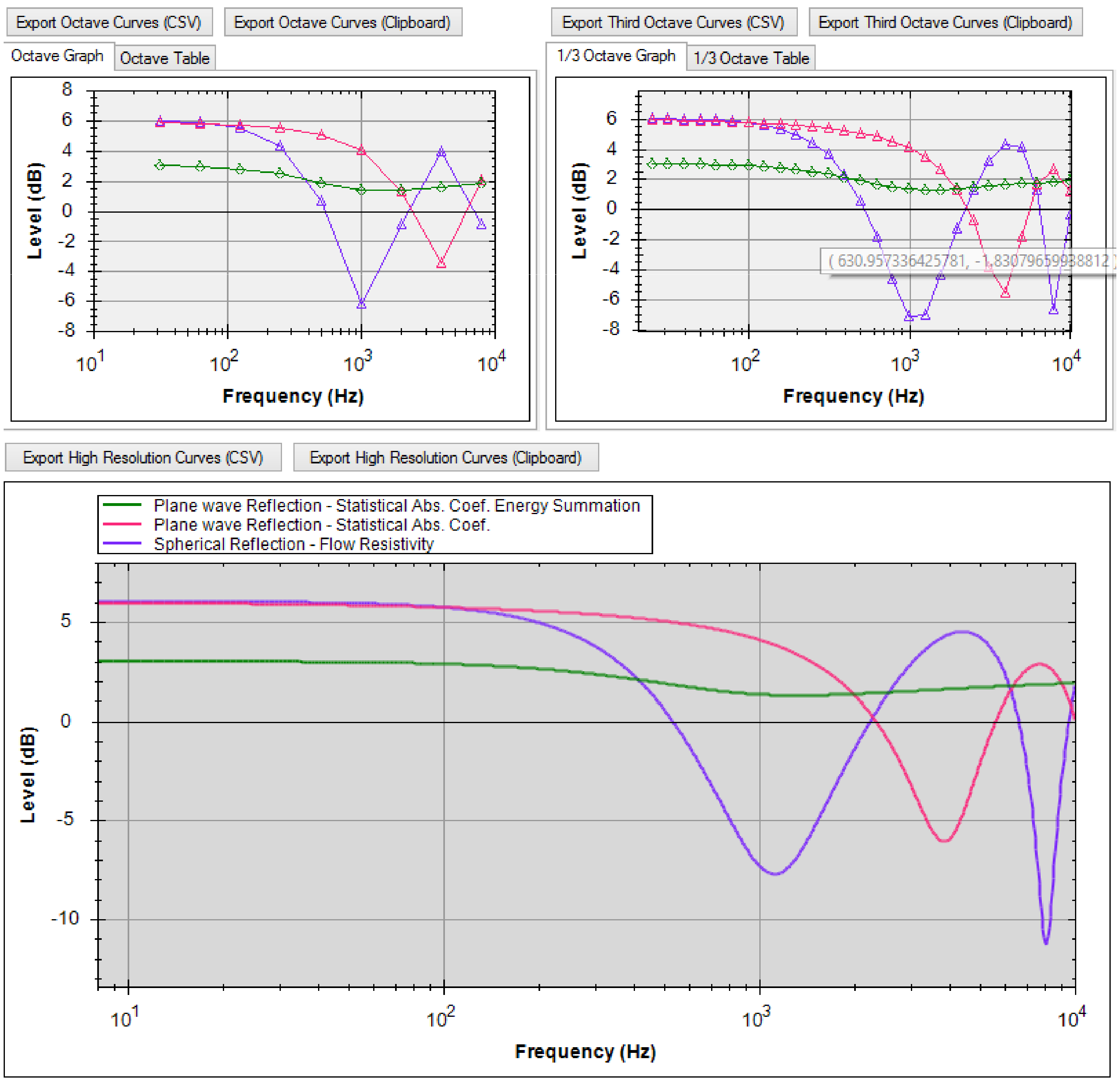
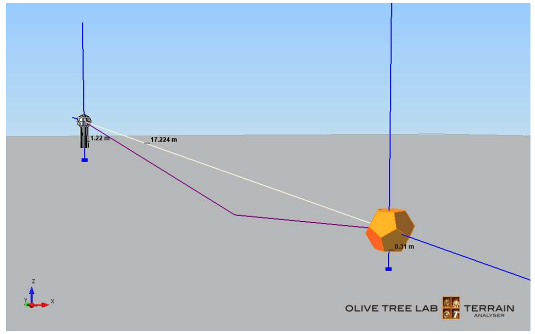
ALL TOGETHER FOR COMPARISON





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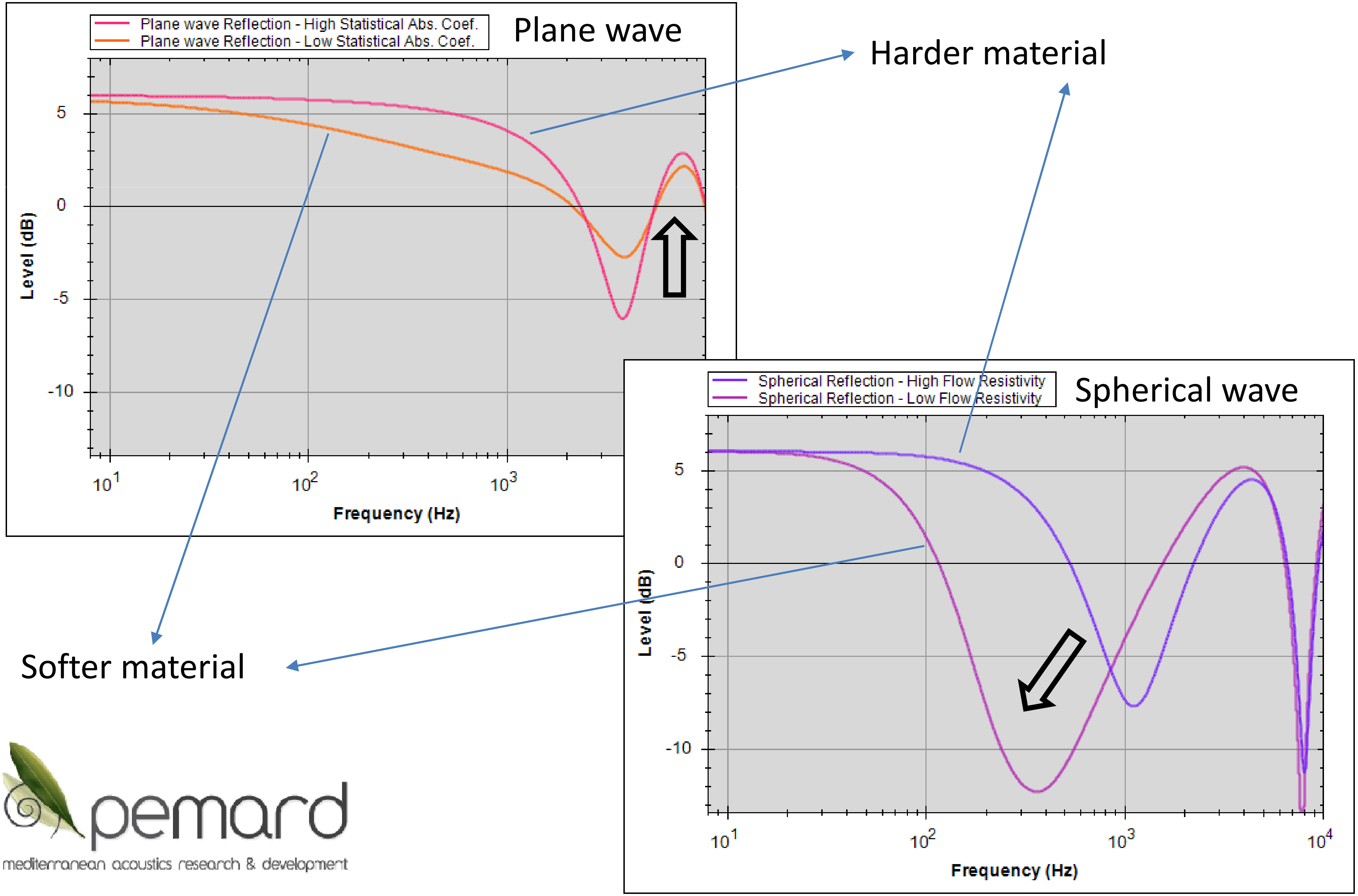
SPHERICAL VS PLANE WAVE REFLECTION COEFFICIENT

Harder to Softer material (flow resistivity from 200 to 10 kPa s m^{-2})



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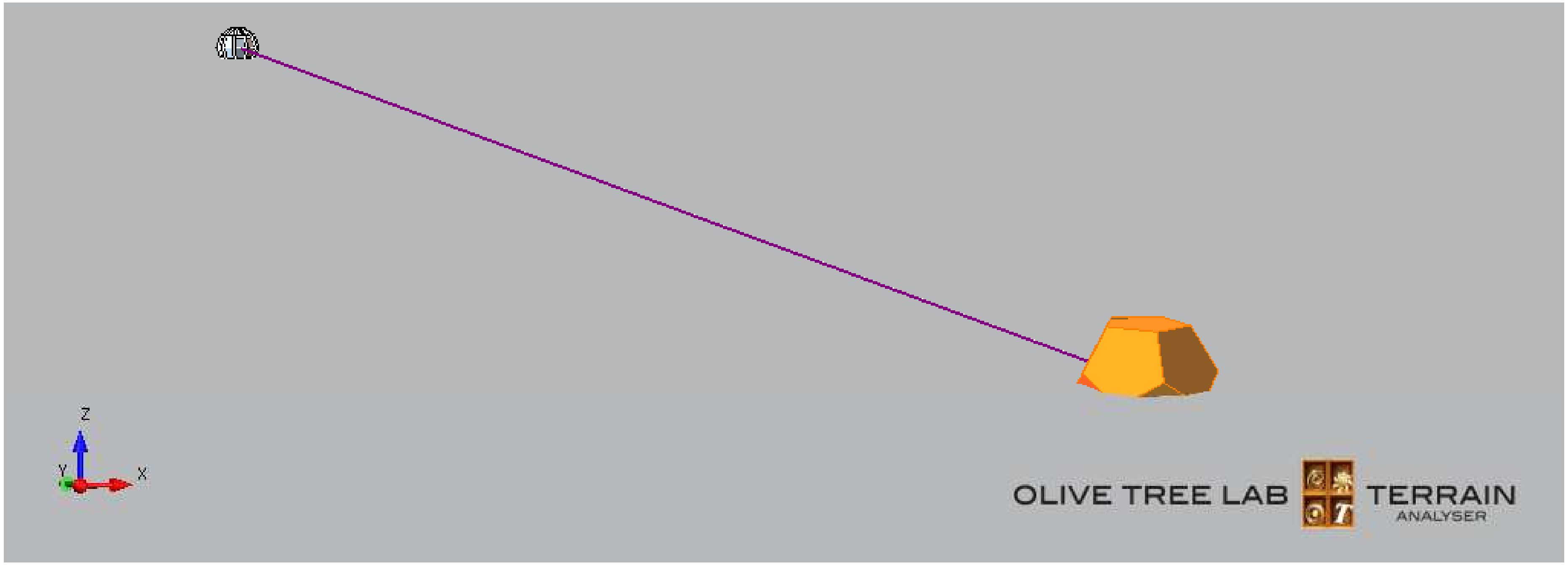
REFLECTION – PREDICTING GROUND WAVE

SOURCE – RECEIVER ON THE SURFACE

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

NO PLANE WAVE REFLECTION IS POSSIBLE

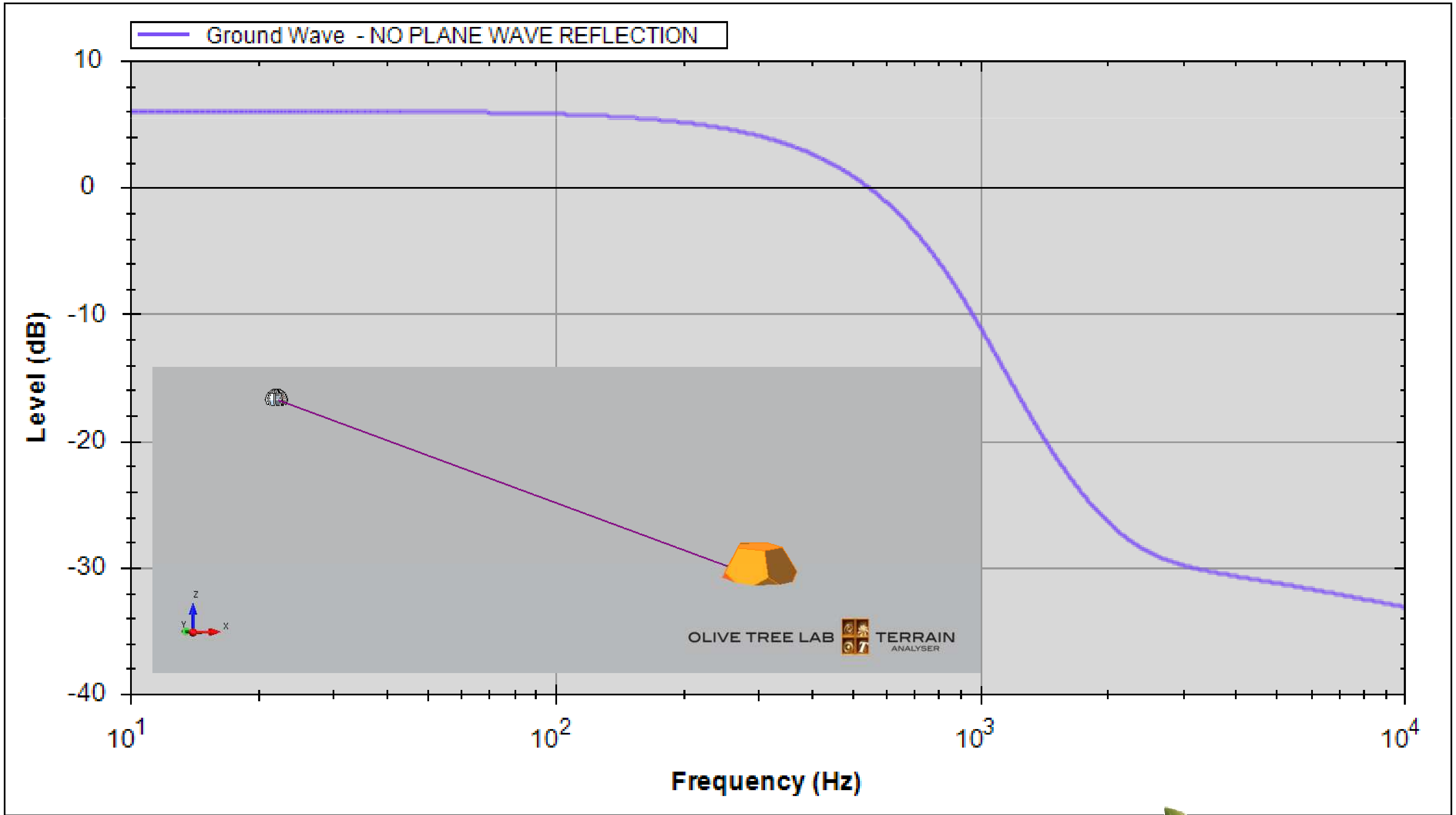


SPHERICAL WAVE REFLECTION COEFFICIENT

PREDICTS **GROUND WAVE**

WHEN PLANE WAVE REFLECTION IS NOT POSSIBLE

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



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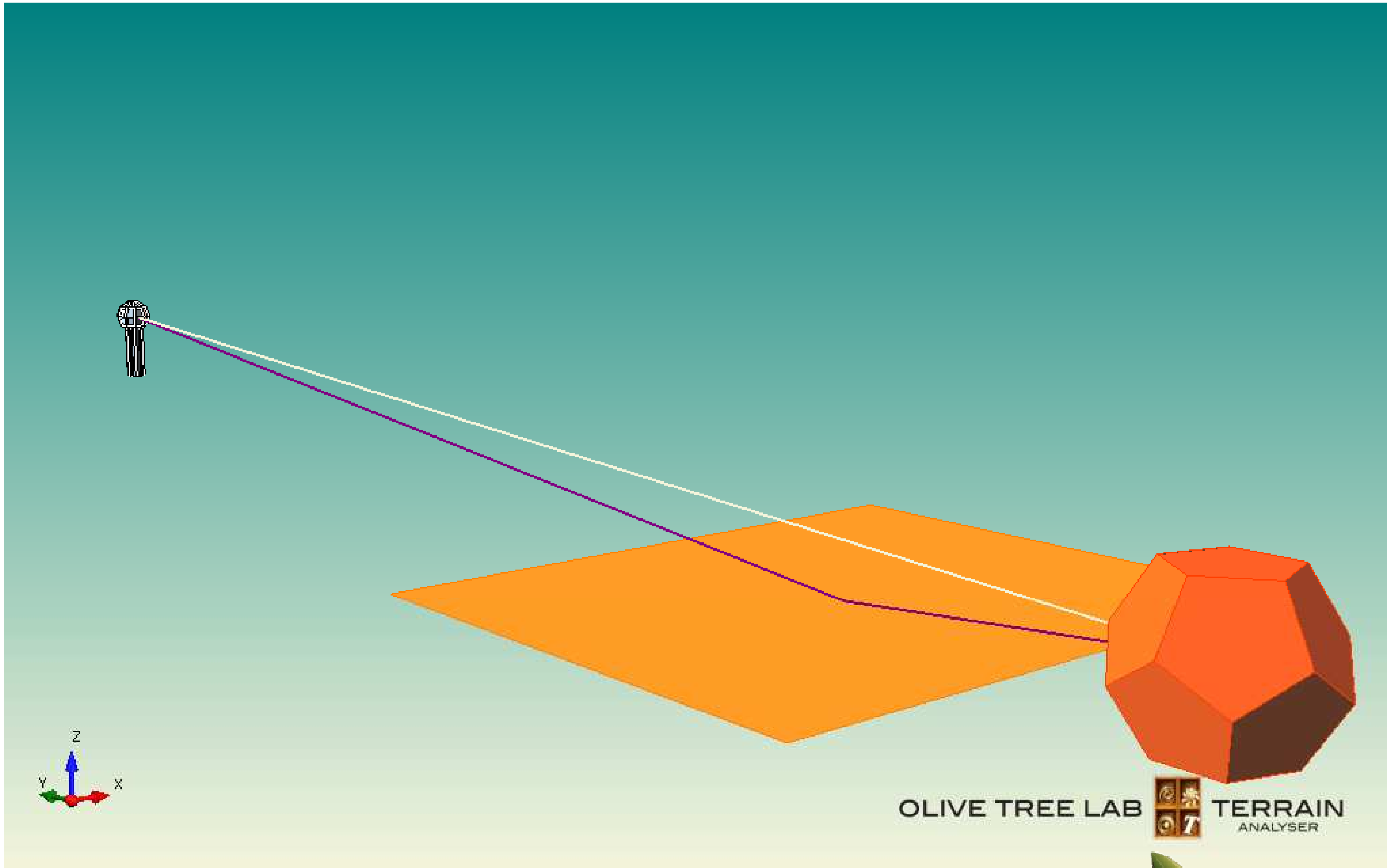
SPHERICAL WAVE REFLECTION COEFFICIENT

CORRECTED FOR REFLECTING SURFACE SIZE

USING FRESNEL ZONES CORRECTION



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SPHERICAL WAVE REFLECTION COEFFICIENT

CORRECTED FOR REFLECTING SURFACE SIZE

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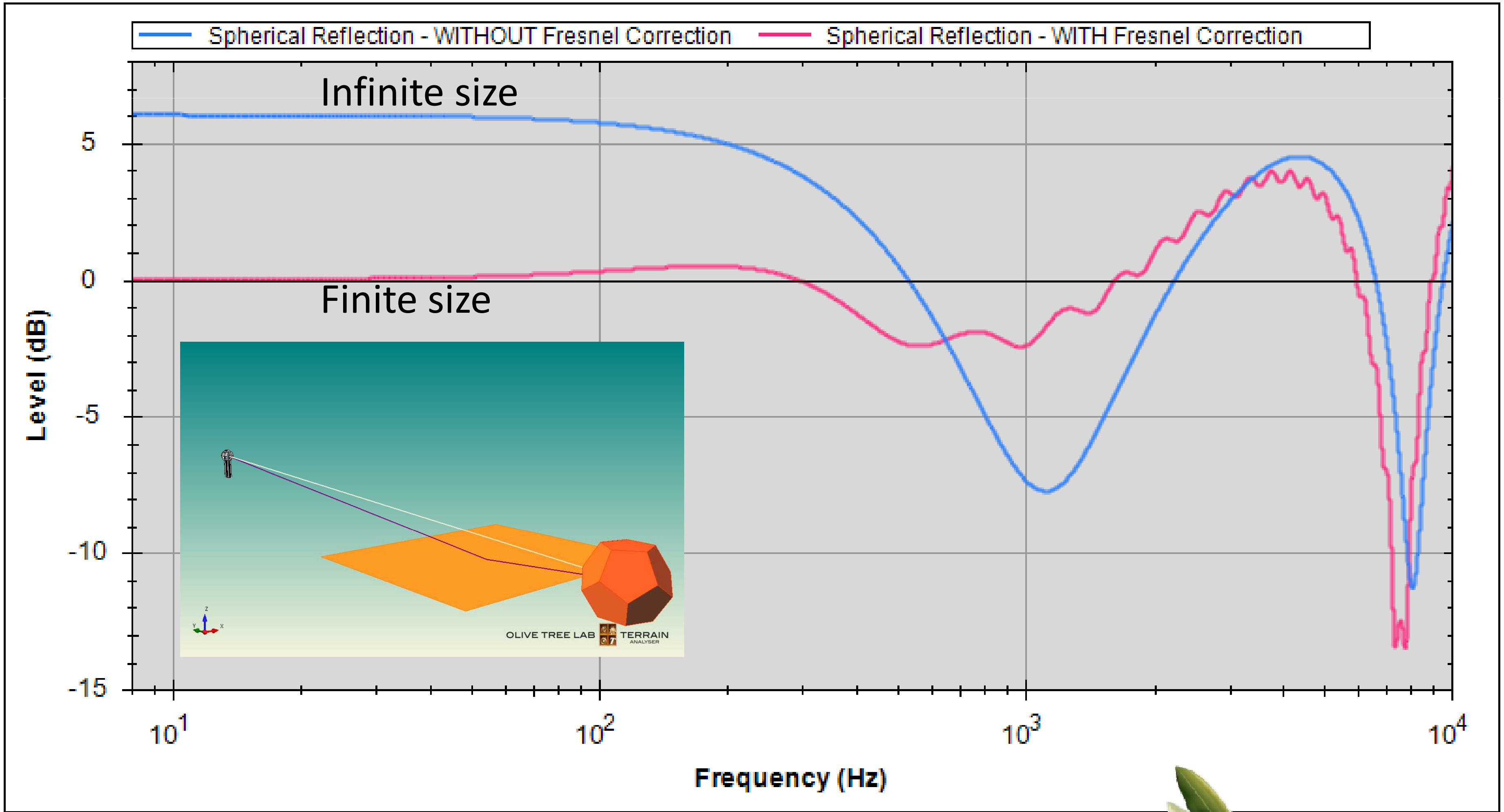

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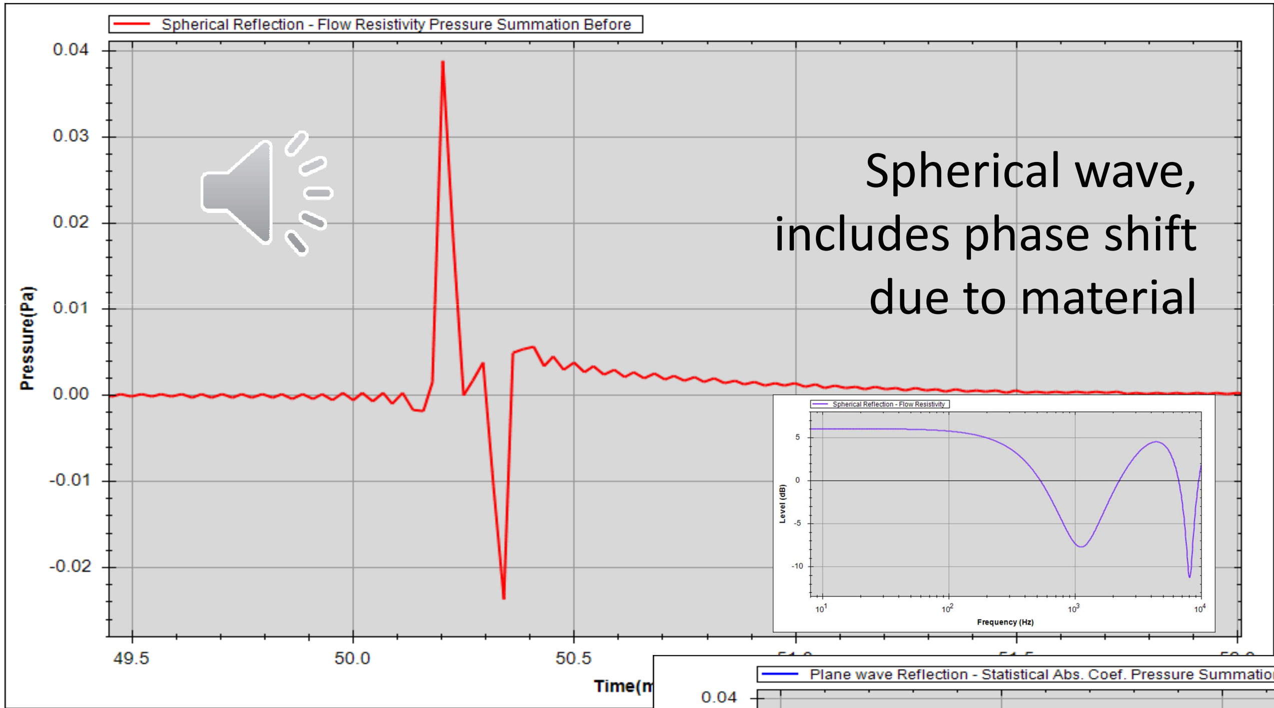
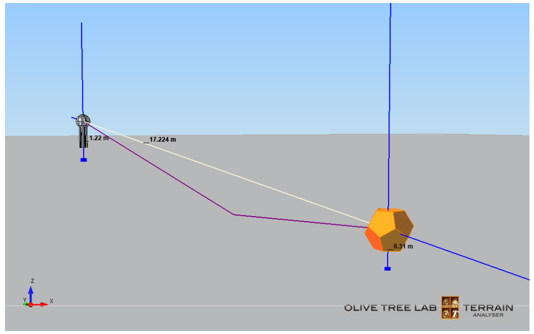
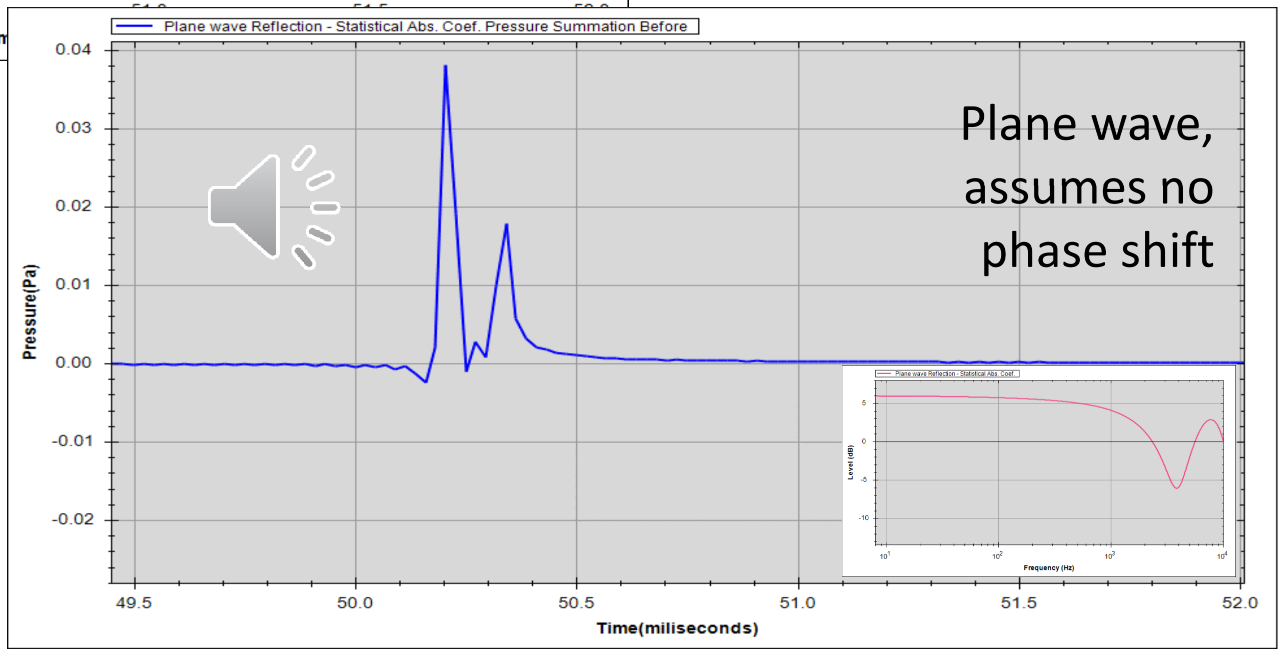
SPHERICAL VS PLANE WAVE REFLECTION COEFFICIENT

IN TIME DOMAIN







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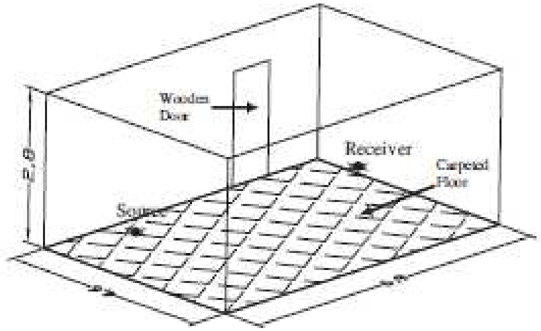
SPHERICAL WAVE CALCULATES ROOM RESONANCES

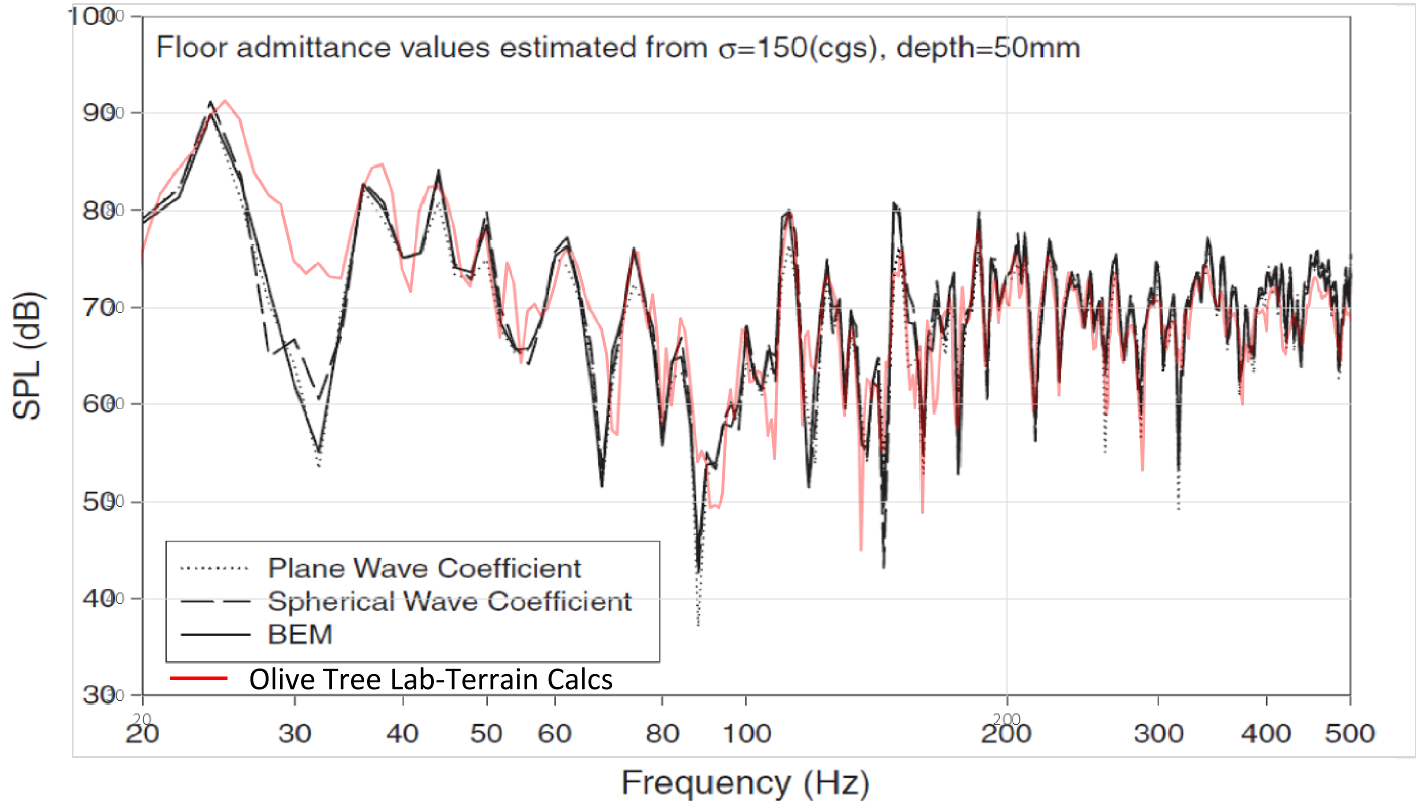
From Lam's paper, where he proves that Spherical Reflection Coefficient matches BEM results.

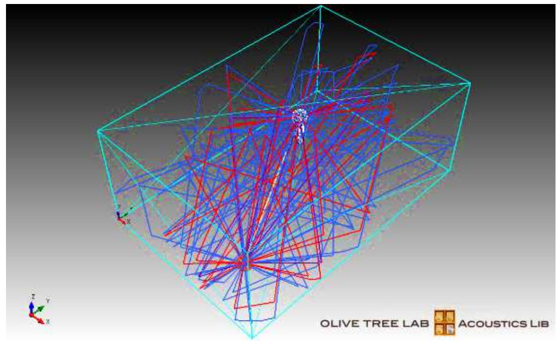
- estimated reflection orders 80,
- our results with 23 orders (calc. time 19 hrs)



Y. W. LAM: COMPUTER MODELLING OF ROOM ACOUSTICS

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





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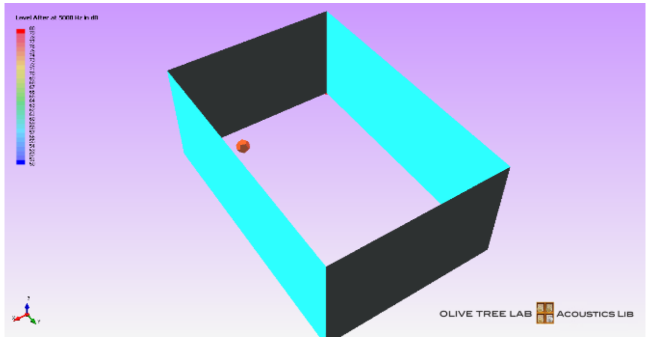
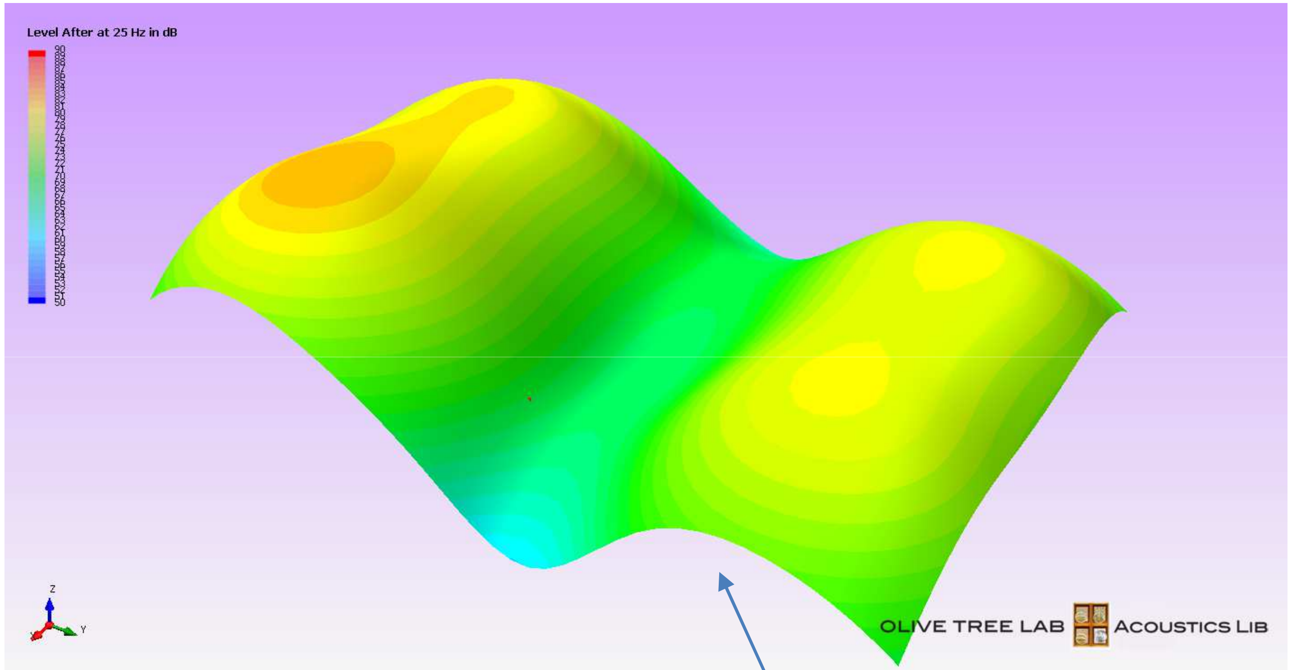
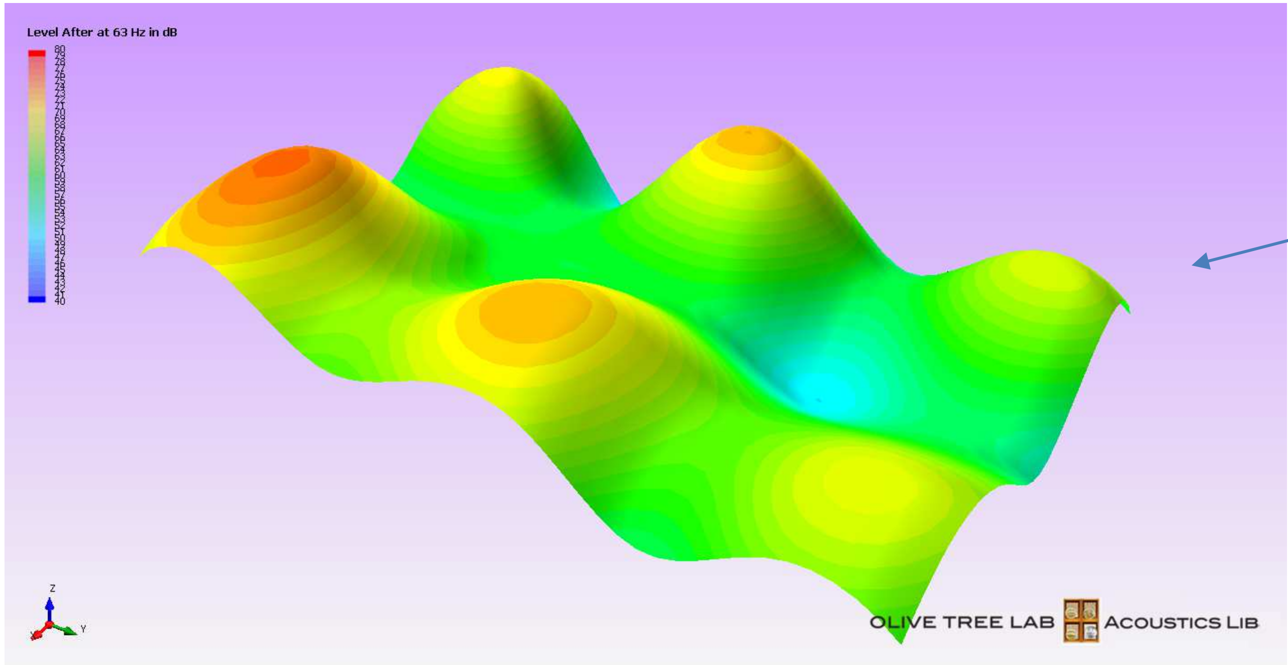
SPHERICAL WAVE CALCULATES ROOM RESONANCES







Above at 25 Hz

Left at 63 Hz

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Olive Tree Lab – Terrain, based on the work of :

- Salomon’s ray model using analytical solutions
- Hadden & Pierce for spherical wave diffraction coefficients
- Chessel for spherical wave reflection coefficients
- Delany & Basley for finite surface impedance
- Clay on finite size reflectors with Fresnel zones
- Keller on his geometrical theory of diffraction
- Sound path explorer – an in-house model to detect and draw diffraction and reflection sound paths in a 3D environment
- Harmonoise for atmospheric turbulence

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PART 3

FROM THEORY TO PRACTICE
AN EXAMPLE:

A block of flats is affected by stadium concerts and a chiller. The background noise level is determined by road traffic between the flats and the stadium

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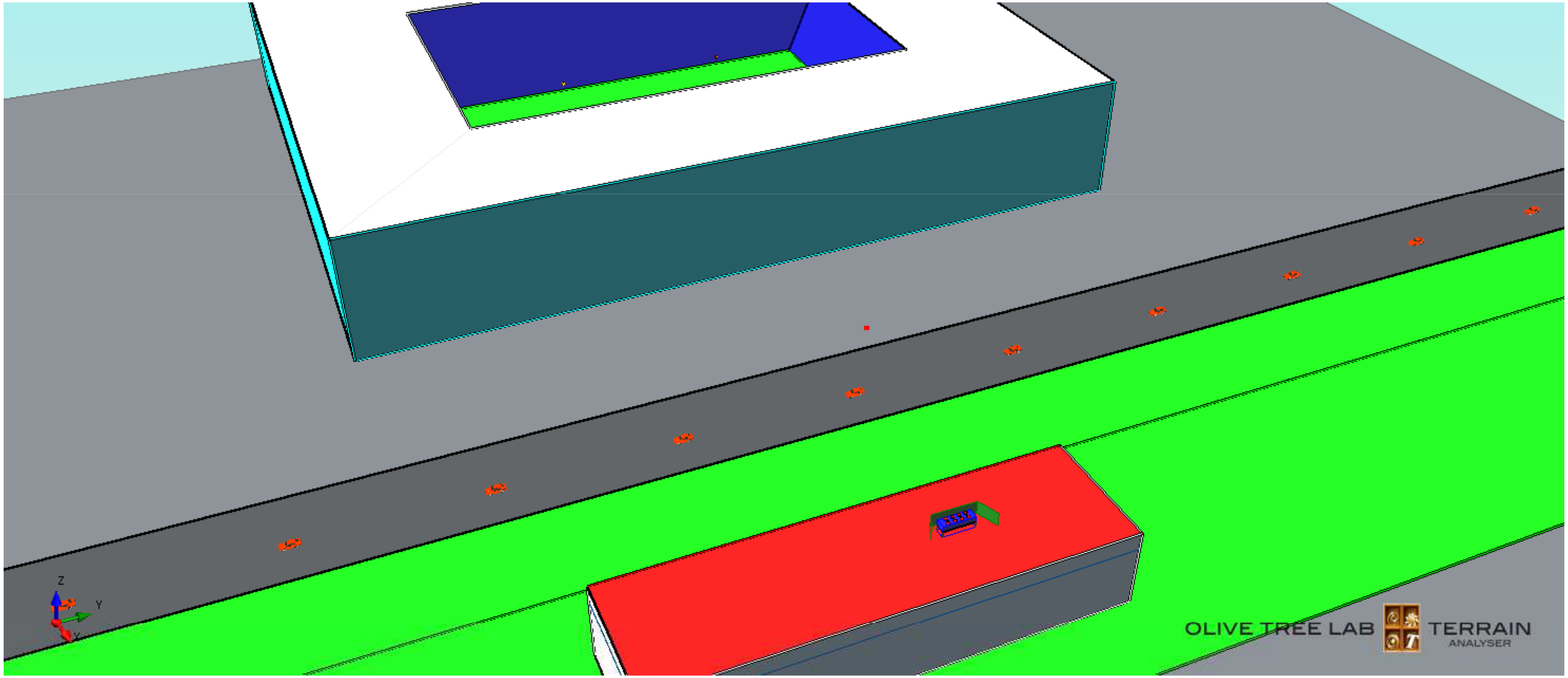
EXAMPLE: A block of flats affected by stadium concerts and a chiller



- A stadium across a block of flats and in between a main road.
- There is a chiller on the roof
- Speakers in the stadium (coherent sources)

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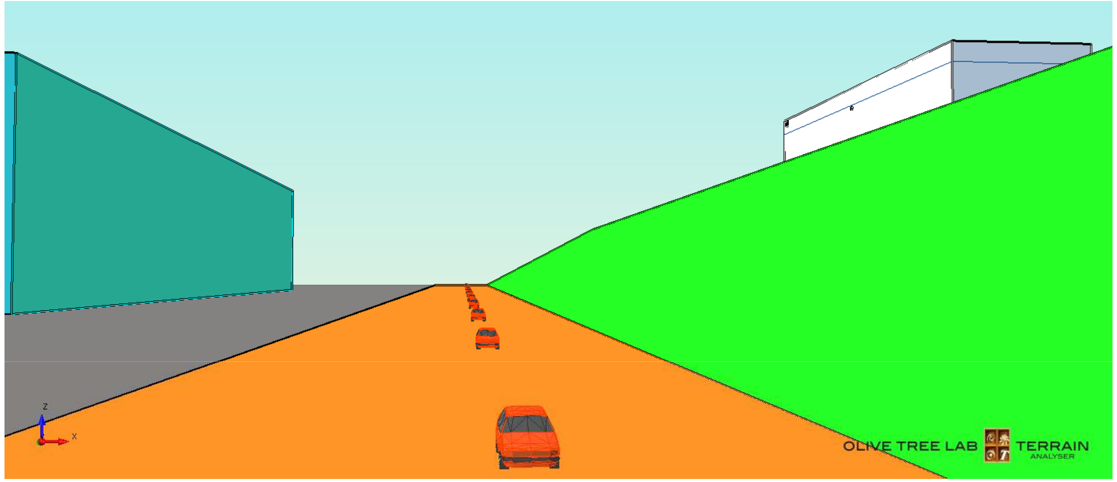
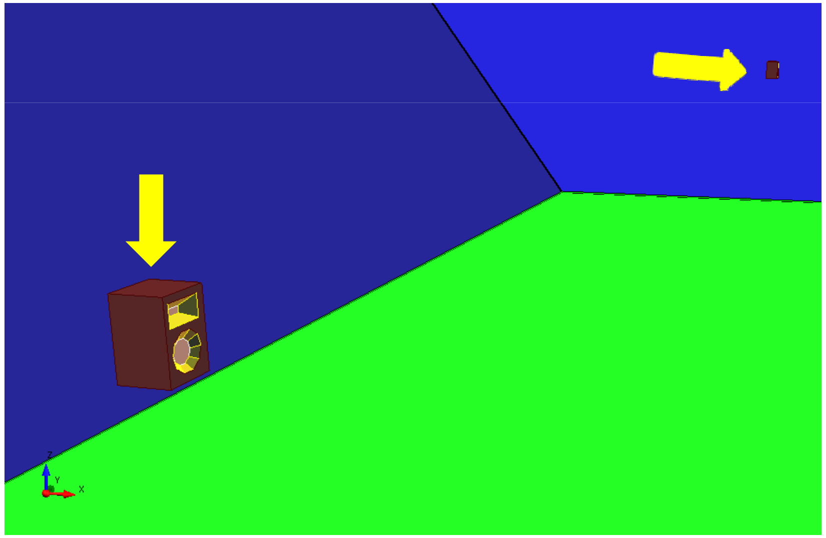
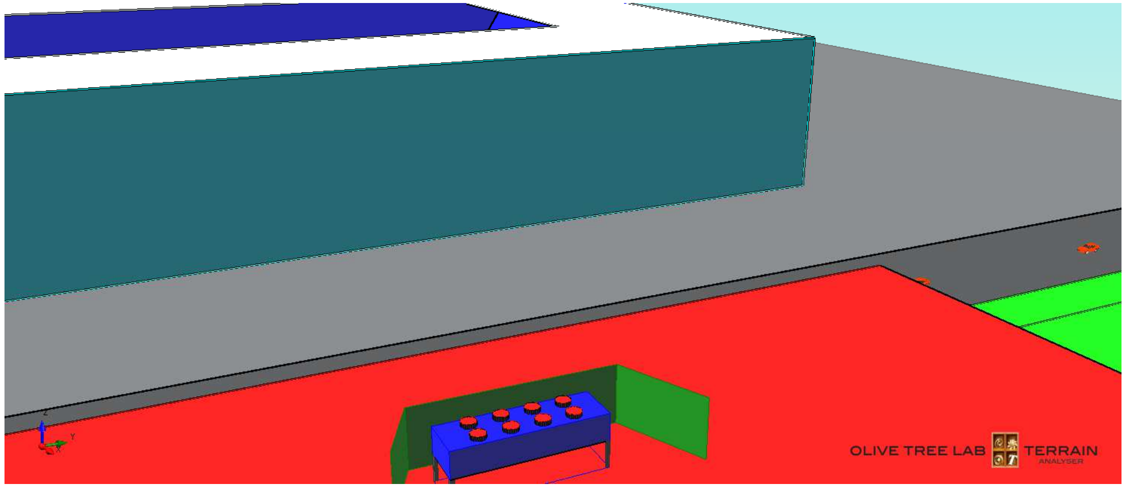
EXAMPLE: A block of flats affected by stadium concerts and a chiller



A stadium across a block of flats and in between a main road.



Speakers in the stadium (coherent sources)



A chiller on the roof

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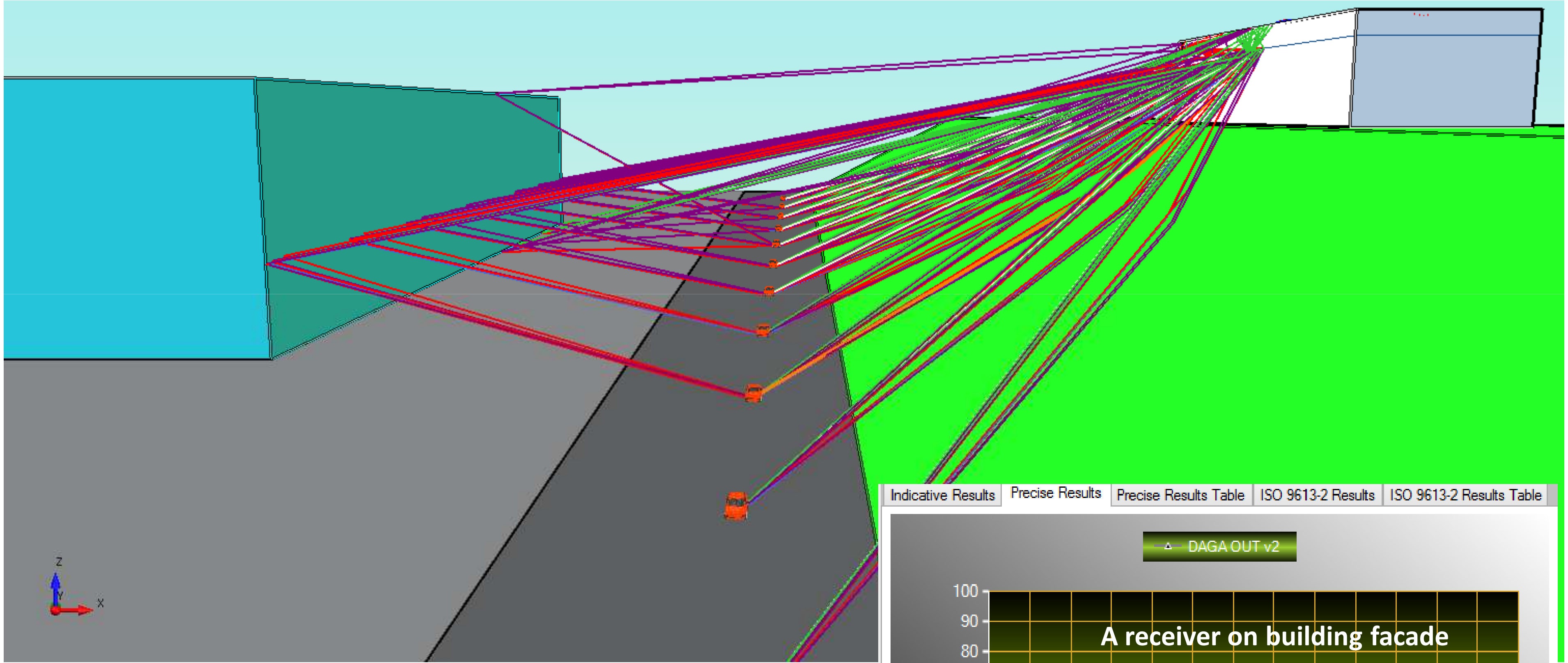
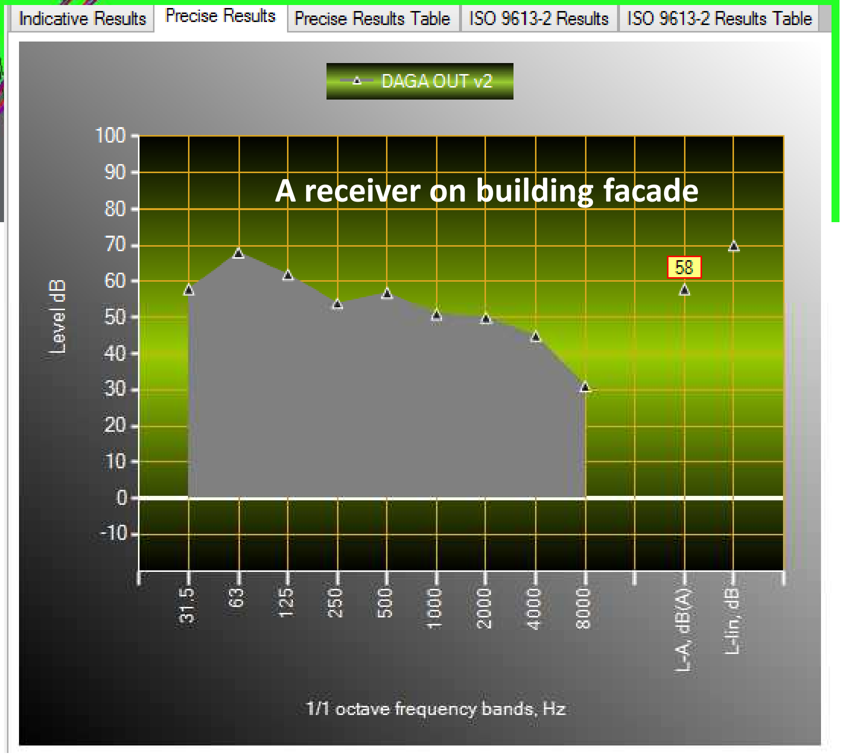
EXAMPLE – NOISE CRITERIA





The BNL at the façade due to road traffic is calculated to be 58 dB(A) having the spectrum shown

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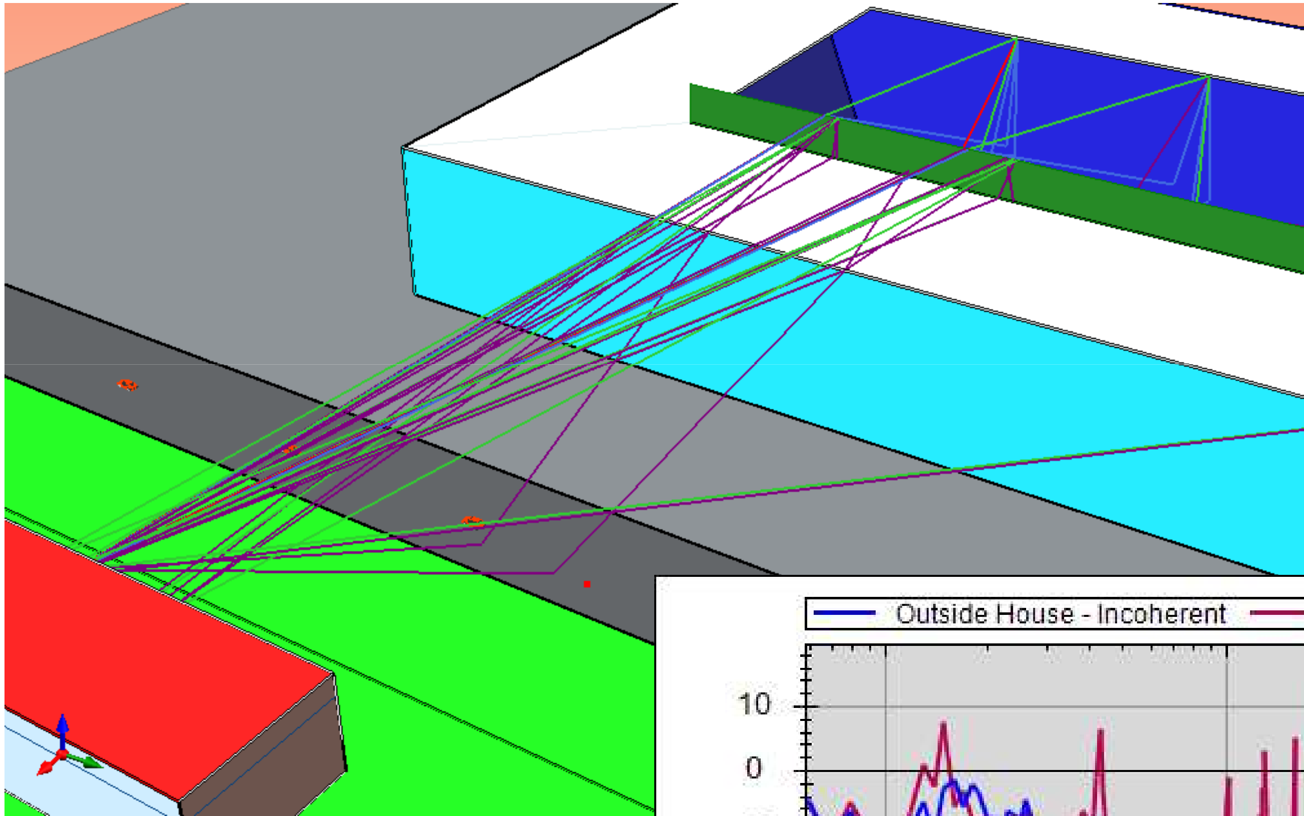
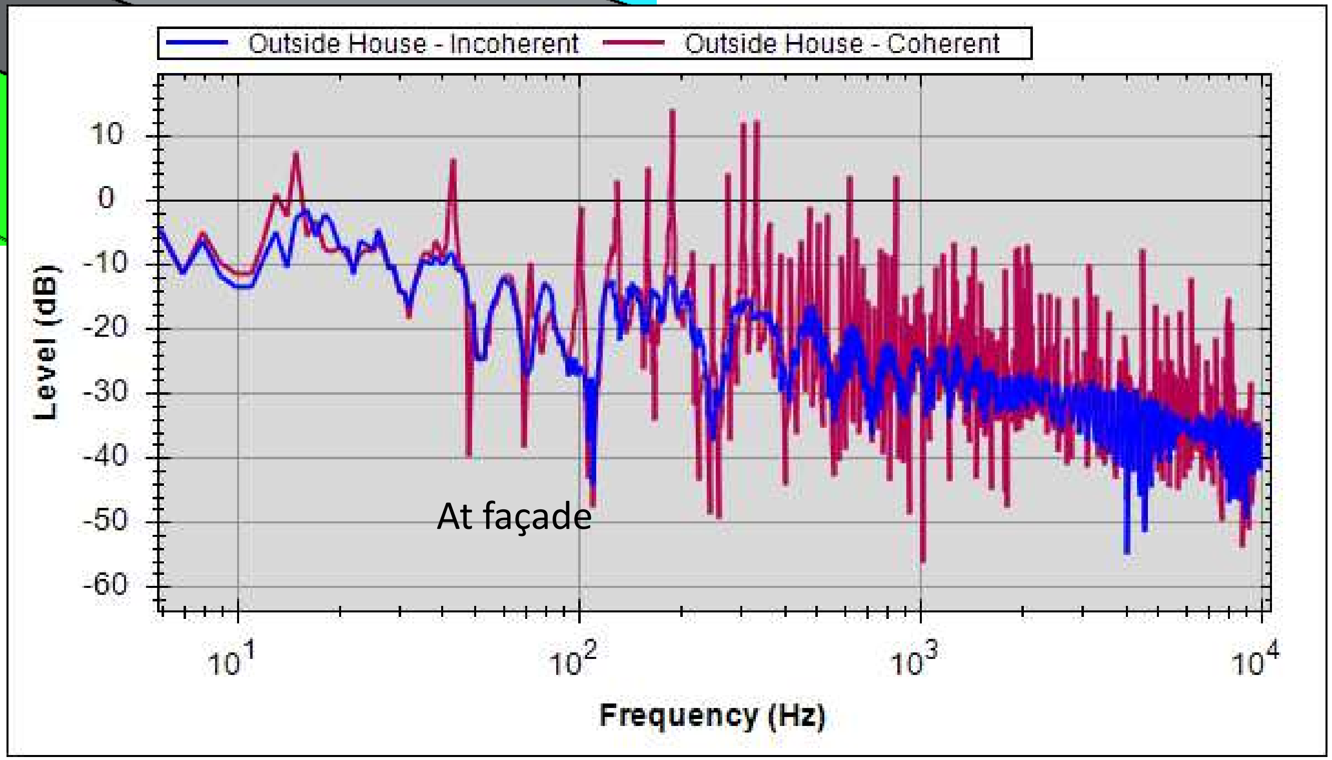
EXAMPLE – COHERENT & INCOHERENT SOURCE ADDITION



Relative Levels outside stadium during a concert.

Levels when speakers are calculated as coherent and incoherent sources.

Note: speakers are omnidirectional.



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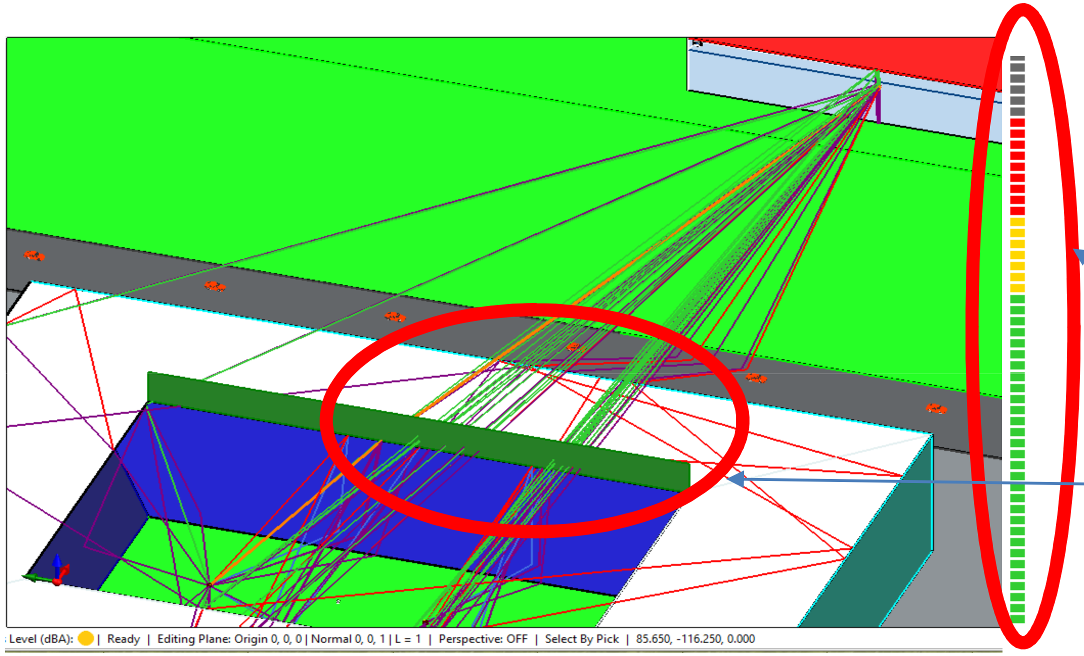
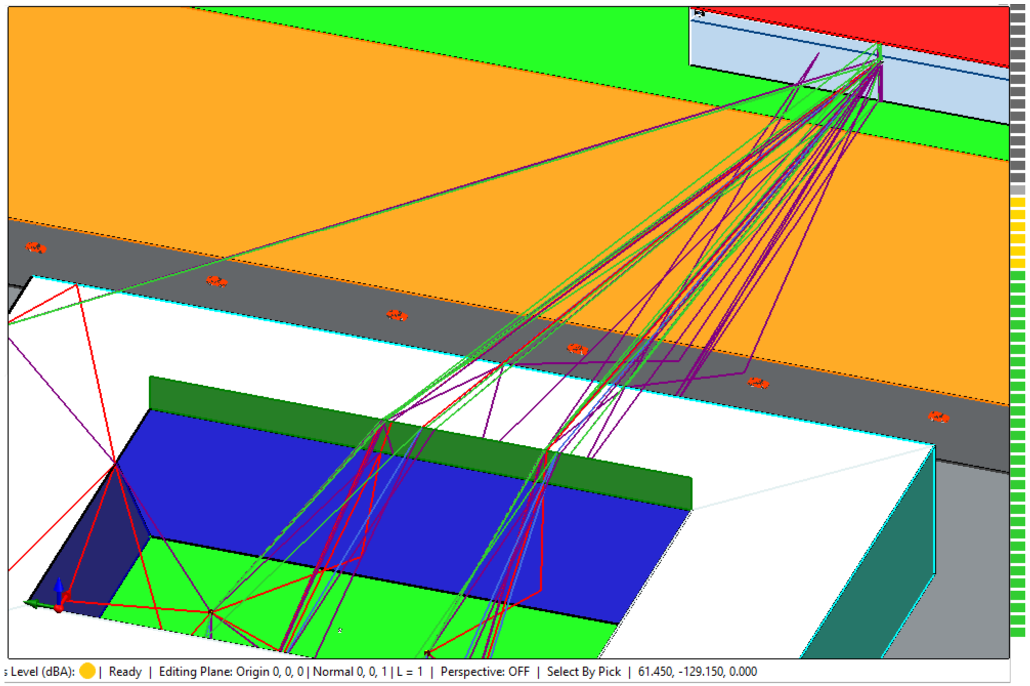
EXAMPLE – PATHS & RESULTS WITH/OUT BARRIER AT FAÇADE





Absolute Levels at façade due to a concert in a stadium. A Noise Barrier (in Green) is placed on Stadium roof

- Bar (LED) meter shows whether noise criteria are met.
- One does not need to remove barrier to calculate levels before the insertion of a barrier

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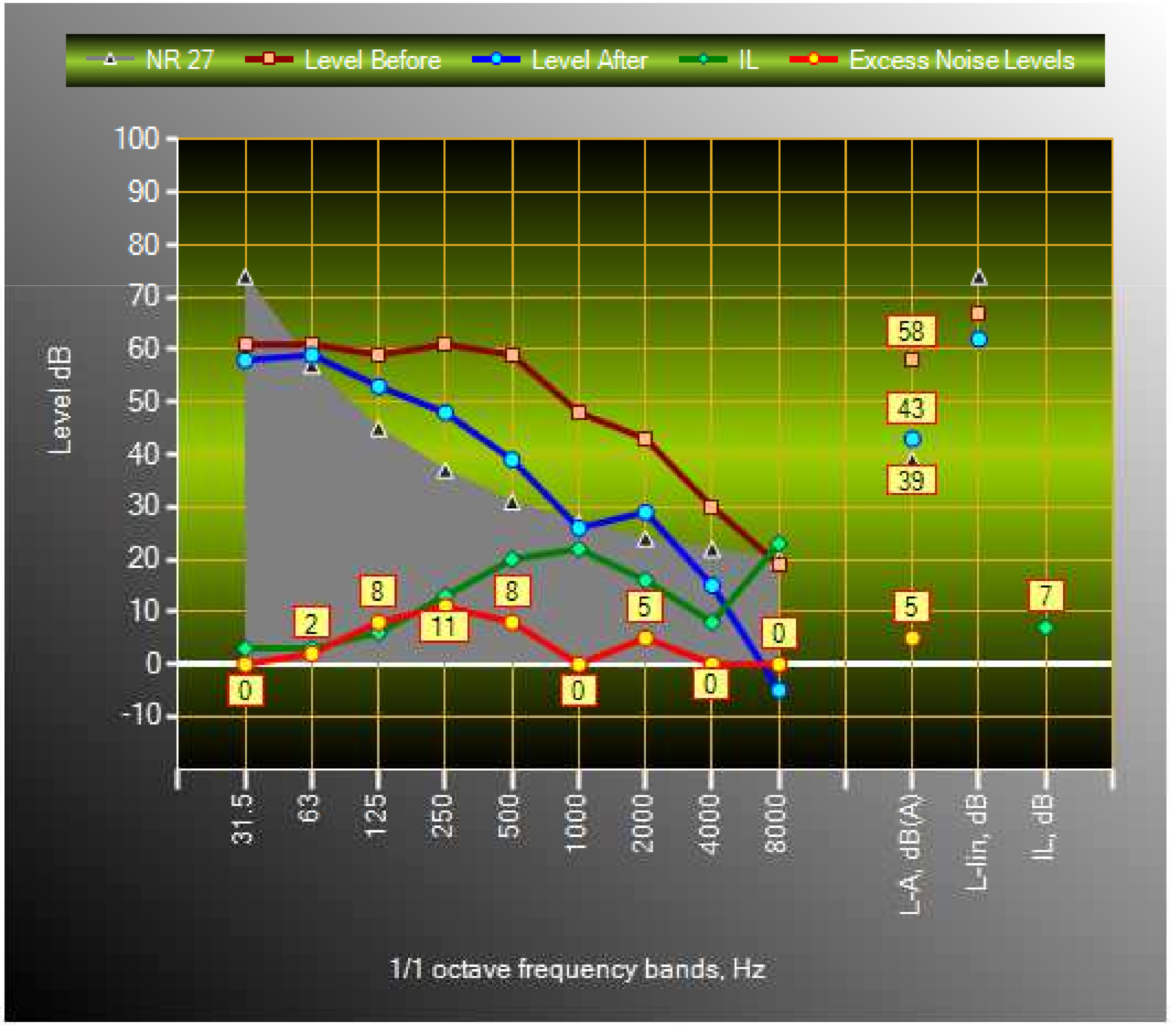
EXAMPLE – AT RECEIVER, A GRAPH THAT SHOWS ALL NECESSARY INFO



A TOOL TO SOLVE A PROBLEM:

ONE GRAPH SHOWS ALL NECESSARY INFO AT A RECEIVER

- Absolute Level Before Barrier Insertion (brown curve)
- Level after insertion of Barrier (blue)
- Noise criteria, Grey Area
- Barrier Insertion Loss (green)
- Excess Level to meet criteria (red, the result of blue minus grey area levels)
- Levels in dB(A) & linear dB
- Average IL

PROBLEM IS SOLVED WHEN BLUE CURVE IS INSIDE GREYED AREA & EXCESS LEVEL IS ZERO

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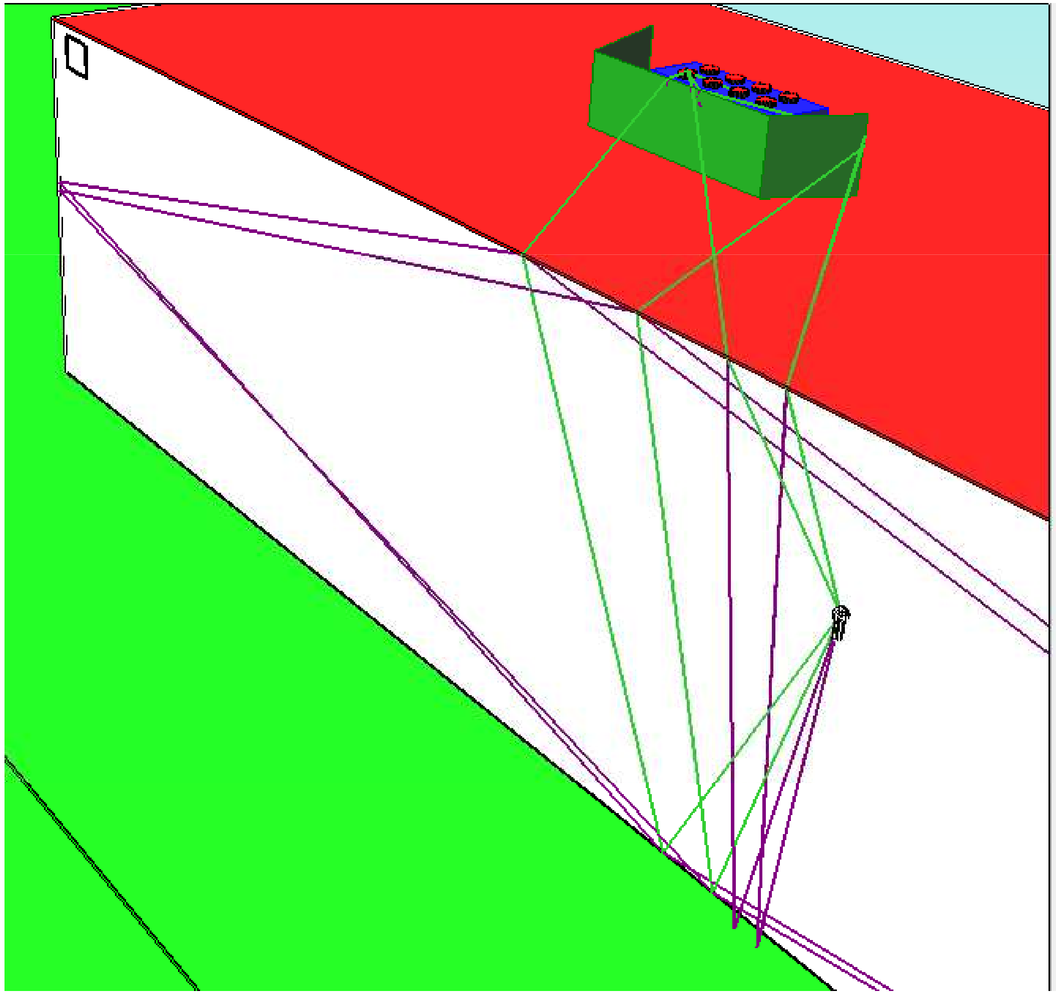
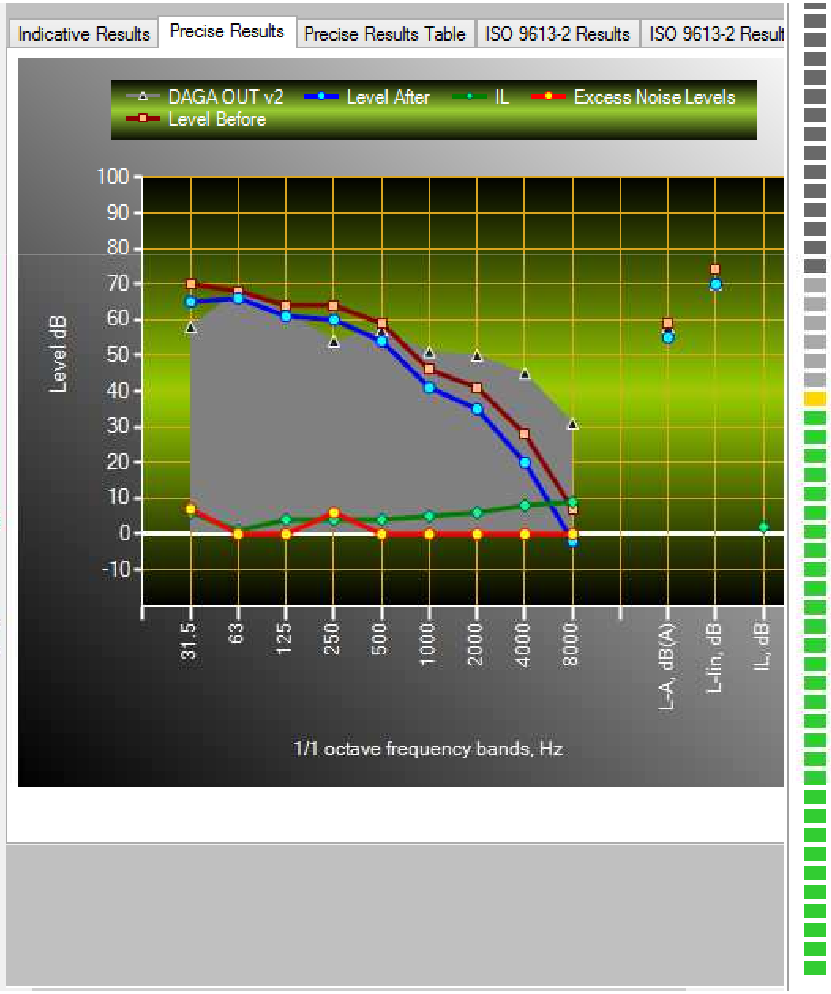
EXAMPLE – CHILLER, PATHS, RESULTS, CALCULATION OPTIONS





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EXAMPLE – CHILLER BARRIER RESULTS TABLES & GRAPHS, REL. LEVELS

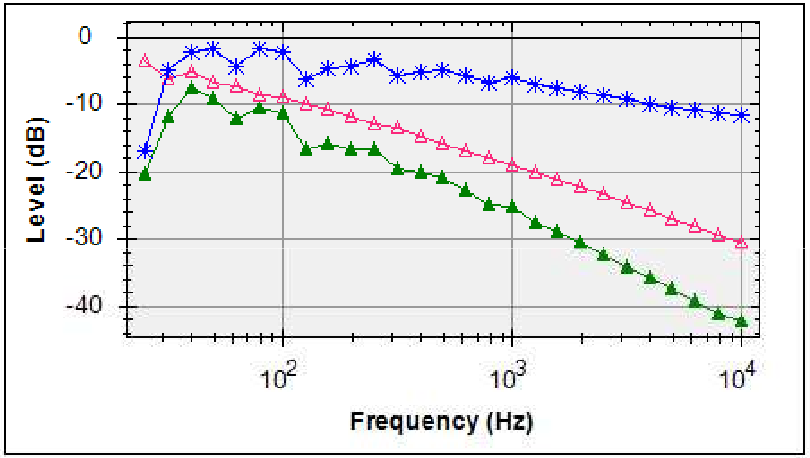
Export Octave Curves (CSV) | Export Octave Curves (Clipboard)

Octave Graph | Octave Table

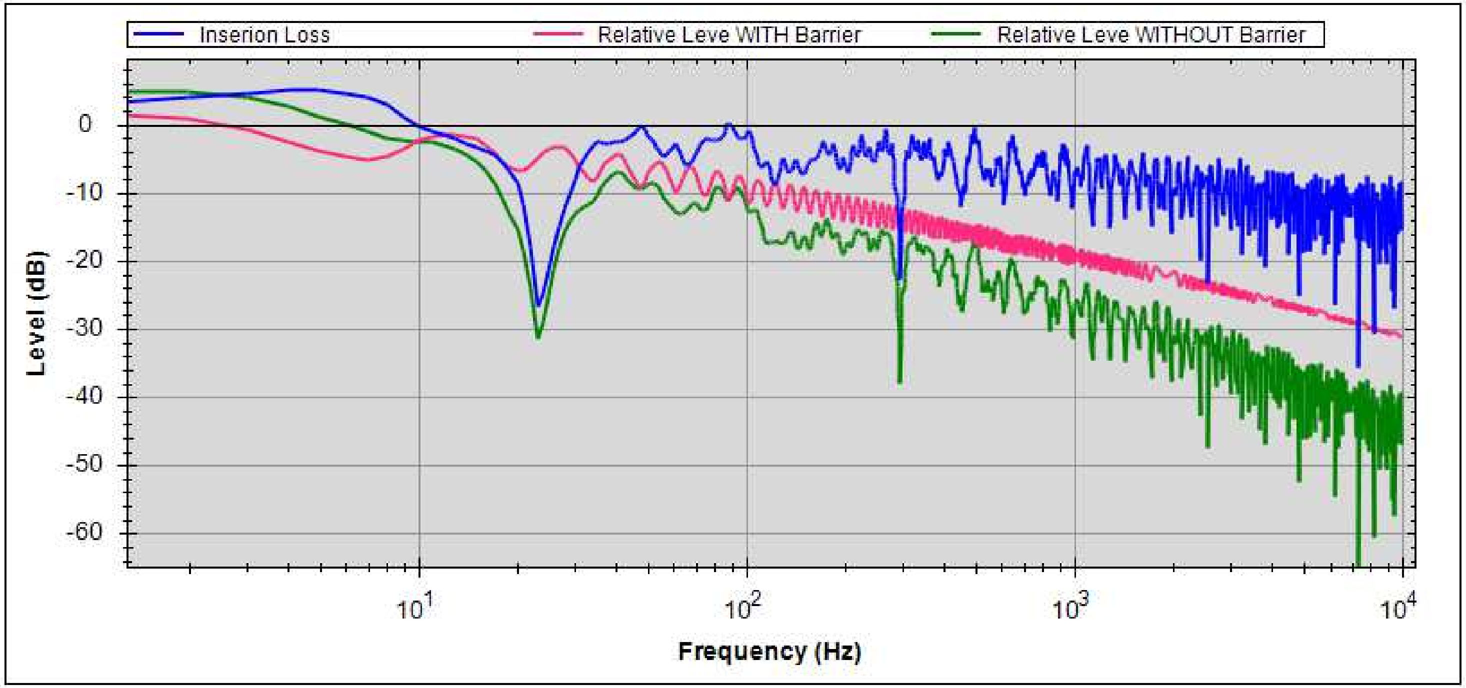
Frequency	Level (dB) [Chiller - Inserion Loss -]	Level (dB) [Chiller - Relative Leve WITH Barrier -]	Level (dB) [Chiller - Relative Leve WITHOUT Barrier -]
32	-4.7	-5.1	-10.4
63	-2.5	-7.8	-10.6
126	-4.4	-10.1	-14.5
251	-4.5	-12.8	-17.5
501	-5.3	-15.9	-21.3
1000	-6.7	-19.1	-25.9
1995	-8.2	-22.3	-30.5
3981	-10	-25.8	-35.7

Export Third Octave Curves (CSV) | Export Third Octave Curves (Clipboard)

1/3 Octave Graph | 1/3 Octave Table



Export High Resolution Curves (CSV) | Export High Resolution Curves (Clipboard)



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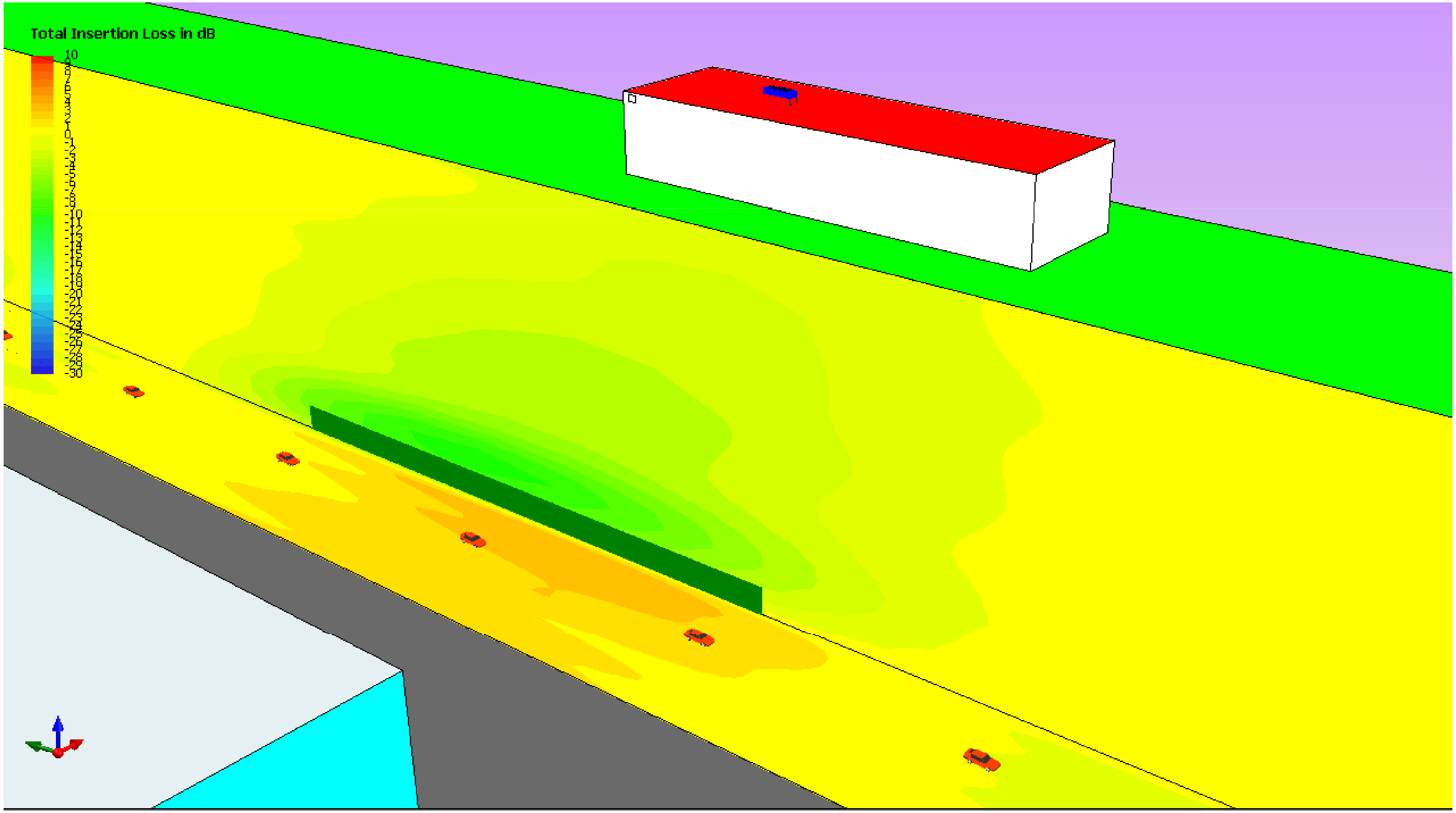
EXAMPLE – BARRIER IL MAPPING, BROADBAND

Mapping of Barrier IL. The effect of the stadium and barrier increase levels on the road



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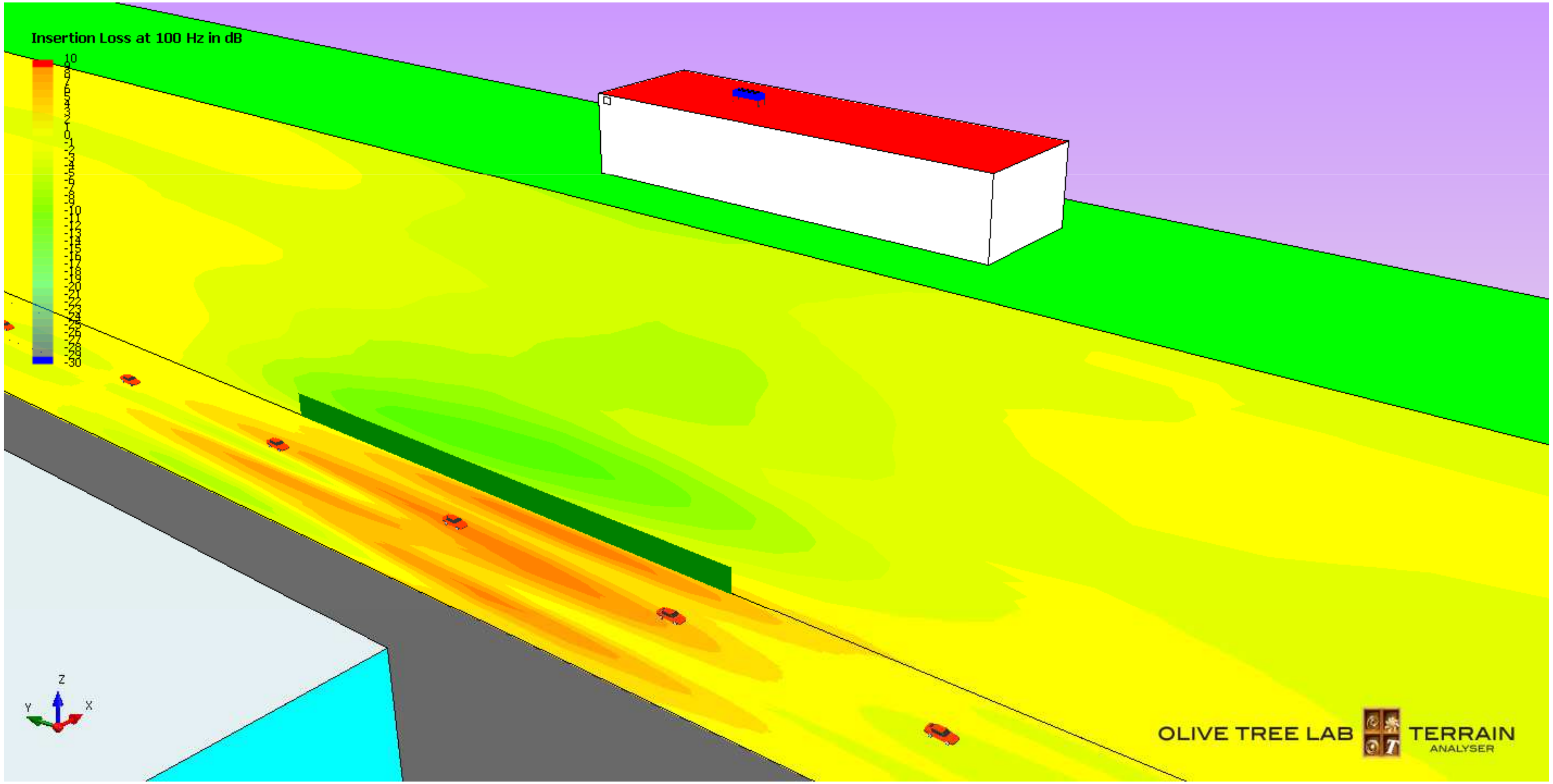
EXAMPLE – BARRIER IL MAPPING, 100Hz

Mapping of Barrier IL. The effect of the stadium and barrier increase levels on the road



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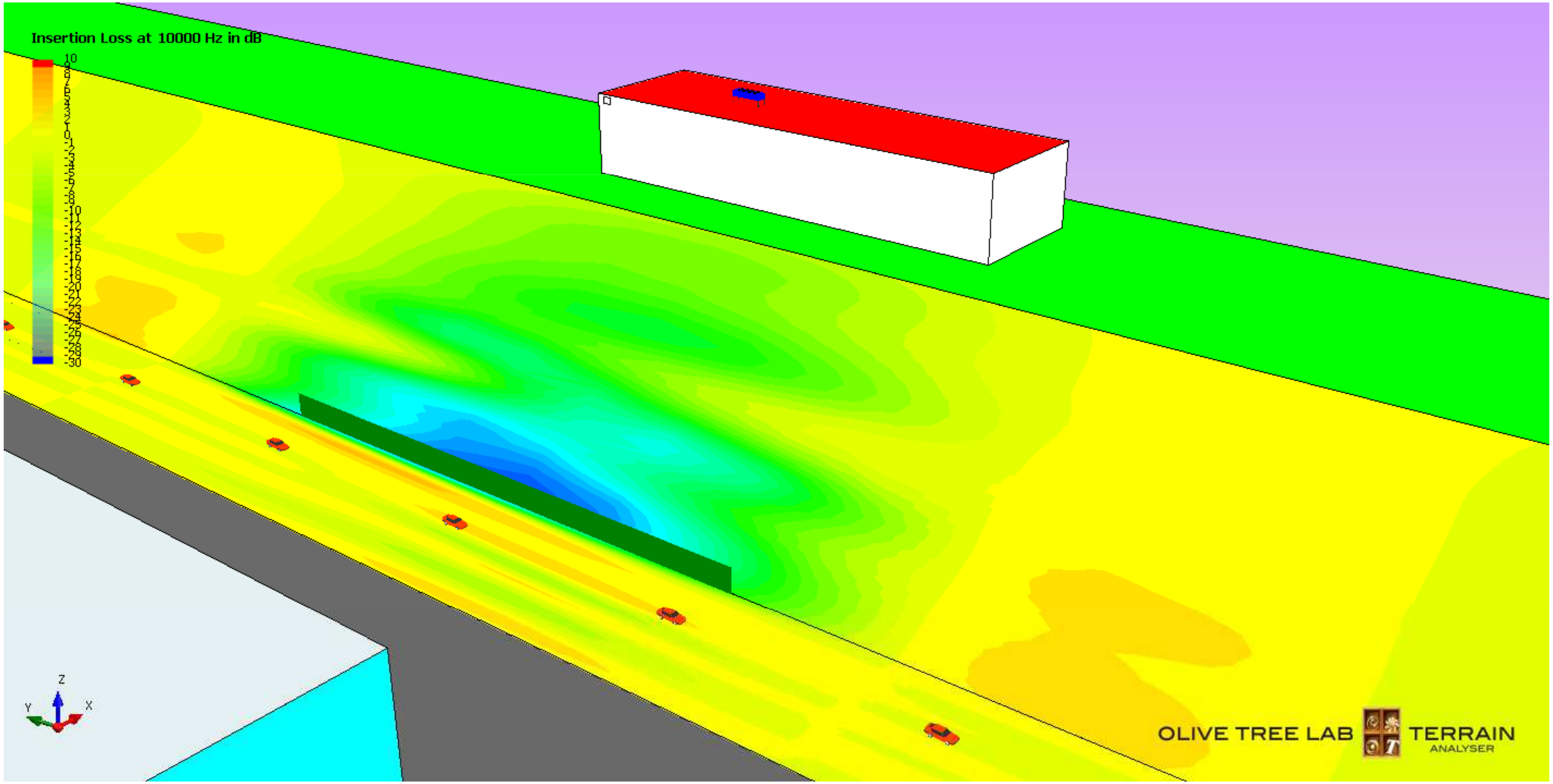
EXAMPLE – BARRIER IL MAPPING, 10kHz

Mapping of Barrier IL. The effect of the stadium and barrier increase levels on the road



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PART 4

CONCLUSIONS

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CONCLUSIONS

- Nowadays technology allows the replacement of simplified calculation methods with advanced calculation methods.
- Advanced calculation methods offer engineers and scientists
  - Accuracy
  - Simplicity
  - More efficiency

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Thank you for your attention.

I would welcome questions or comments.