ISLAMIC UNIVERSITY OF TECHNOLOGY (IUT)

Room Acoustic Parameters of an Auditorium using Ray Tracing Method

B.Sc. Engineering (Mechanical) THESIS

BY

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MARCH 2021

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A THESIS PRESENTED TO THE DEPARTMENT OF MECHANICAL AND PRODUCTION ENGINEERING, ISLAMIC UNIVERSITY OF TECHNOLOGY DHAKA IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE AWARD OF DEGREE FOR

BACHELOR OF SCIENCE (B. Sc.) IN MECHANICAL ENGINEERING

MARCH 2021

The thesis titled “**Room Acoustic Parameters of an Auditorium using Ray Tracing Method**” submitted by **Md. Mesbahul Maruf (160011016)** and **Abrar MD Mubashshir Antar (160011009)** has been accepted as satisfactory in partial fulfilment of the requirement for the Degree of Bachelor of Science in **Mechanical Engineering**.

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It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

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Acknowledgements

We would like to begin by saying Alhamdulillah and grateful to Almighty Allah who made it possible for us to finish this work successfully on time. Equally say a big thank you to our supervisor **Mr. Nagib Mehfuz**, Lecturer, Department of Mechanical and Production Engineering, IUT for all his support, ideas about experiments, discussions, time and for explaining so patiently the hard topics and checking this thesis and papers above all his care and concern. These will ever remain in our memory. Thanks to our examiners for their constructive ideas, suggestions and double checking our work.

Abstract

Sound quality is important for concert halls, seminar room even in room of house too. Ray acoustic is used in simulating the high frequency limit when the wavelengths is smaller than the geometrical features. The ray acoustic model can play a vital role in designing an auditorium or a concert hall. The shape of the room and the building materials can impact on the sound quality. The diffusion and absorption coefficient of sounds are the main parameters of the simulation, different materials contain different value of this. The model should contain geometrical setup, different parameters of room acoustics and sound sources. The room acoustic parameters also known as sound absorption coefficient which is vary according to the materials properties. For simulation the reflection and noise of sound should consider as low or zero where for experiment it is impossible to reduce sound noise and reflection in zero. For the ideal case in auditorium, an omnidirectional sound source is used, where two models are simulated through COMSOL Multiphysics. The results contain reverberation time, sound pressure level and temporal impulse response. The main objective is to improve sound pressure level of an auditorium, also improving the audience`s listening experience and improving the reverberation time.

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Introduction

In this model the acoustic of an auditorium is analysed. Two model has setup for this simulation. The first model setup contains omnidirectional sound source and for the second model two more sound sources is added. The both model contains wall boundary conditions for specular and diffuse scattering, sound pressure evaluation, a receiver data set used to reconstruct a temporal impulse response plot, and an energy response.

Reverberation time is defined as the time it takes for sound to decay by 60dB (SPL decrease by 60dB). It is an important metric to describe the acoustical properties of a room. It is denoted by T_{60} and differences of 0.05 are noticeable[1].

Impulse response is a reaction of instant changes of any system in response to some external changes of that system. Fast Fourier Transform (FFT) is an algorithm that transfer time domain to frequency domain. Ray Tracing Method is used for calculating path of waves through a system. Sound Absorption Coefficient is used to evaluate the sound absorption efficiency of materials.

Room acoustic contains three basic approaches. Geometrical acoustic is commonly used in ray tracing of sound and image. Ray acoustic methods are used when the wavelength is smaller than the geometrical features otherwise if the wavelength of sound becomes comparable to the dimensions of the room, the wave properties of sound become important to be neglected. Fourier transformation is commonly used to calculate the pressure impulse response from the transfer function of the room.

Background and Literature Review

Literature Review

The present work is integrated with ray tracing model. Ray tracing model developed by Hodgson *et al.* [2]. Hereafter called PRAY- based on the ray tracing algorithm of Ondet and Barbry [3]. This model predicts Sound Pressure Level (SPL), any cubic number of receiver cell in horizontal plane room the sound pressure level can be predicted. The improve model of this was introduced by Hodgson[4], where includes the diffuse surface reflections according to Lambert`s Law. This model called DRAY, was further improved to calculate the energy echogram.

Sound absorb by converting sound energy to heat within the materials, resulting in a reduction of the sound pressure[5]. Sound absorption materials are widely used in many noise control applications. The room acoustic parameters are basically defined the materials absorption coefficient. Reverberation is regarded as the most important room acoustical parameters too.

Theoretical Background

1. Room Acoustics

Room Acoustics contains three basic approaches. They are:

- Geometrical acoustics is used for tracing rays in sound, also useful for understanding how rooms function with regards to hearing.
- Statistical acoustics, which is useful for measuring sound power and sound-absorption
- Physical acoustics is also known as wave theory, which is useful to understand why the previous two approaches do not work for low frequencies and/or small rooms.[6]

2. Prediction Models in Room Acoustic

Prediction models in room acoustics used to find the temporal and spatial distributions of sound pressure (SP) inside a room or closed space. Predictions are basically two type, energy based or wave based[2]. Energy based models ignore phase, modelling propagating sound waves as rays or energy [7]. Room echograms and steady state levels are predicted through this model. Room acoustical prediction can be placed in model theory, diffuse field theory, geometrical room acoustic and diffusion models. Diffuse field theory[8] assumes a diffuse sound field and room restrictive characteristics.

3. Ray Acoustics Approaches

Ray acoustic methods are used when the wavelength is smaller than the geometrical features otherwise if the wavelength of sound becomes comparable to the dimensions of the room, the wave properties of sound become important to be neglected.

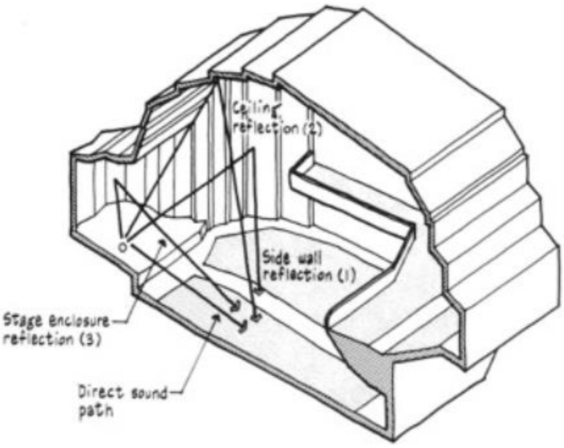


Figure 1: The Ray Approach[1]

Fast Fourier transformation is commonly used to calculate the pressure impulse response from the transfer function of the room. This requires knowledge of the phase spectrum of the transfer function. If phase information is not available, one can assume the transfer function to be minimum-phase and obtain the phase using a Hilbert transform [2].

4. Reverberation Time

Reverberation time is defined as the time it takes for sound to decay by 60dB.
It is an important metric to describe the acoustical properties of a room. Reverberation time plays a crucial role in the quality of sound and the ability to

understand speech in a room or given space. It is difficult to choose an optimum reverberation time in a multifunction space, as different uses require different reverberation times.

5. Sabine Formula

Measuring the reverberation time of a space is a good way to identify a noise control problem. Sabine Formula is used to measuring the reverberation time.

$$T_{60} = 0.161 \frac{V}{S\bar{\alpha} + 4mV}$$

Where,

- *V* is the room volume,
- *S* is the total surface area,
- *m* is the volume attenuation,
- α is the average wall absorption

Sabine formula can be used in following approximate conditions:

- When the room absorption coefficient is below 0.3.
- The sound absorbing surface are approximately disturbed over the room.
- The shape of the room is not complex. [1]

Development of the Model

Geometry

In this model the acoustic of an auditorium is analysed. The model is that of a listening environment with a volume of 460 m^3 and a total surface area of 390 m^2. The model setup includes omnidirectional sound sources, wall boundary condition and diffuse scattering. The model consist of windows, stage, entrance and seating area. Omnidirectional sound sources are located in the figure below.

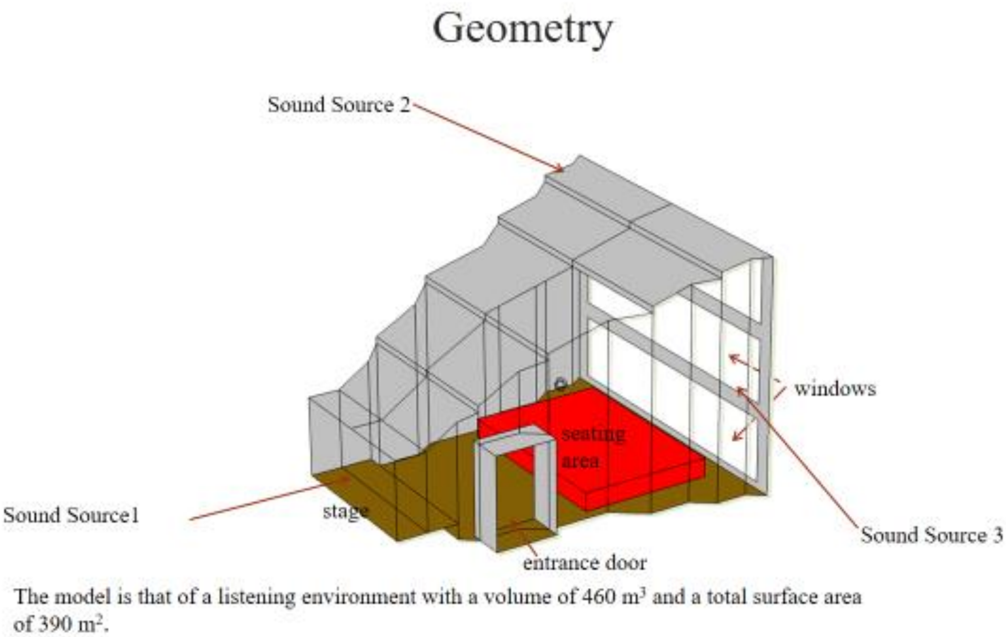


Figure 2: Model setup for simulation

The sound source 1 used as the primary sound source and then the sound source 2 and 3 have added for the multiple sources analysis.

Parameters of Room Acoustics (Absorption Coefficient)

Table 1: Absorption Coefficient

Frequency (Hz)	**Walls**	**Windows**	**Entrance**	**Floor**	**Diffusers**	**Absorber**	**Seats**
125	**0.1**	**0.4**	**0.01**	**0.02**	**0.1**	**0.24**	**0.1**
250	**0.07**	**0.2**	**0.01**	**0.03**	**0.1**	**0.4**	**0.4**
500	**0.05**	**0.12**	**0.02**	**0.05**	**0.1**	**0.78**	**0.7**
1000	**0.04**	**0.07**	**0.02**	**0.1**	**0.1**	**0.98**	**0.6**
2000	**0.04**	**0.05**	**0.02**	**0.3**	**0.1**	**0.96**	**0.3**
4000	**0.05**	**0.05**	**0.03**	**0.5**	**0.1**	**0.87**	**0.2**
8000	**0.08**	**0.05**	**0.04**	**0.5**	**0.1**	**0.75**	**0.1**
16000	**0.1**	**0.05**	**0.05**	**0.5**	**0.1**	**0.6**	**0.1**

The absorption coefficients are taken from reference [9] as they are generic value.

Modelling Instructions

1) In the New window, Model Wizard > 3D.

2) In the Select Physics tree, Acoustics>Geometrical Acoustics>Ray Acoustics (rac) was selected. Then a new study, Ray Tracing from Preset Studies for Selected Physics Interfaces was added. A geometry sequence featuring an Auditorium geometry was imported in the model wizard.

In the Model Builder window, under Component 1 (comp1)>Geometry 1 by right-clicking Import 1 (imp1) and Build All Objects was chosen. After Clicking the Zoom Extents button in the Graphics toolbar, we got the figure

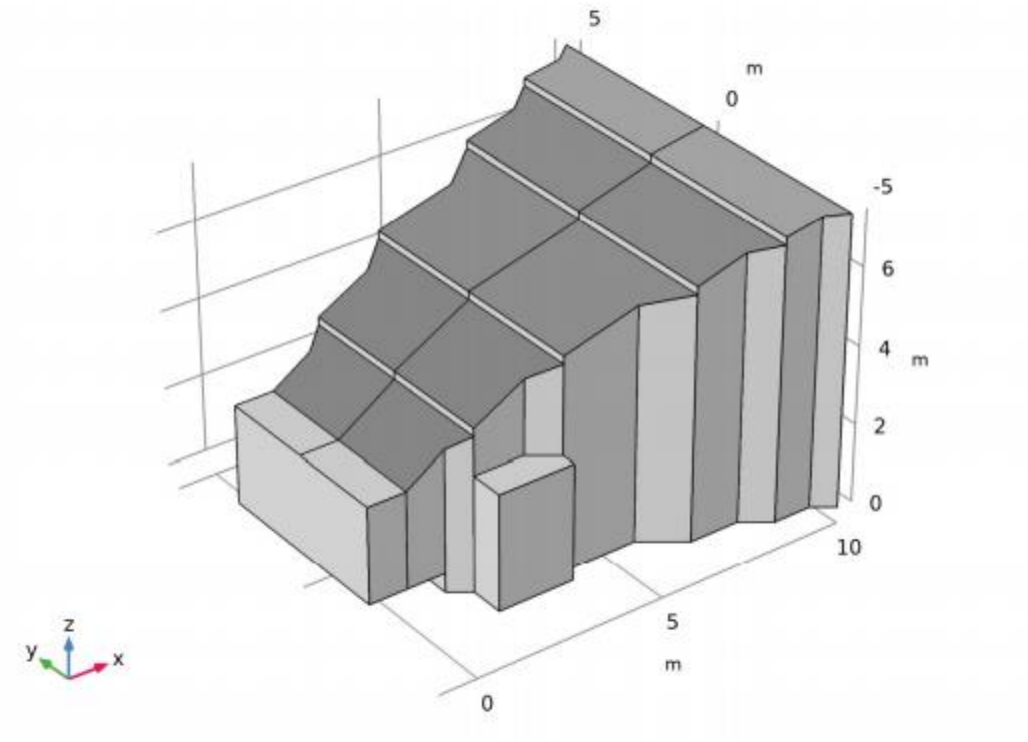
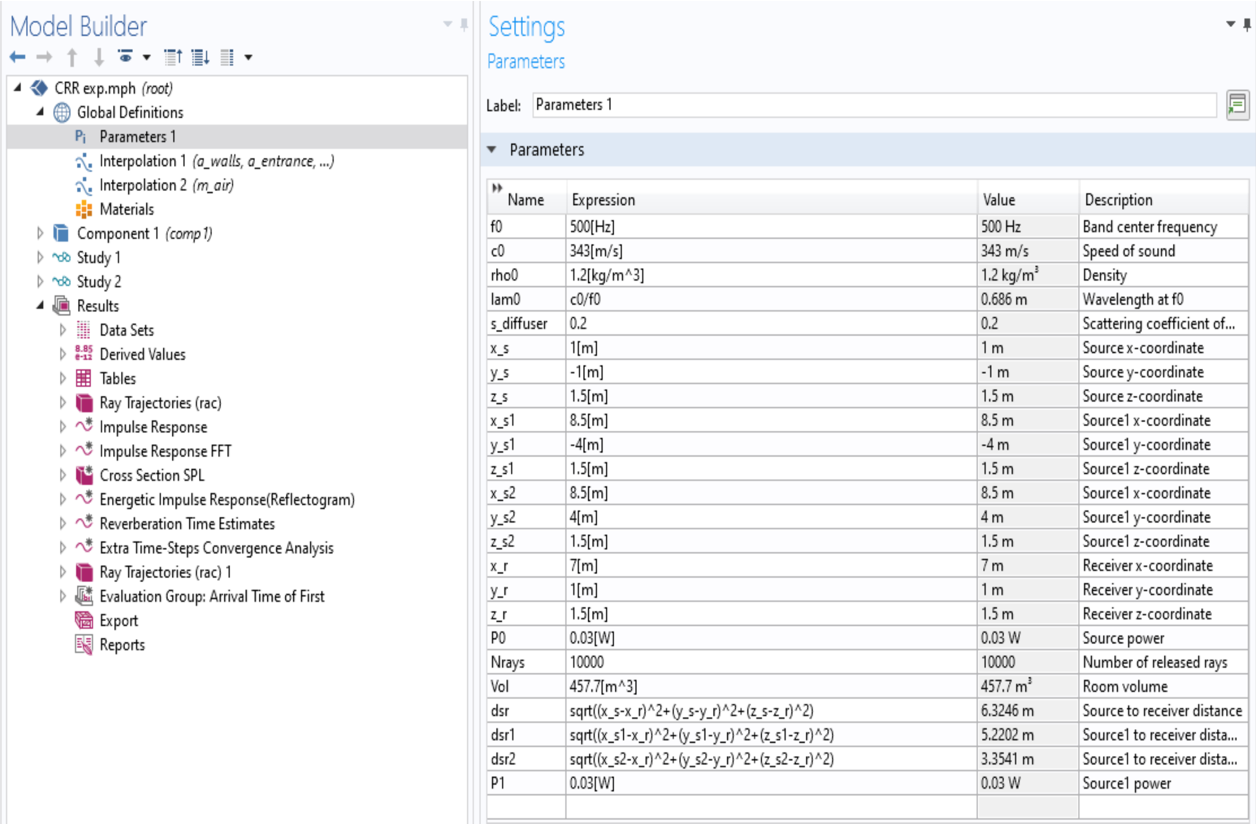


Figure 3: Geometry of the Auditorium

At first, In the Model Builder window, under Global Definitions, Parameters 1 was selected. Then in the Parameters section, a file was imported where the name of functions and values of these functions were given. The parameters include the band center frequency f0, the location of the source and receiver, as well as the room volume. [10]

Three location were selected for setting three sound sources.



Name	Expression	Value	Description
f0	500[Hz]	500 Hz	Band center frequency
c0	343[m/s]	343 m/s	Speed of sound
rho0	1.2[kg/m^3]	1.2 kg/m³	Density
lam0	c0/f0	0.686 m	Wavelength at f0
s_diffuser	0.2	0.2	Scattering coefficient of...
x_s	1[m]	1 m	Source x-coordinate
y_s	-1[m]	-1 m	Source y-coordinate
z_s	1.5[m]	1.5 m	Source z-coordinate
x_s1	8.5[m]	8.5 m	Source1 x-coordinate
y_s1	-4[m]	-4 m	Source1 y-coordinate
z_s1	1.5[m]	1.5 m	Source1 z-coordinate
x_s2	8.5[m]	8.5 m	Source1 x-coordinate
y_s2	4[m]	4 m	Source1 y-coordinate
z_s2	1.5[m]	1.5 m	Source1 z-coordinate
x_r	7[m]	7 m	Receiver x-coordinate
y_r	1[m]	1 m	Receiver y-coordinate
z_r	1.5[m]	1.5 m	Receiver z-coordinate
P0	0.03[W]	0.03 W	Source power
Nrays	10000	10000	Number of released rays
Vol	457.7[m^3]	457.7 m³	Room volume
dsr	sqrt((x_s-x_r)^2+(y_s-y_r)^2+(z_s-z_r)^2)	6.3246 m	Source to receiver distance
dsr1	sqrt((x_s1-x_r)^2+(y_s1-y_r)^2+(z_s1-z_r)^2)	5.2202 m	Source1 to receiver dista...
dsr2	sqrt((x_s2-x_r)^2+(y_s2-y_r)^2+(z_s2-z_r)^2)	3.3541 m	Source1 to receiver dista...
P1	0.03[W]	0.03 W	Source1 power

Figure 4: Parameters Input of the model

In the Home toolbar, Functions >Global>Interpolation, this path was followed. In the Settings window for Interpolation, a file containing interpolation functions for the absorption coefficients of the different surfaces in the Auditorium.

In functions subsection, the name of functions and location of them in the file were given.

In the Interpolation and Extrapolation section, From the Interpolation list, nearest neighbour were chosen. In the Units section, In the Arguments text field, type Hz. In the Function text field, type 1.

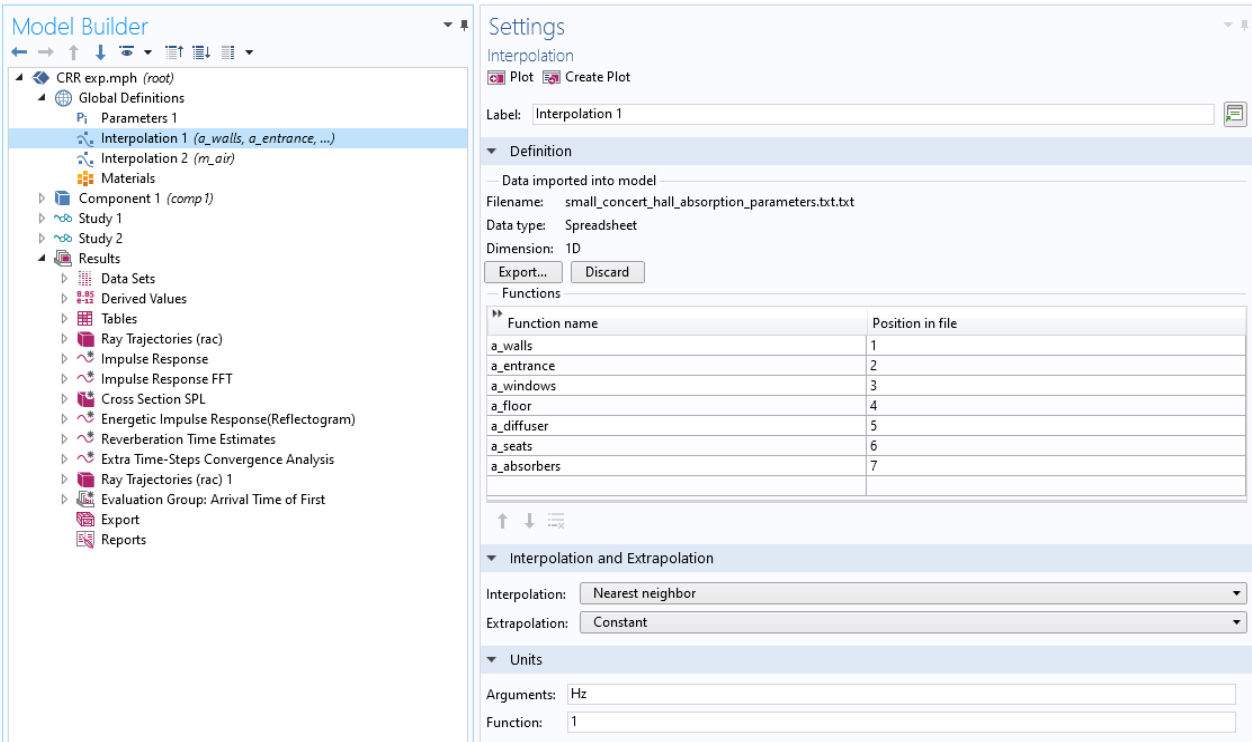


Figure 5: Interpolation 1

Another Interpolation were selected for volume absorption of Auditorium. A file was imported in interpolation 2 which also define an interpolation function for the intensity attenuation of air.

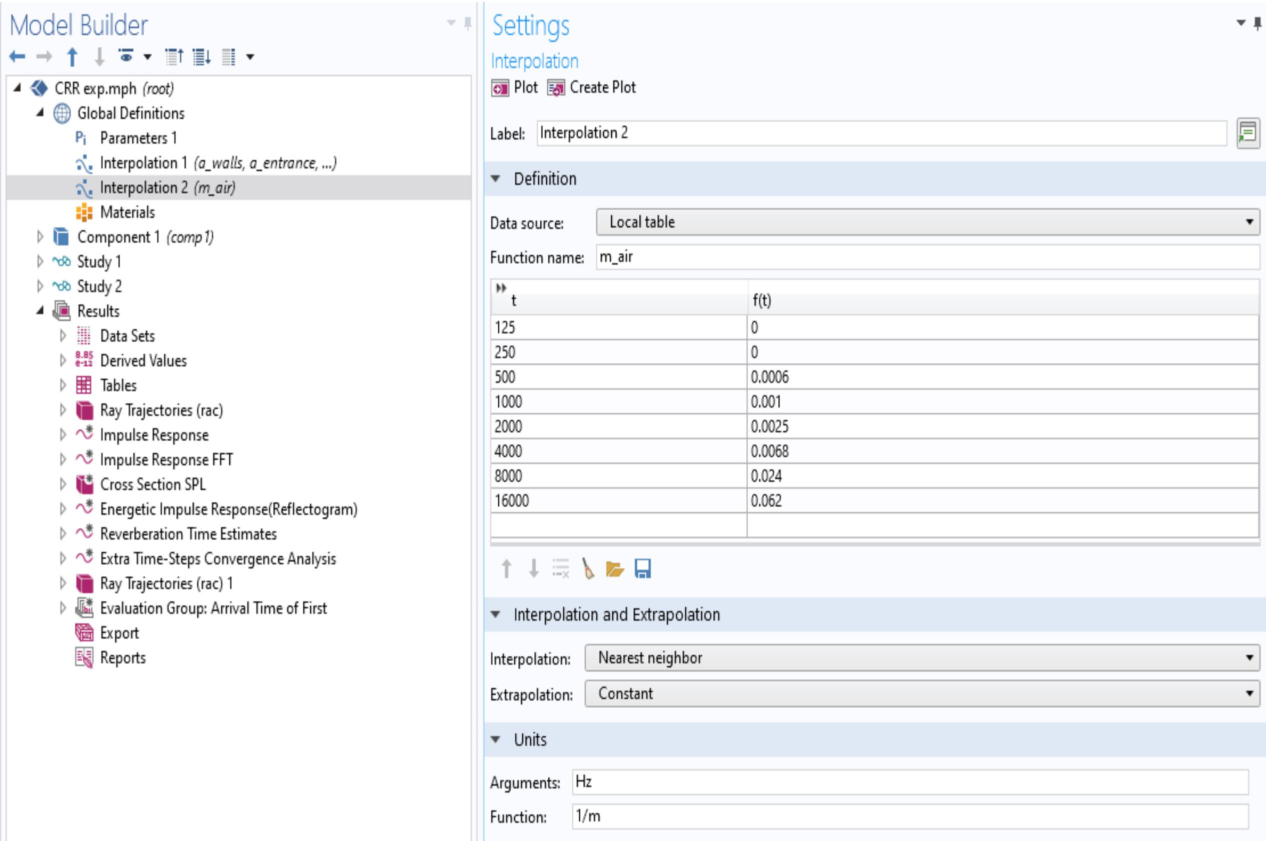


Figure 6: Interpolation 2

In the Interpolation and Extrapolation section, From the Interpolation list, nearest neighbour were chosen. In the Units section, In the Arguments text field, type Hz. In the Function text field, type 1/m.

Definitions

In this node, a variable featuring Reverberation Time was added. Then 7 integration form was added to label windows, seats, diffusers, absorbers, entrance, and wall. The variables that define the reverberation time (T60) based on the simple Sabine equations was imported. This also requires setting up integration operators for all the surfaces. For all the integration, 'Boundary' was chosen for 'Geometric entity level'.

```
A intop_windows(1)*a_windows(f0)+intop_seats(1)*a_seats(f0)+intop_diffusers
(1)*a_diffuser(f0)+intop_floor(1)*a_floor(f0)+intop_entrance(1)*a_entrance
(f0)+intop_walls(1)*a_walls(f0)+intop_absorbers(1)*a_absorbers(f0) "Total
absorption"
S intop_windows(1)+intop_seats(1)+intop_diffusers(1)+intop_floor
(1)+intop_entrance(1)+intop_walls(1)+intop_absorbers(1) "Total surface area"
T60 0.161*Vol/(A+4*m_air(f0)*Vol) "Reverberation time (Sabine)"
T60_na 0.161*Vol/A "Reverberation time (no air absorption, Sabine)"
```

Figure 7: Variable for Reverberation Time

_This file was imported to variable section.

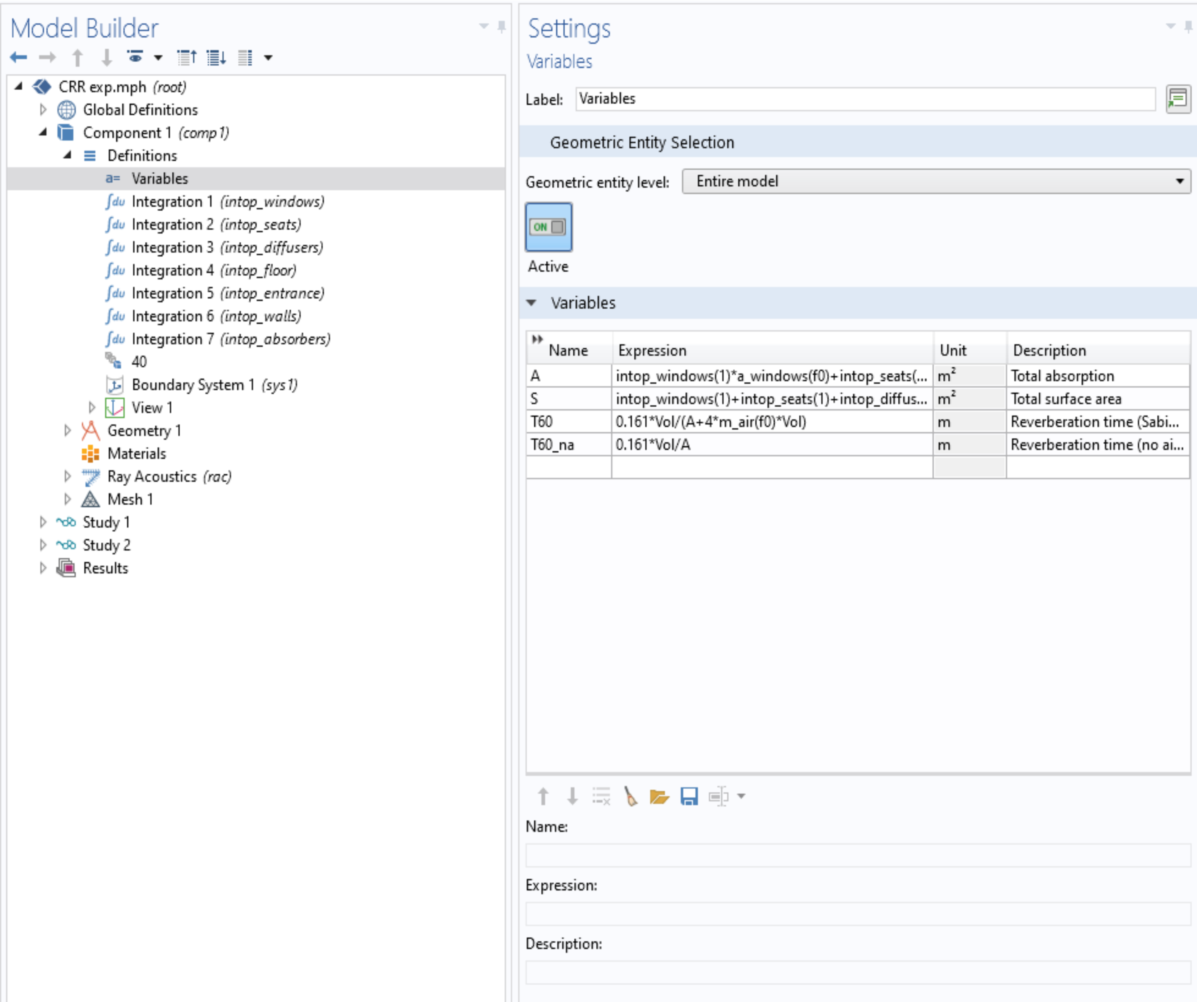
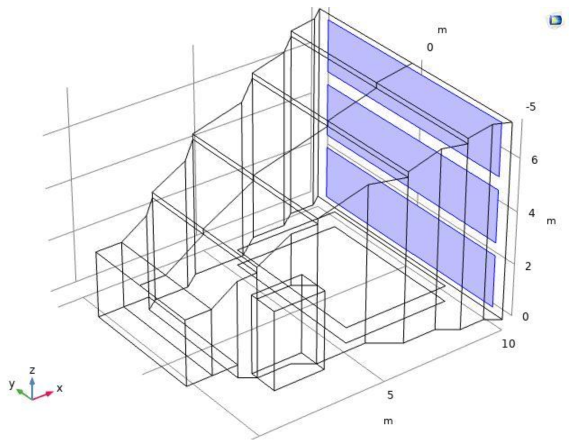
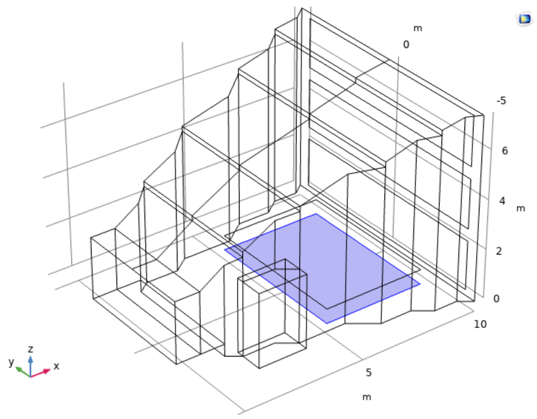


Figure 8: Variables Input

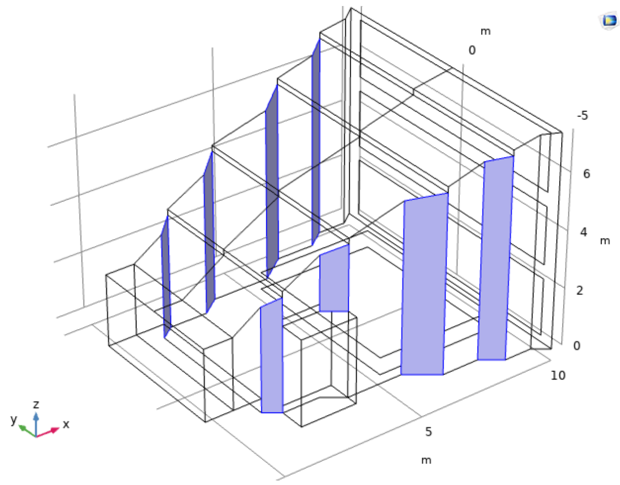
In this figure, under the definitions node, there are 7 integration. These 7 integration form are labelled as windows, seats, diffusers, entrance, and wall absorbers.



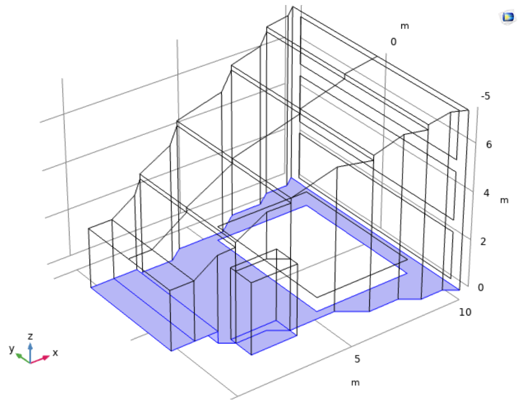
Integration 1 (Windows)



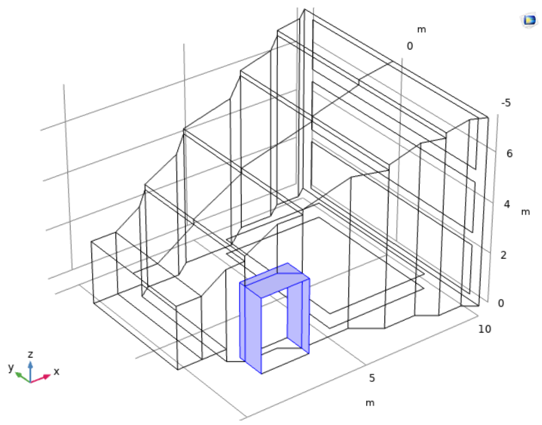
Integration 2 (Seats)



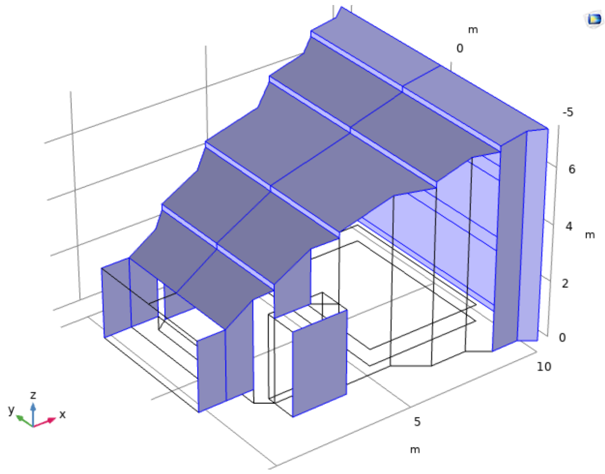
Integration 3 (Diffusers)



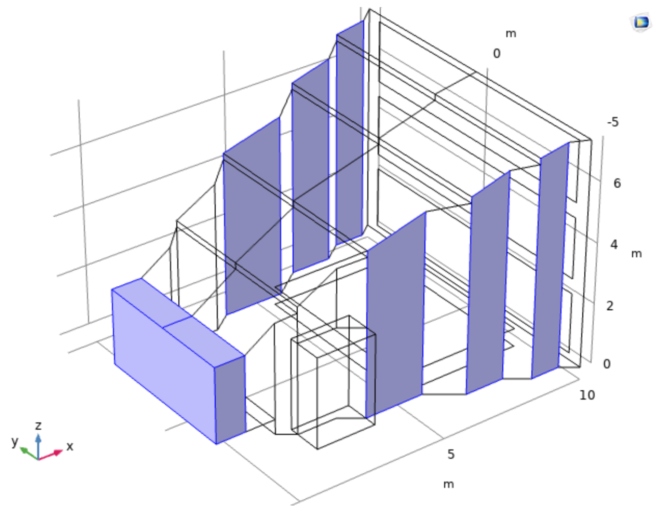
Integration 4 (Floor)



Integration 5 (Entrance)



Integration 6 (Walls)



Integration 7 (Absorbers)

Figure 9: Integration of each component inside the Auditorium

The components of an auditorium is selected mention as the figure above.

Ray Acoustic (RAC)

In this node, the physics and boundary conditions of the auditorium were set. This node will compute the impulse response and also will model the intensity and power along the rays.

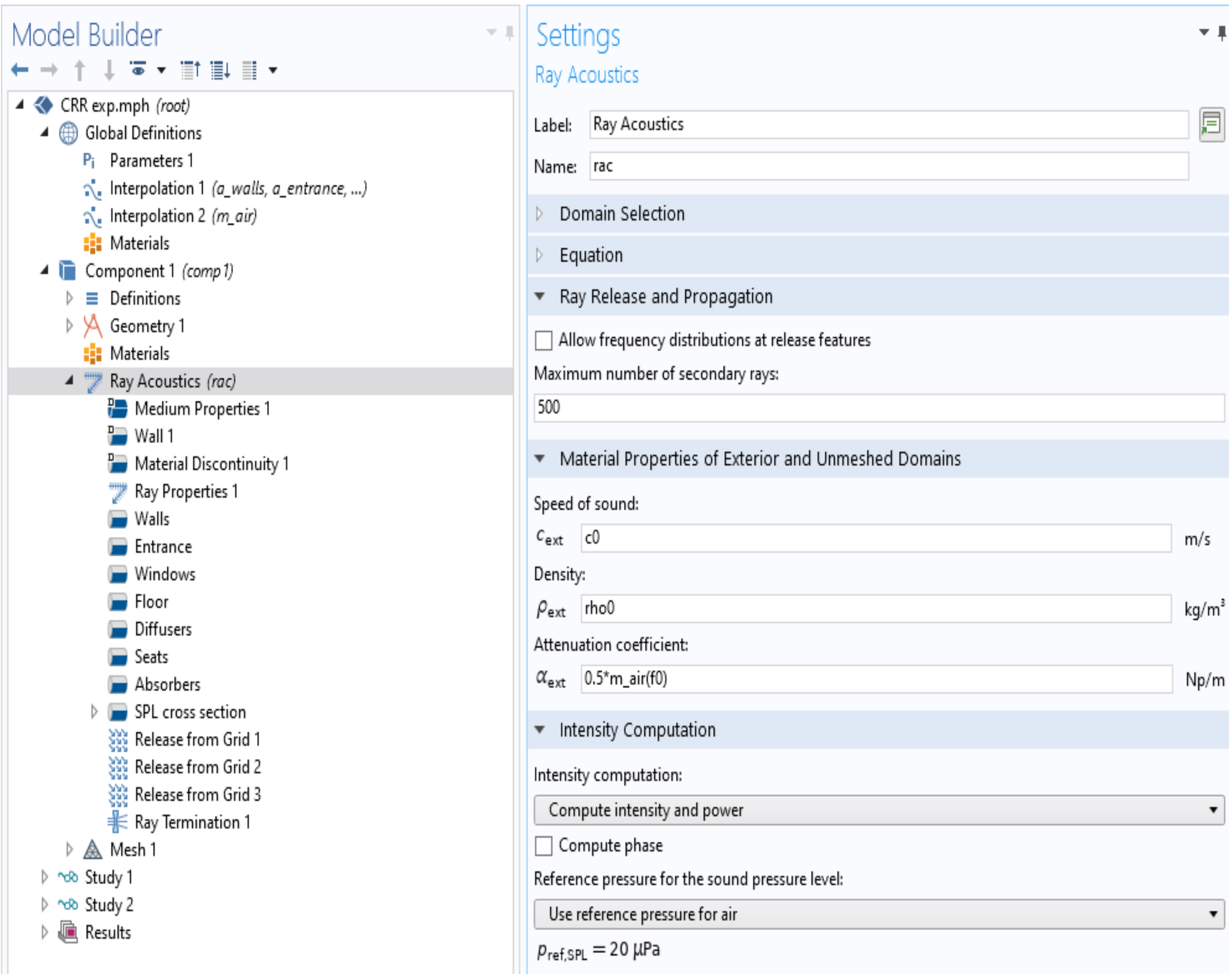


Figure 10: Ray acoustics Node

In the Physics toolbar, several boundaries were added featuring walls, windows, seats, diffusers, floors, entrance, absorbers and SPL Cross section. Wall condition for walls, windows, seats, floors, entrance, absorbers were given as specular reflection. But for diffusers, wall condition is mixed diffuse and specular reflection. Also for SPL cross section, it is Pass through.

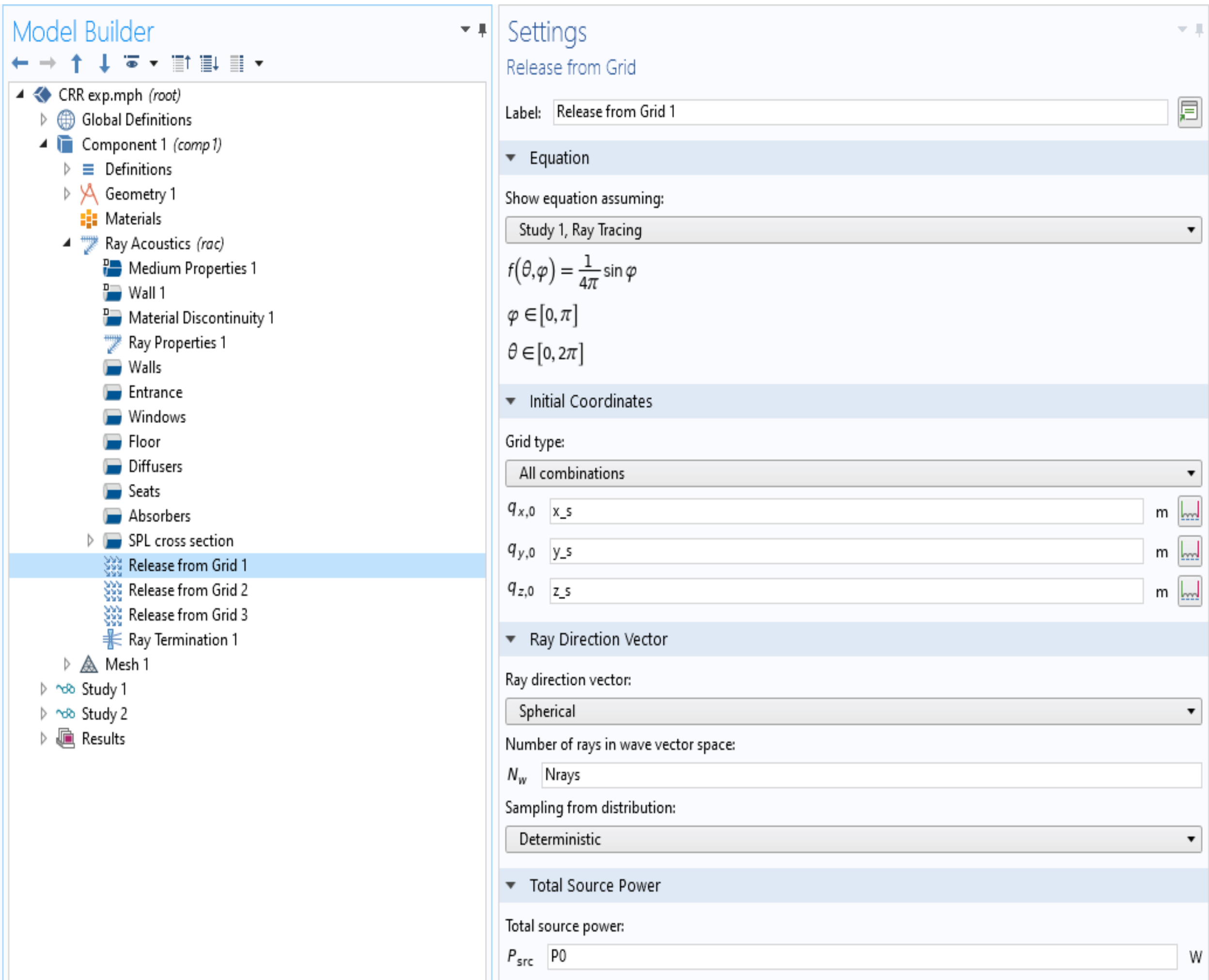


Figure 11: Release from Grid 1

Under the SPL Cross section, three attributes were added for Sound Pressure Level Calculation. They are named as

- Release from Grid 1
- Release from Grid 2
- Release from Grid 3

Each of them indicates the location of three different sound sources.

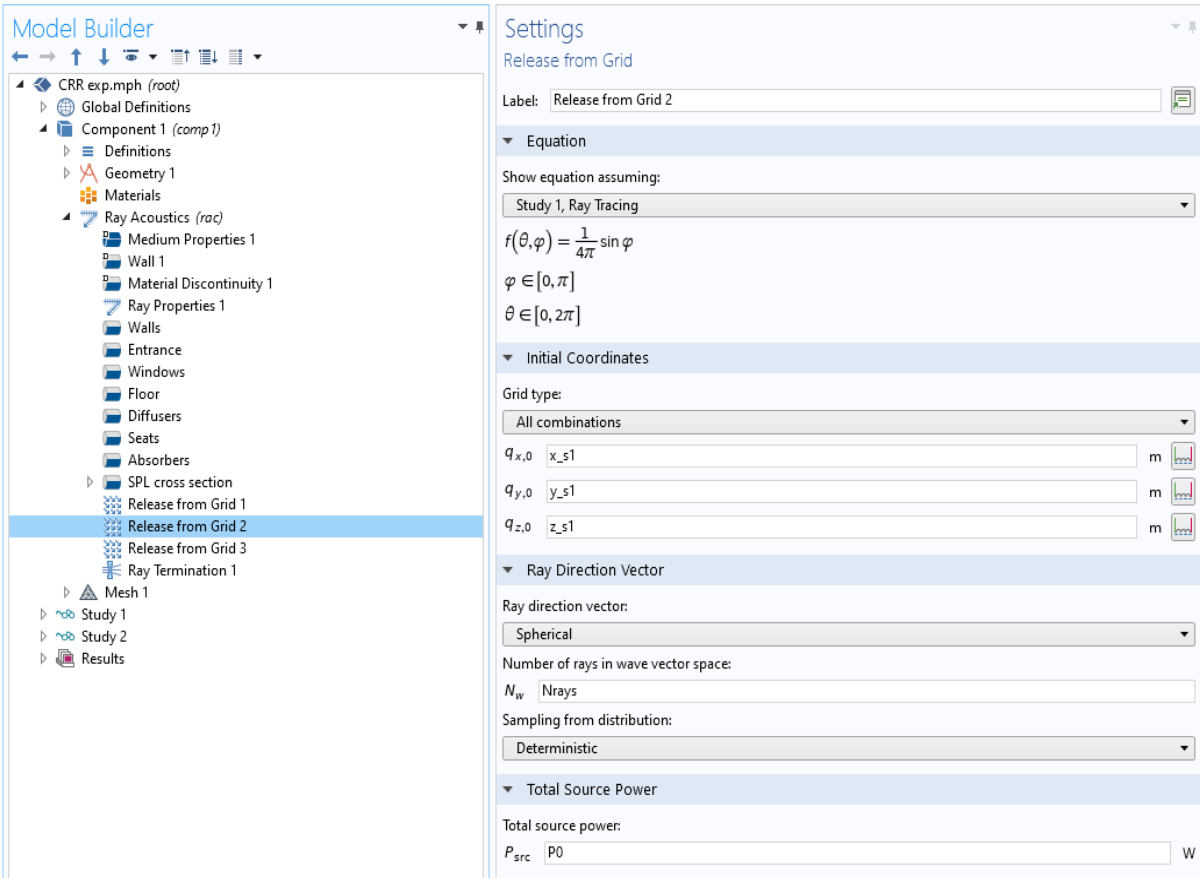


Figure 12: Release from Grid 2

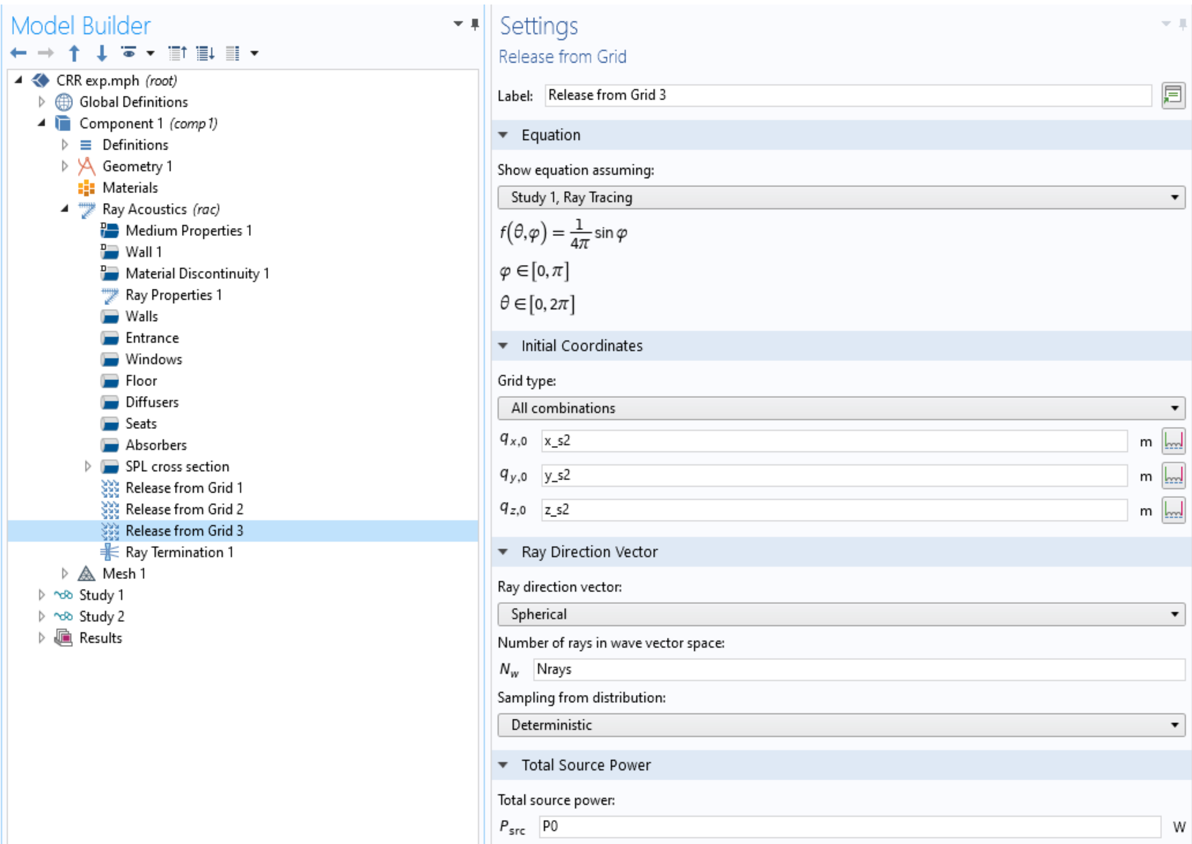


Figure 13: Release from Grid 3

Mesh

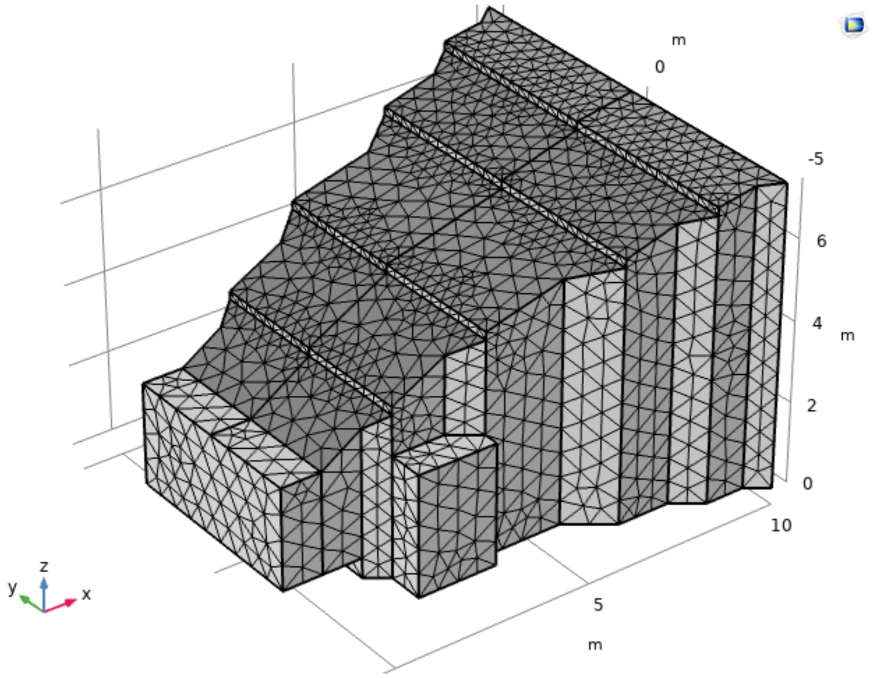


Figure 14: Mesh of the model

Mesh represent the geometric object of a finite element analysis. For build the auditorium structure, finer mesh type has selected. Number of elements are 4364 and mess face area is 416.4m^3. The geometric entity level selected all the boundaries.

Study Node

By adding a parametric sweep over the center frequency variable f0, the model was solved. This represents the center frequency of the octave bands analysed in this model, in order to get a broadband response.

Parametric Sweep were added from study toolbar. Using the parametric sweep is important as this gives the frequency resolution (here in full octaves). The ray propagation model is solved once per frequency band. The data is collected in post processing, by the receiver data set and the impulse response plot, to generate the broadband response.

ISO preferred frequencies was chosen as entry method. Start frequency was set 500 and Stop frequency was set 20000.

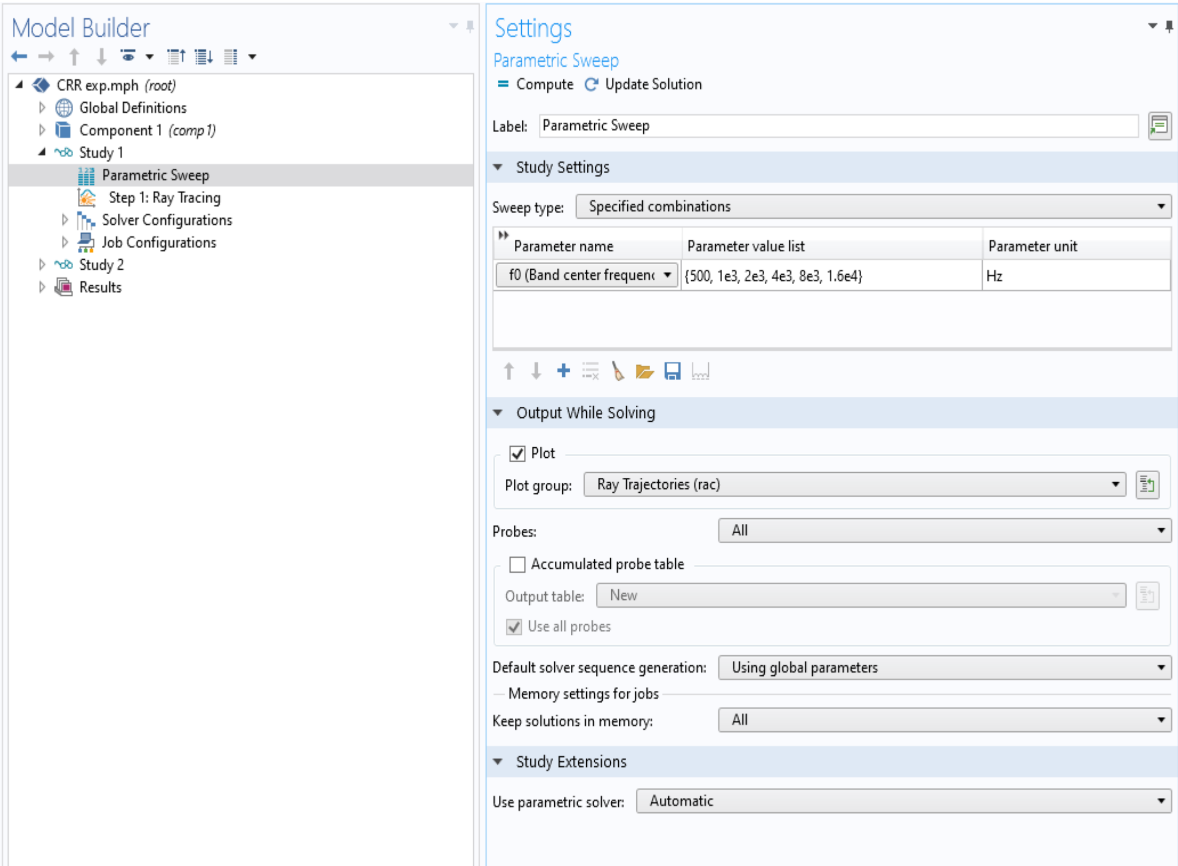


Figure 15: Parametric Sweep Node

Then in the Model Builder window, expanding the Study 1 node, Step 1: Ray Tracing was clicked.

In the Times text field, 0 0.01 0.02 range (0.1, 0.1, 1.4) was typed as input. The times entered here represent instances where the solution is stored. Much smaller time steps were used. Then clicking compute, results were shown.

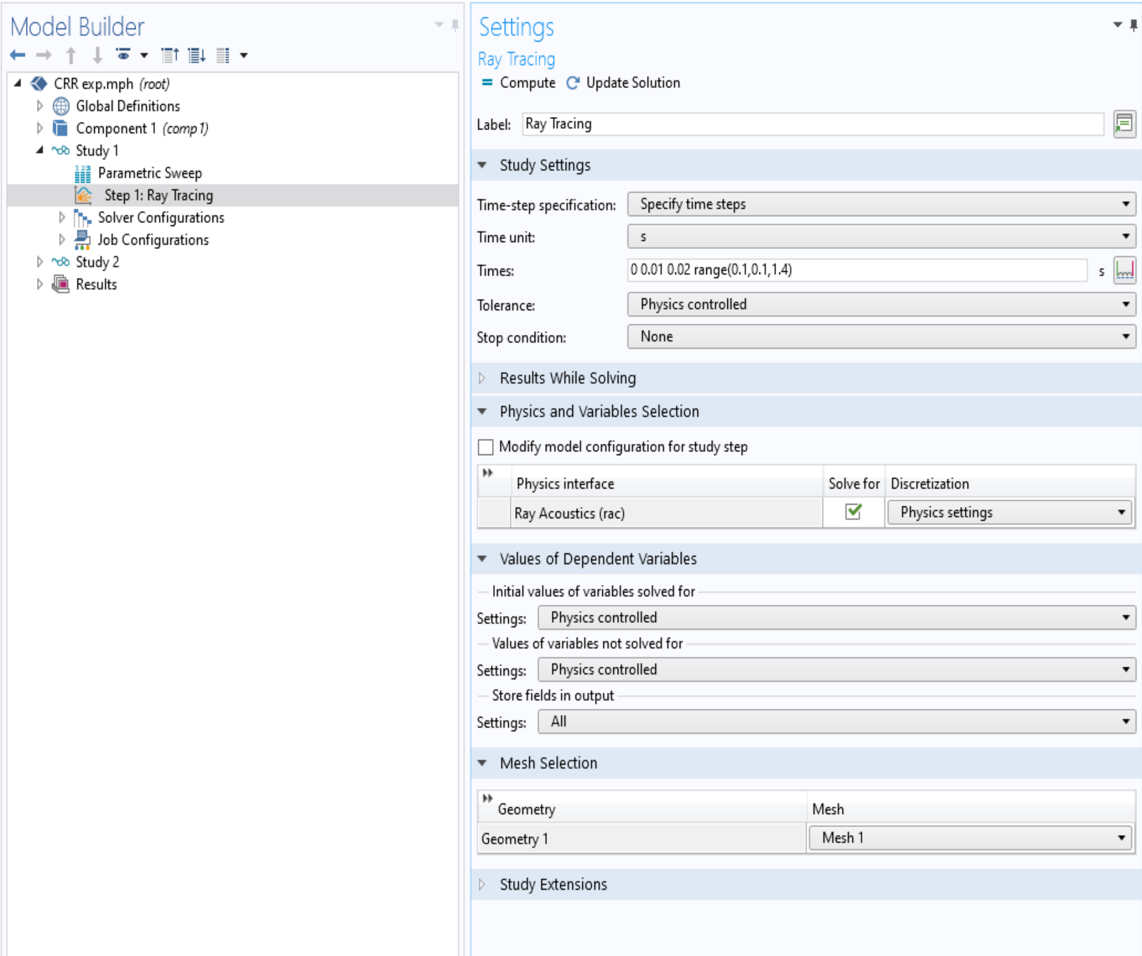


Figure 16: Ray Tracing Node

Results

At first, only Release from Grid 1 was enabled, other two were disabled. We got the results for only single sound source. Then Release from Grid 2 and Release from Grid 3 were enabled. We got result using multiple sound source. When the compute intensity option is selected, in the Ray Acoustics interface, wave front curvature, intensity, and SPL is calculated along each ray. They allow visualization of the local acoustic properties. However, it is the acoustic power transported by each ray that is important when calculating the impulse response (IR) and when visualizing the sound pressure level at surfaces. Comparison between them by altering time delay and initial frequency (f0) has shown below,

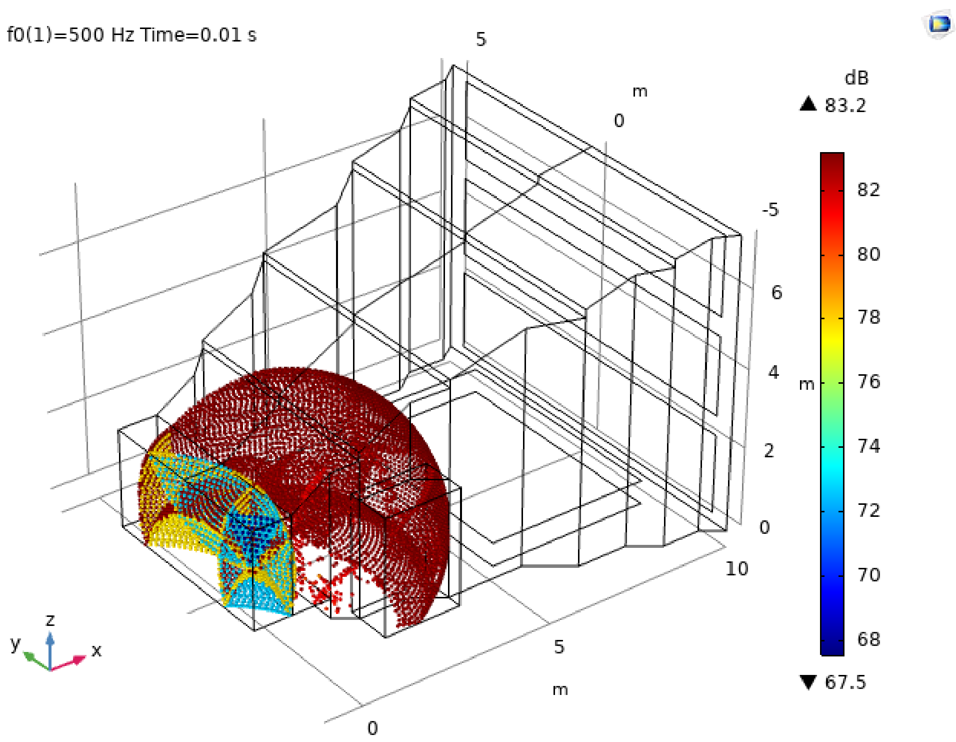


Figure 17: Ray location and SPL after 10ms (Single Sound Source)

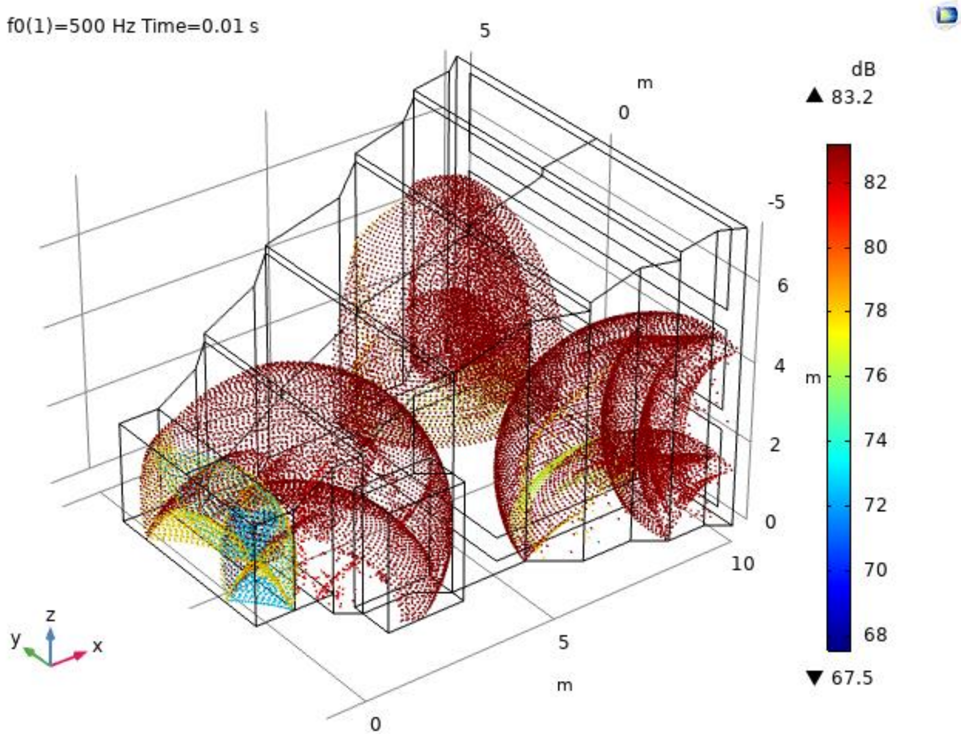


Figure 18: Ray location and SPL after 10ms (Multiple Sound Sources)

The Figure 18 and 19 shows the differences of Sound Pressure Level and Ray location between the single and multiple sound sources, where the frequency is 500Hz. After adding multiple sound sources the sound rays are more scattered than the single source.

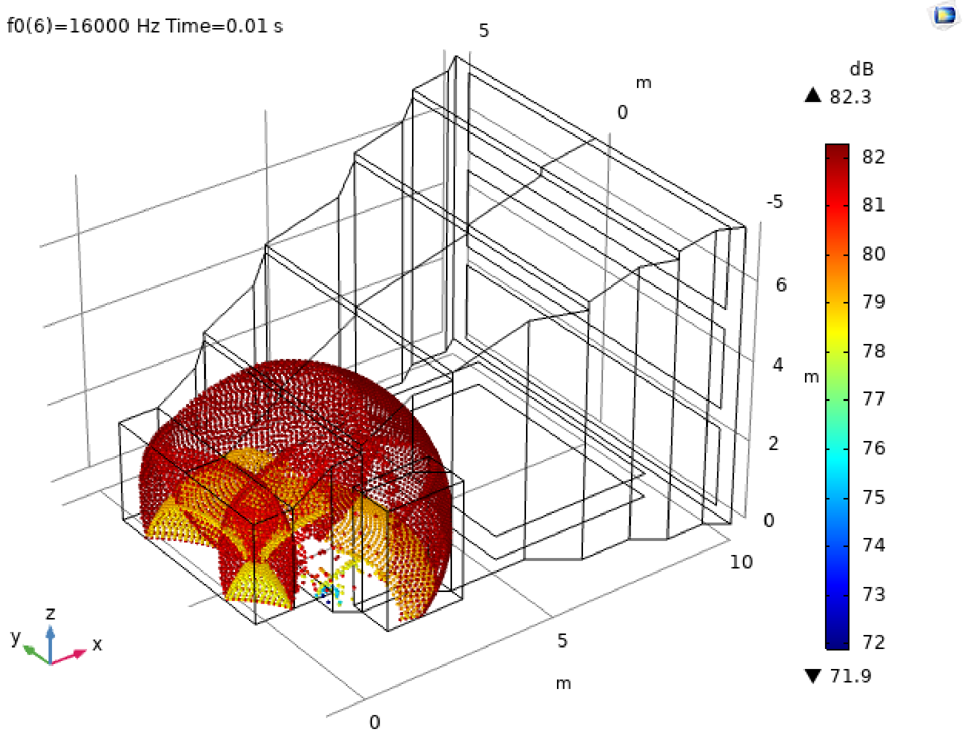


Figure 19: Ray location and SPL after 10 ms at 16K Hz (Single Sound Source)

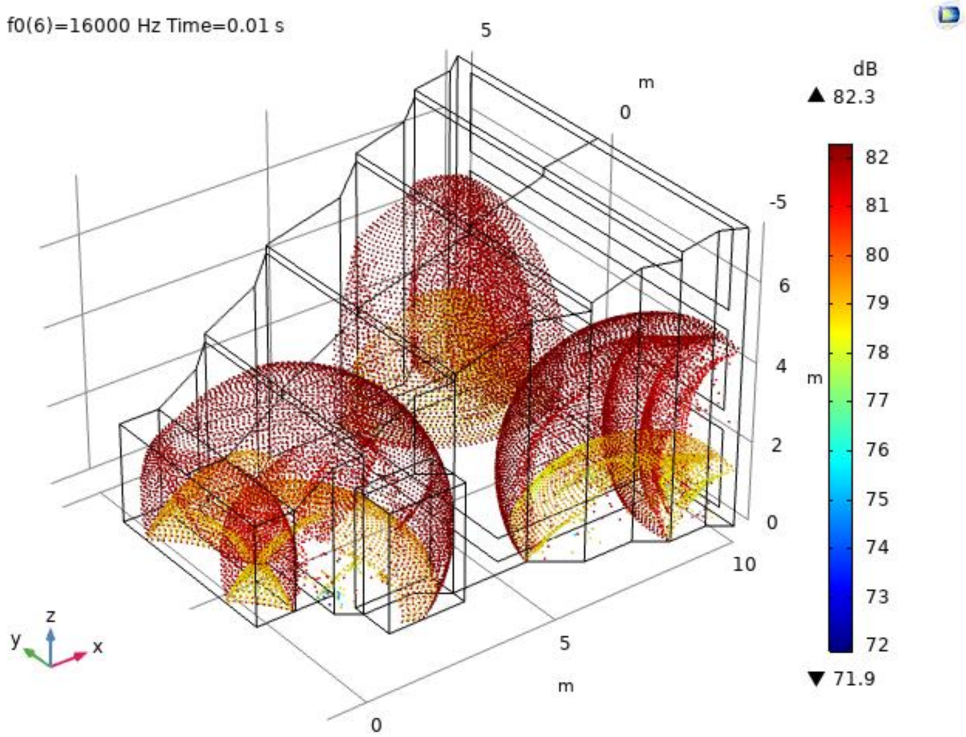


Figure 20: Ray location and SPL after 10 ms at 16K Hz (Multiple Sound Sources)

The Figure 20 and 21 shows the differences of Sound Pressure Level and Ray location between the single and multiple sound sources, where the frequency is 16000Hz. After adding multiple sound sources the sound rays are more scattered than the single source and the sound pressure level is higher than 500Hz.

Also, the figures below show the results of changes the sound scattering after 20ms and changing rays and SPL with frequency.

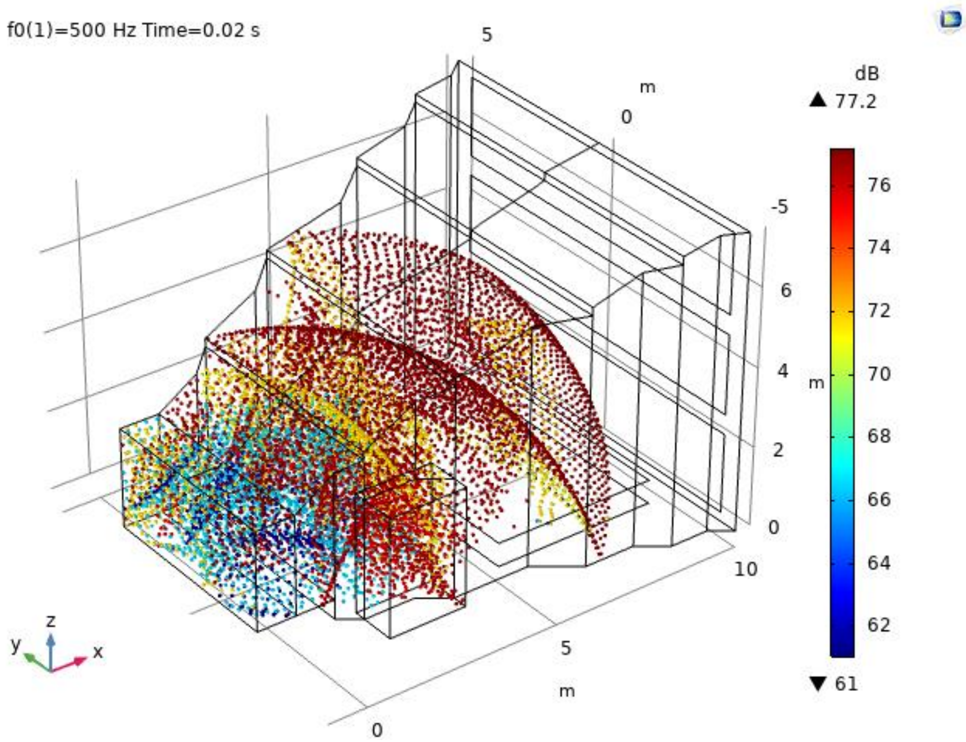


Figure 21: Ray location and SPL after 20 ms at 500 Hz (Single Sound Source)

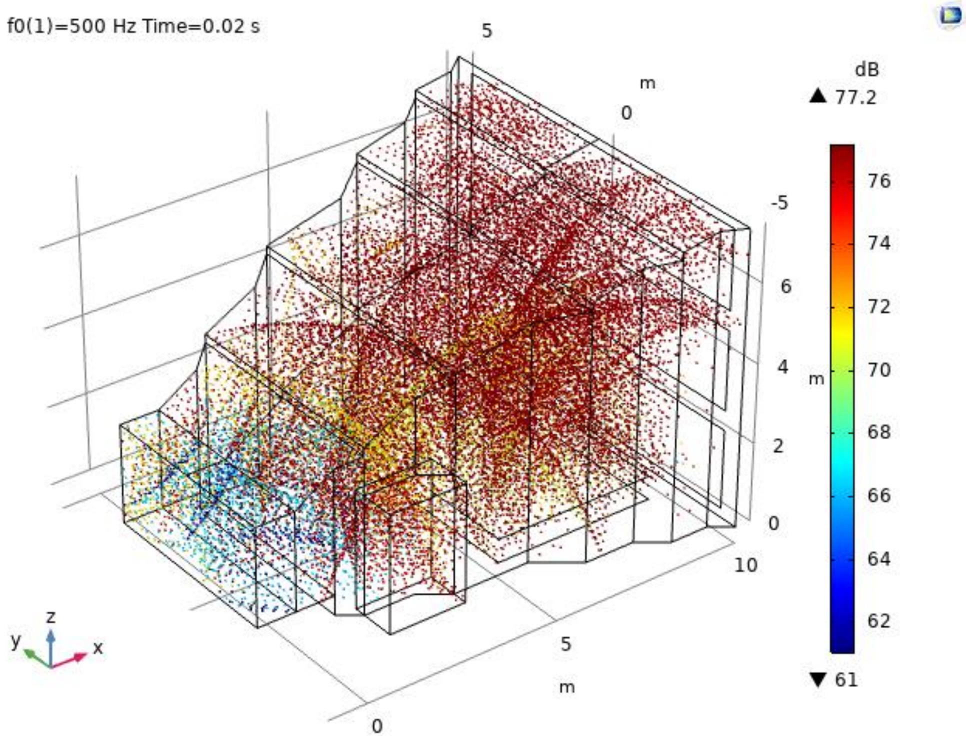


Figure 22: Ray location and SPL after 20 ms at 500Hz (Multiple Sound Sources)

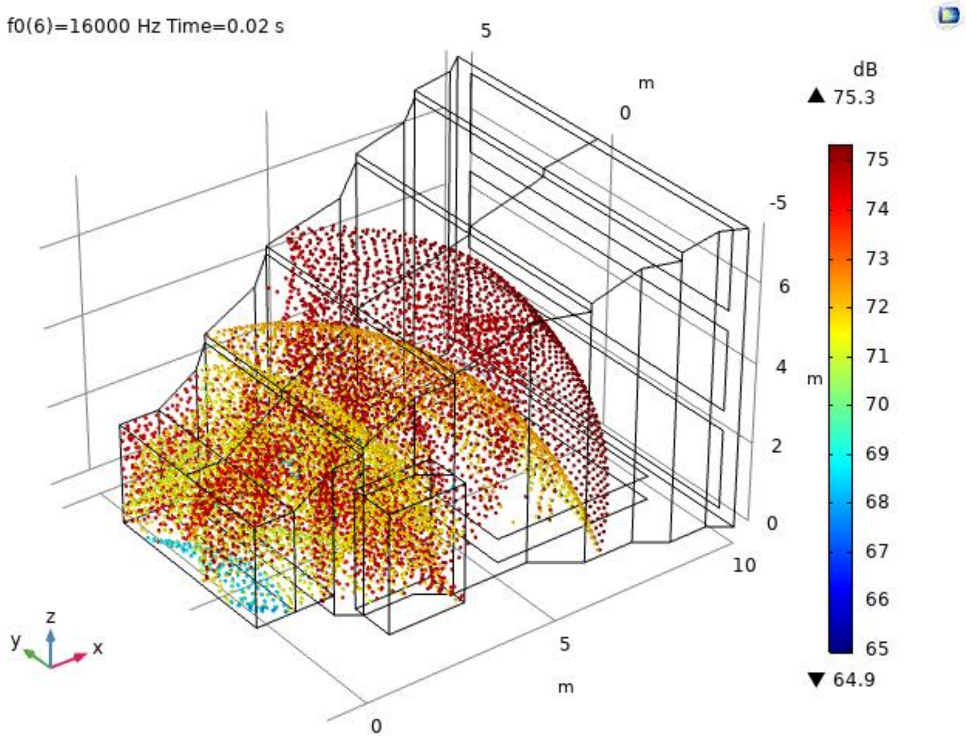


Figure 23: Ray location and SPL after 20 ms at 16K Hz (Single Sound Source)

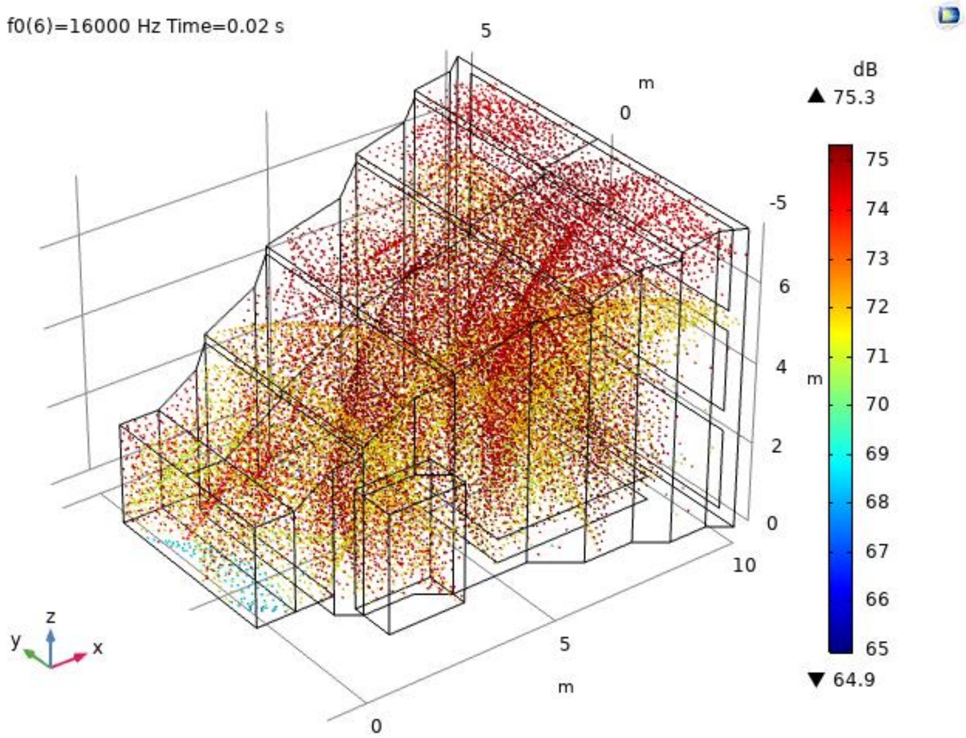


Figure 24: Ray location and SPL after 10 ms at 16K Hz (Multiple sound Sources)

For multiple sound sources the SPL and rays of sounds are more than the single sound source.

Impulse Response

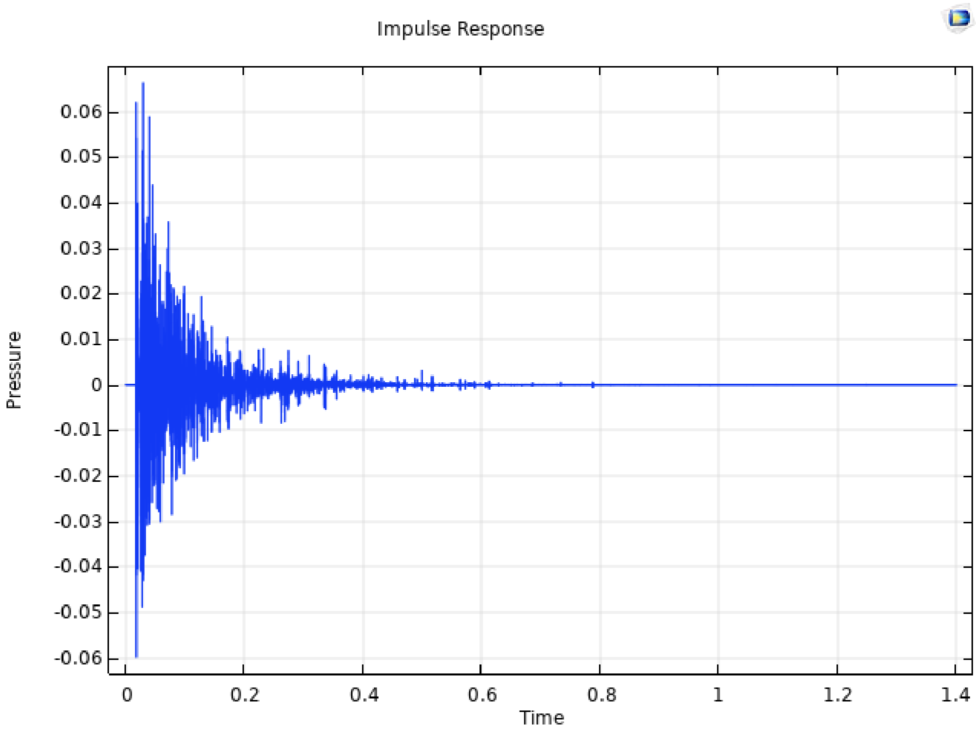


Figure 25: Impulse Response (Single Sound Source)

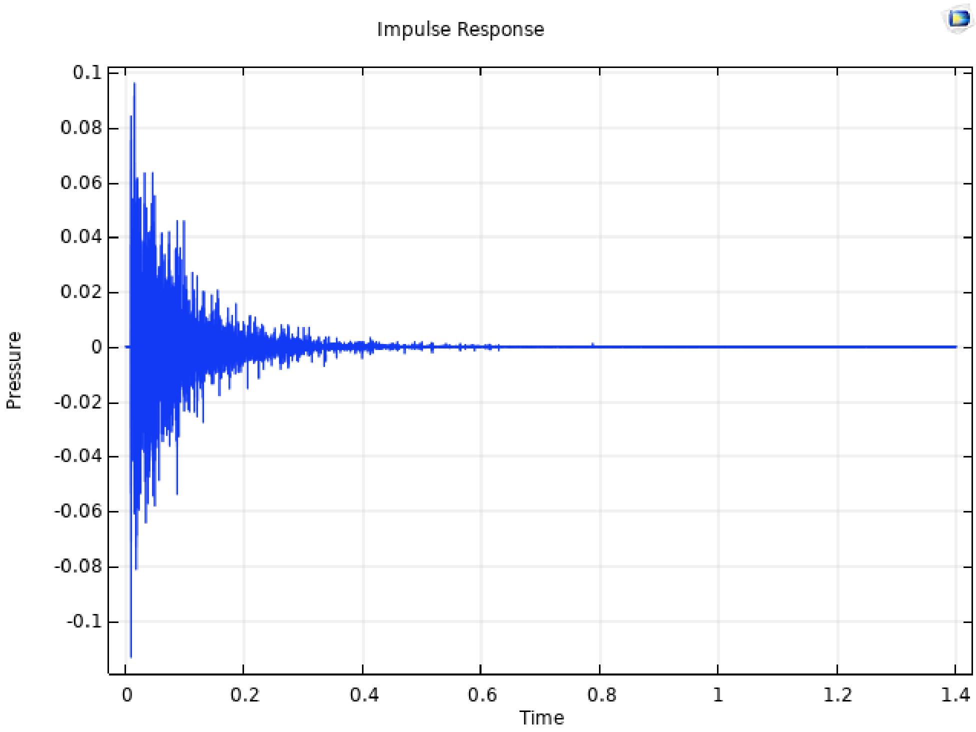


Figure 26: Impulse Response (Multiple Sound Source)

When an IR is reconstructed from a ray tracing simulation information is inferred and put back into the time signal. The quality of the simulated IR increases with the number of rays (this model uses 10000) as well as the frequency resolution of the absorption, scattering, and source data (this data can be difficult to get from vendors but can often be simulated). In this model octave band resolution is used.

Comparing figure 26 and figure 27, the SPL of multiple sound sources is greater than single sound source. In these figures we can see that, just after the release of sound, we get the higher sound pressure using multiple sound sources, which indicates the more chance of spreading of sound. And also audience will receive the sound more quickly and clearly.

We also plotted another graph for impulse response using Fast Fourier Transform (FFT).This algorithm converts the time domain of impulse response into frequency domain. Figure 28 and figure 29 shows the result and this time it shows the change of sound pressure level along with frequency instead of time.

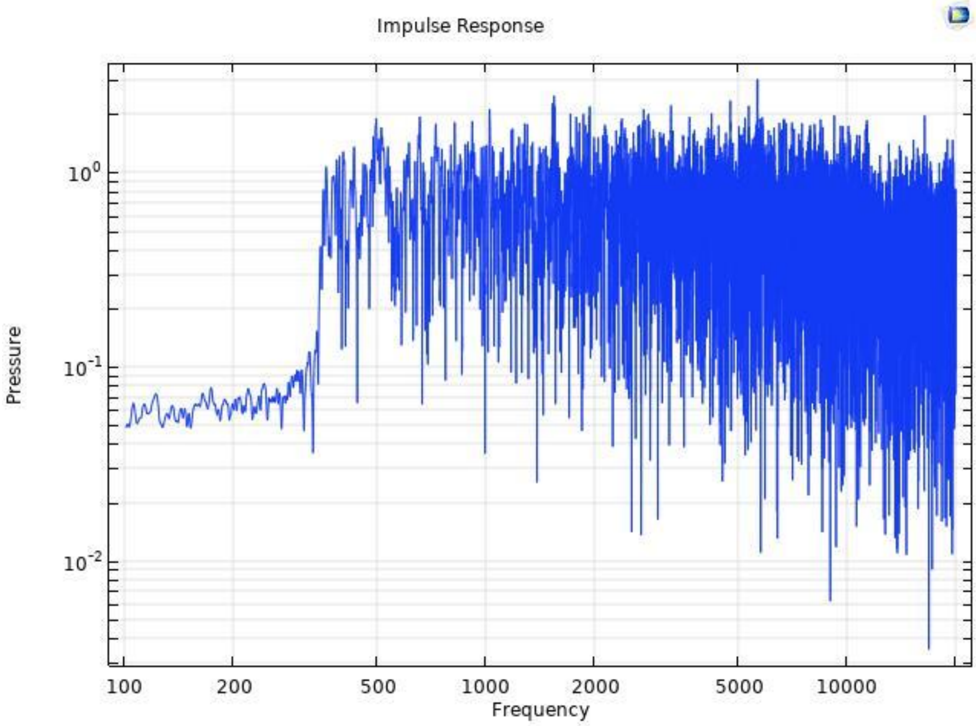


Figure 27: Impulse Response using FFT (Single Sound Source)

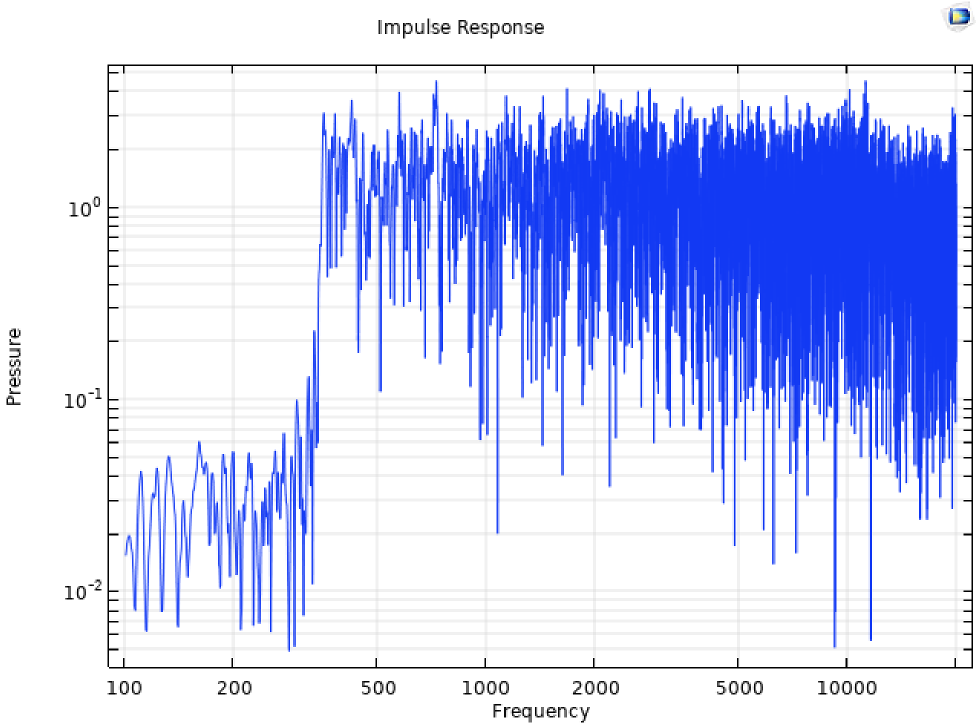


Figure 28: Impulse Response using FFT (Multiple Sound Sources)

Cross section SPL

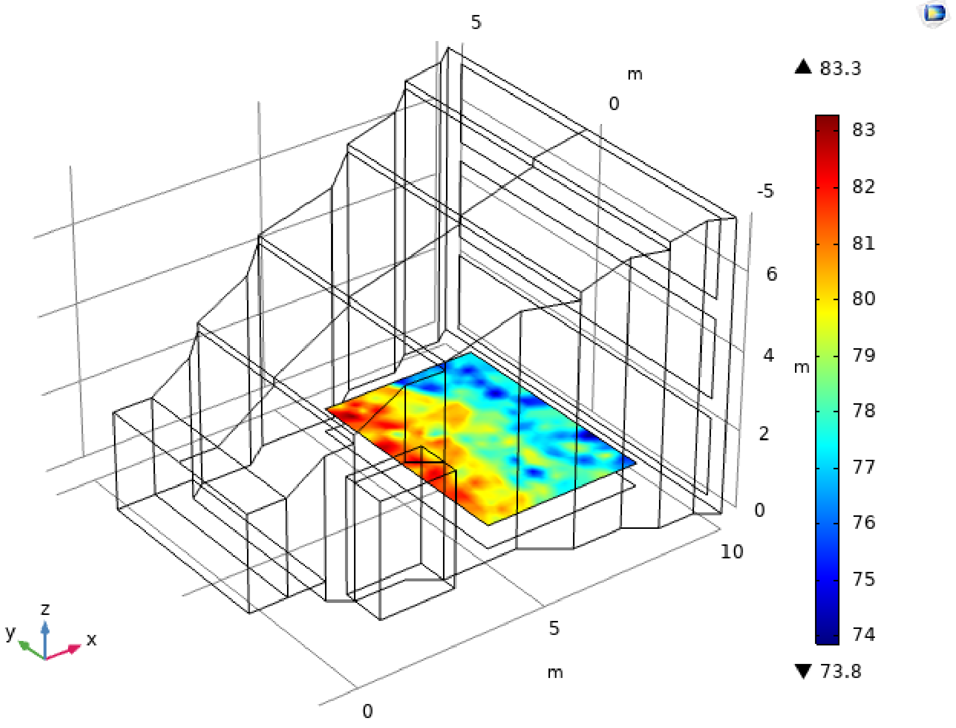


Figure 29: SPL in a cross section 60 cm above the ground at the location of the audience (Single Sound Source)

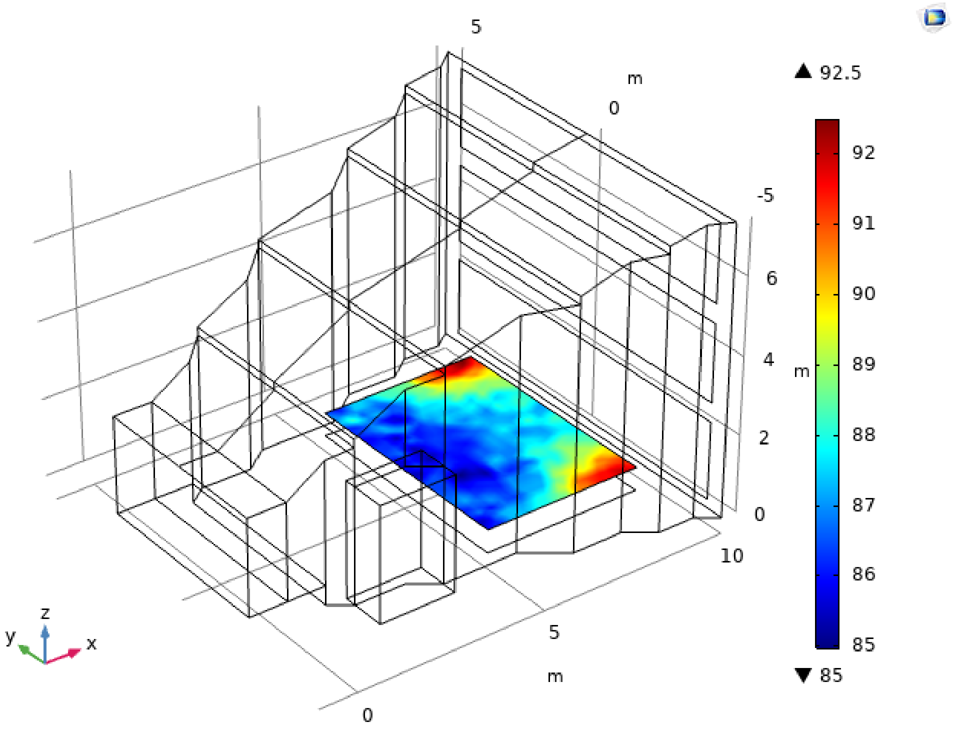


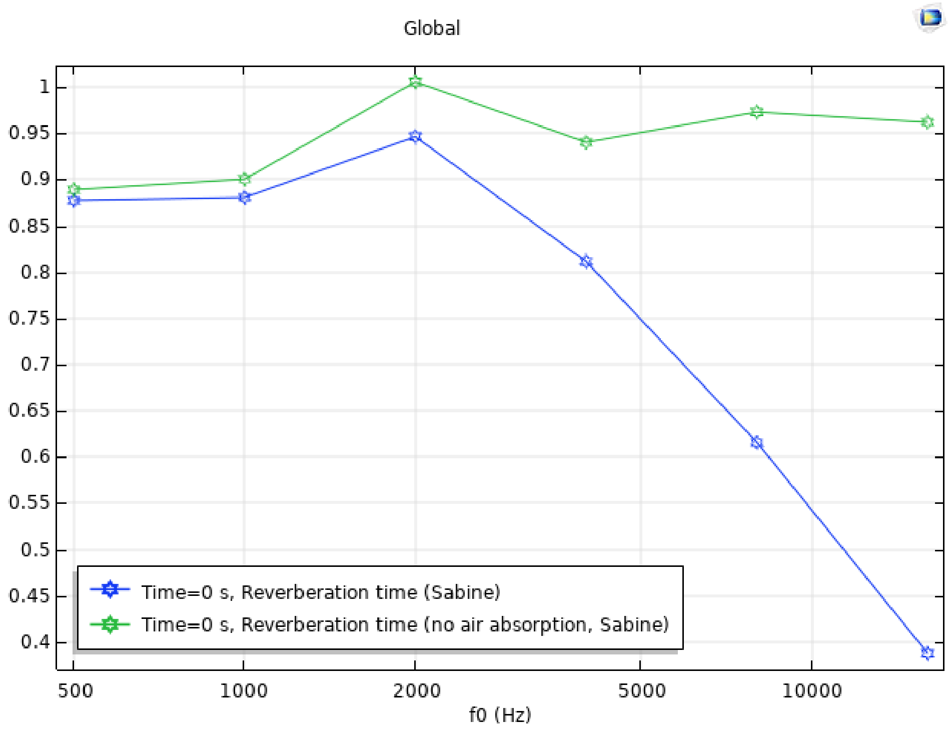
Figure 30: PL in a cross section 60 cm above the ground at the location of the audience (Multiple Sound Sources)

The sound pressure level in a cross section located above the seating section is depicted in Figure 30 and Figure 31. It is calculated using the Sound Pressure Level Calculation feature, available as a sub-node to all wall conditions. In this case it is added to a transparent surface (Pass through used as Wall condition). The feature can be added to all other walls to post process the SPL distribution there if necessary.

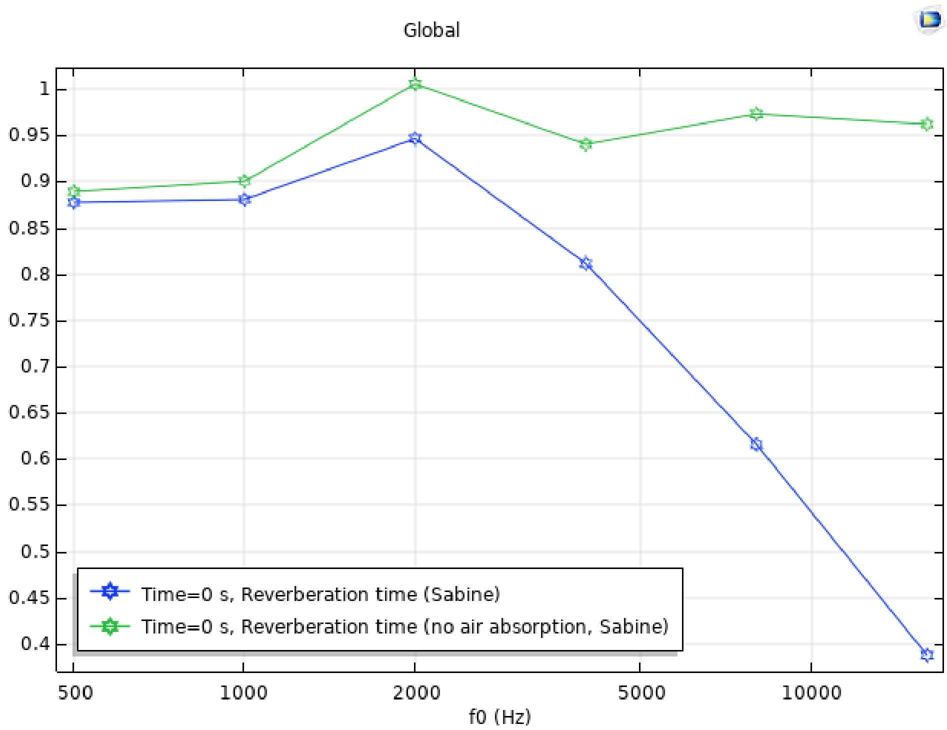
At figure 30, using single sound source, we can see that the front of seat area has the higher sound pressure level. Because sound source was set in front of the seat area. SPL is 79 dB to 83 dB at front area and 74 dB to 77 dB at the back side of seat. That means audience at front side will listen more.

At figure 31, using multiple sound sources, we can see that all the sitting area covers SPL 85 dB to 88dB. Just near the sound source, at back side of seat, audience will hear at 90 to 92 dB, which is so loud.

Reverberation Time



(Single Sound Source)



(Multiple Sound Source)

Figure 31: Comparison of Reverberation time

The reverberation time is same for both because of reverberation time depends on the absorption coefficient and geometrical structure. Though the room components didn`t change and the absorption coefficient are same for both cases so the reverberation time is same for both cases.

Conclusion

From this simulation, the results shows the differences between the impacts of multiple sound sources. The sound pressure level of multiple sources is greater than single sound source because sound pressure level depends on the sound sources, where the room environment and parameters are unchanged. By changing the parameters and room environment, the sound pressure level can be changed. The room acoustics depend on the geometrical shape of the auditorium, so it is mandatory for better sound quality to design the auditorium according to the shape which can provide better quality. For complex shape the Sabine formula can be ignored. The absorber can impact on the sound quality too, it can also changes the SPL, Impulse responses and reverberation time. The noise and reflection of the room is consider as low so that can be neglected in this simulation. For reverberation time sources are not so important, when the parameters are unchanged and the impact of components or absorption confidents are noticeable. The reverberation time is same for both because of reverberation time depends on the absorption coefficient and geometrical structure. Changing the room environment such as position of the windows, entrances, floor can also changes the results.

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