Created in COMSOL Multiphysics 6.1

Small Concert Hall Acoustics

Introduction

Designing structures and open spaces with respect to sound quality is important for concert halls, outdoor environments, and even the rooms of a house. Simulating acoustics in the high-frequency limit, where the wavelength is smaller than the geometrical features, is best done with ray acoustics.

This tutorial model shows the basic steps and principles used when setting up a model using the *Ray Acoustics* physics interface. In the model, the acoustics of a small concert hall is analyzed. The model setup includes an omnidirectional sound source, a directional loudspeaker, wall boundary conditions for specular and diffuse scattering, surface sound pressure level evaluation, analyzing the impulse response, evaluation of objective room acoustic metrics, and a reflectogram. The metric results are compared to simple analytical estimates.

Model Definition

In this model the acoustics of a generic small concert hall is analyzed. Its geometry is depicted in Figure 1. It is a fan-shaped hall with a volume of 460 m^3 and a total surface area of 390 m^2, fitted with absorbers and diffusers. The location of the different materials is not particularly optimized and does not necessarily follow design rules. Rather than accuracy, the aim of this tutorial is to describe the important modeling steps to perform a room acoustics simulation using ray tracing. The back wall of the room consists of windows and reflective surfaces only, with all the absorption and diffusion being located on the side walls. The stage lies 0.5 m above the ground. The seating area is modeled as a box extruding 1 m high from the ground. It is common practice in ray acoustics to simplify geometry details, and seating is typically represented as a box with equivalent absorption and scattering.

In order to derive the room acoustic metrics, an omnidirectional source is located at the coordinates $(x_{\mathrm{src}}, y_{\mathrm{src}}, z_{\mathrm{src}})$ at the front of the stage. It generates a pulse that has an SPL of 100 dB at 1 m from the source. The receiver (microphone) is located at the coordinates $(x_{\mathrm{rec}}, y_{\mathrm{rec}}, z_{\mathrm{rec}})$. These are parameters found under **Global Definitions>Parameters**. The location of the receiver can be changed in postprocessing, while the location of the source needs to be changed before running the model. The size of the receiver is set to match the common width of a seat, with a receiver radius r = 0.3 m. This value is entered on the **Receiver 3D** dataset with the **Radius input** option **Fixed size**. The number of rays emitted by the source is then determined to limit the error in the calculated impulse response. For an expected error of 1 dB in every time interval Δt of the response, the number of rays should be (see Ref. 1)

$$N_{\text{rays}} = 4.34^2 \frac{V}{\pi r^2 c \Delta t} \quad (1)$$

With Δt = 0.01 s, the resulting value gives N_{rays} = 9000 after rounding up. Determining the number of rays from the volume of the room and the receiver size is a favorable option as default and when there are multiple receivers in the space. Nevertheless, it is also possible to set a desired number of rays and use the predefined expression to calculate the size of the receiver according to the volume of the room, the distance to the source, and the number of rays. This corresponds to the **Radius input** option **Variable size (large room volume)** on the **Receiver 3D** dataset. This option can be an interesting approach in the case of a single receiver. A directional loudspeaker is also included at the coordinates (x_{spk}, y_{spk}, z_{spk}). It is used in a separate study where the sound pressure level in the hall is investigated.

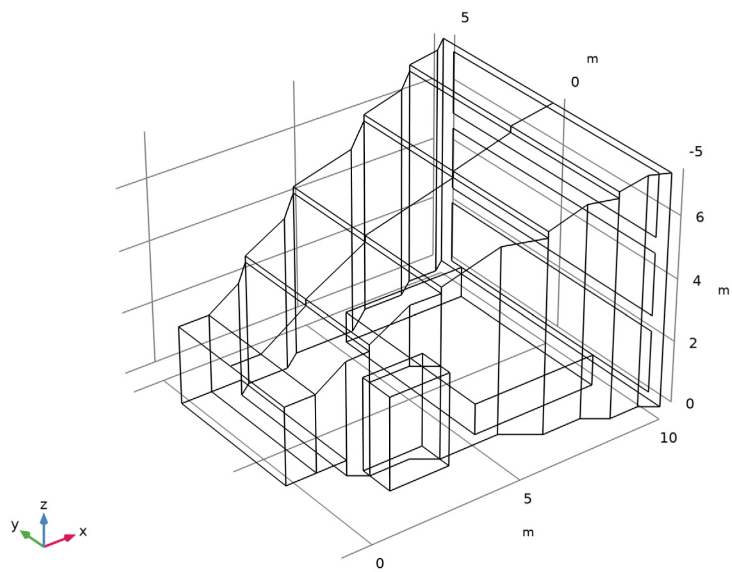


Figure 1: Geometry of the small concert hall.

The absorption properties of the various surfaces (floor, walls, windows, seating, entrance, absorbers, and diffusers) are values taken from Ref. 1–3. The windows are taken as large panes of heavy glass, and the seating area is considered unoccupied. The data is given in octave bands and imported from the file `small_concert_hall_absorption_parameters.txt` into an interpolation function (lookup table). The scattering coefficients of the diffusers and seating areas are also taken from Ref. 3. For seemingly flat surfaces, a default scattering coefficient $s = 0.05$ is defined to account for the roughness of the materials. Moreover, the amplitude attenuation of air at 20°C and 50% humidity is imported from the file `small_concert_hall_air_attenuation.txt`. The imported parameter a_{air} can be entered directly in the **Material Properties of Exterior and Unmeshed Domains** section, as an amplitude attenuation $\alpha_{\mathrm{ext}} = a_{\mathrm{air}}(f_0)$.

Results and Discussion

The first study allows to derive the room impulse response and the objective quality metrics by activating only the omnidirectional source. The local wavefront sound pressure level (SPL) is depicted in Figure 2 after 10 ms and in Figure 3 after 20 ms propagation for the 8 kHz frequency band. This type of plot can be used to inspect holes in the geometry and potential standing wave patterns. Creating an animated version is easily done and can help the visual inspection. When the **Compute intensity** option is selected in the *Ray Acoustics* interface, wavefront curvature, intensity, and SPL is calculated along each ray. They allow visualization of the (spatially) 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. This means that the **Compute power** option should always be selected for IR computation, while the **Compute intensity** can be turned off. Only selecting **Compute power** will also reduce the number of degrees of freedom (DOFs) solved for, making the model run faster and the size of the saved file smaller. The **Count reflections** option is also necessary when analyzing the IR.

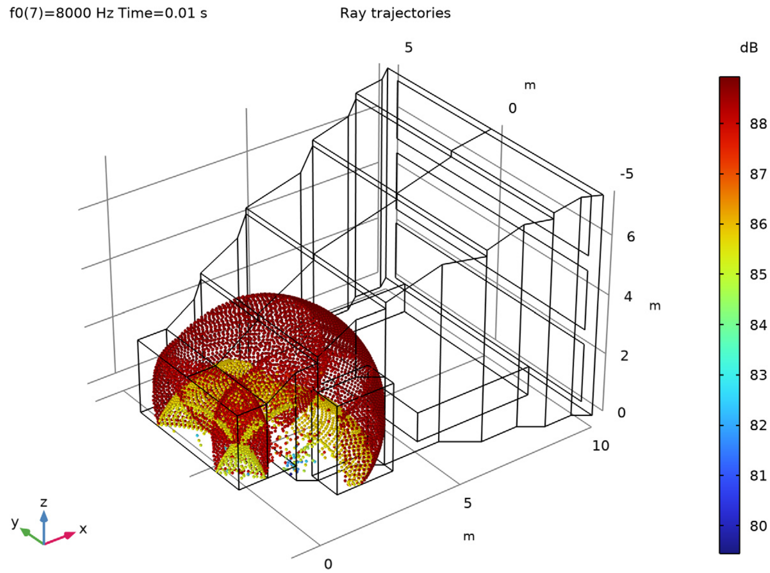


Figure 2: Ray location and SPL after 10 ms with the omnidirectional source.

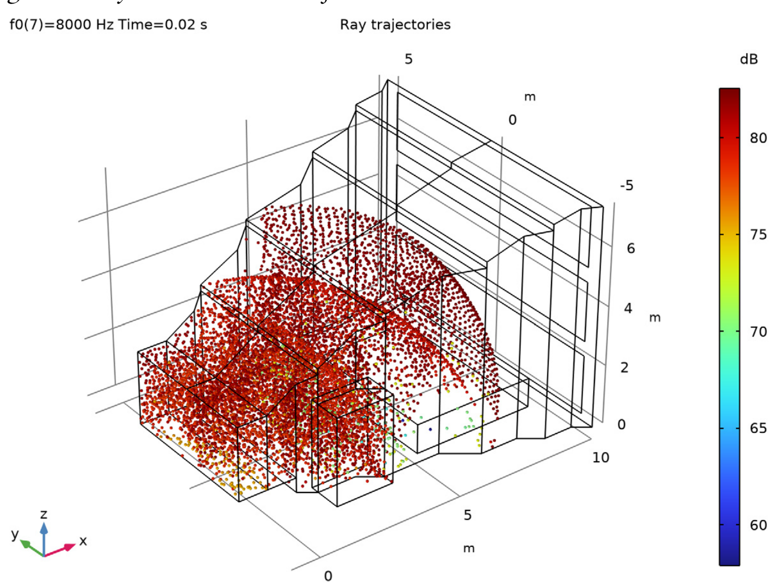


Figure 3: Ray location and SPL after 20 ms with the omnidirectional source.

The temporal impulse response (IR) for the source and receiver configuration used in the model is depicted in Figure 4. The frequency domain (FFT) of the IR is depicted in Figure 5. The curve is smoothed with a 1/3-octave running average.

When an IR is reconstructed from a ray tracing simulation, information is inferred and put back into the time signal using the temporal filter kernels. The quality of the simulated IR increases with the number of rays 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. The Impulse Response plot also allows the use of 1/3-octave and 1/6-octave frequency resolution.

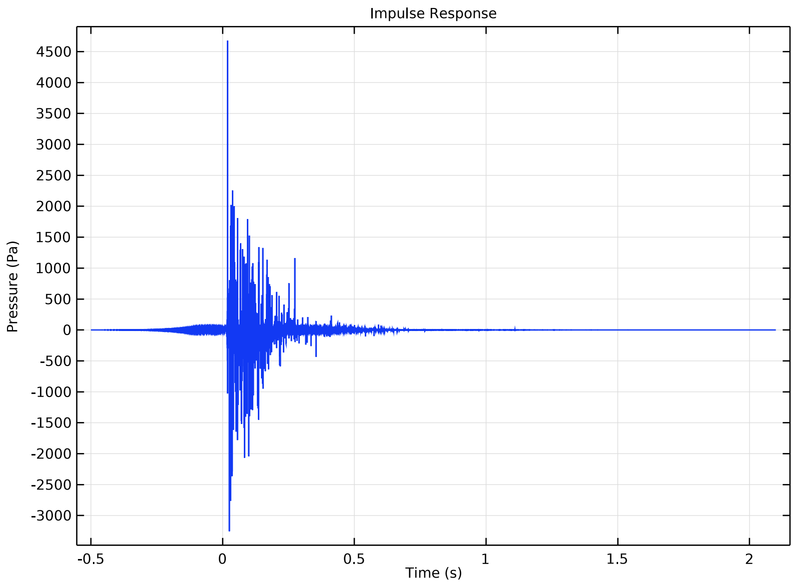


Figure 4: Room impulse response computed at the receiver location.

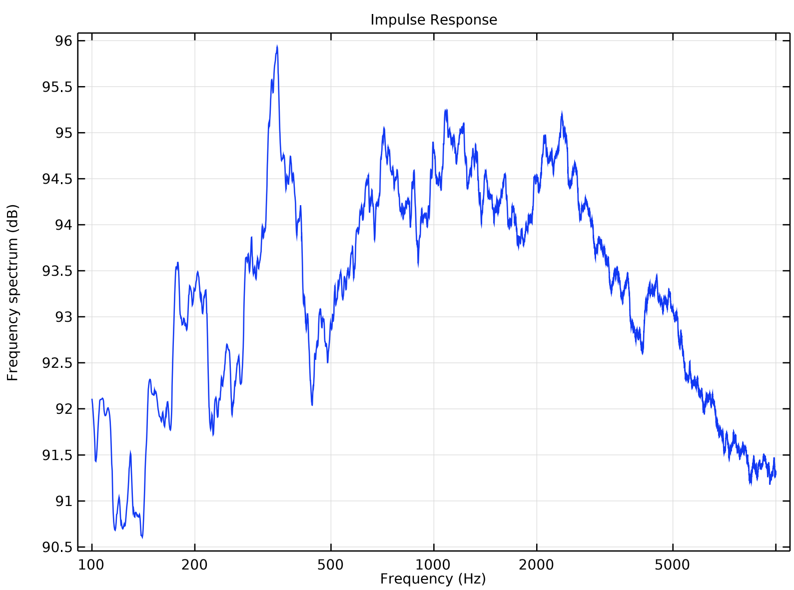


Figure 5: FFT of the room impulse response (1/3-octave running average).

The IR is further analyzed using the **Energy Decay** subfeature to the **Impulse Response** plot. The feature allows the computation of the objective room acoustic metrics like clarity C_{80}; definition D; early decay time EDT; center time t_s; reverberation times T_{20}, T_{30}, and T_{60}; and speech transmission index STI. The level decay curves for the seven octave bands used in the model (computed by the **Energy Decay** subfeature) are depicted in Figure 6. The metrics can be found in the **Objective Quality Metrics** table in the model (**Results>Tables**). The values are depicted graphically in Figure 9 and Figure 10.

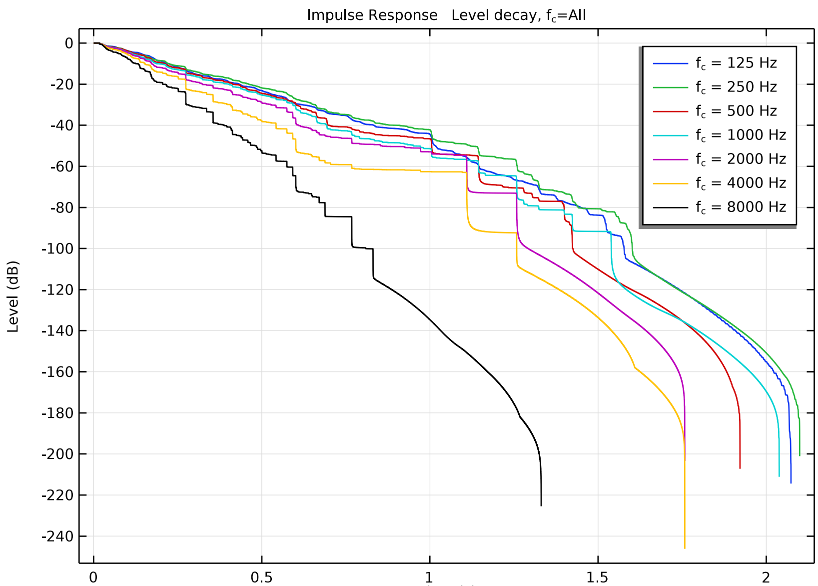


Figure 6: Level decay curves for the 7 octave bands used in the model.

In order to obtain accurate room acoustic metrics, it is important to ensure the quality of the level decay curves from which they are calculated. The first indicator for quality is the smoothness of the curves. If there are flat sections followed by sudden large drops in level, the number of rays in the simulation should be increased. The default value given in Equation 1 should be sufficient for this in the majority of cases. The second aspect to look at is the amplitude of level decay before the termination point where the curves become vertical and fade out. There should indeed be a large enough decay to fit the definitions of the different room acoustic metrics (for example, T_{60} takes into account the decay from –5 dB to –65 dB). A general guideline for this to be true is to set the impulse response duration approximately equal to or larger than the reverberation time. This is done in **Study 1>Step 1: Ray Tracing>Output times**, where the entered values should be 0 and the end time of the simulation. The other parameter controlling the decay amplitude is the energy threshold at which rays are terminated. This threshold should be sufficiently low to avoid losing valuable information. Its value is found in **Component 1>Ray Acoustics>Ray Termination 1**, where the default recommendation is to use **Power** as **Additional termination criteria** and a threshold equal to the initial power of individual rays multiplied by 10^{-7}. This expression ensures a consistent termination criterion according to the source power and number of rays in the simulation, with the factor 10^{-7} allowing a large enough decay in most cases.

The sound pressure level on the seating area is depicted in Figure 7 for the 8 kHz band. It is calculated using the **Sound Pressure Level Calculation** feature, available as a subnode to all **Wall** boundary conditions. In this case it is added to the top surface of the box representing the seating area. The feature can be added to all other walls to postprocess the SPL distribution if necessary.

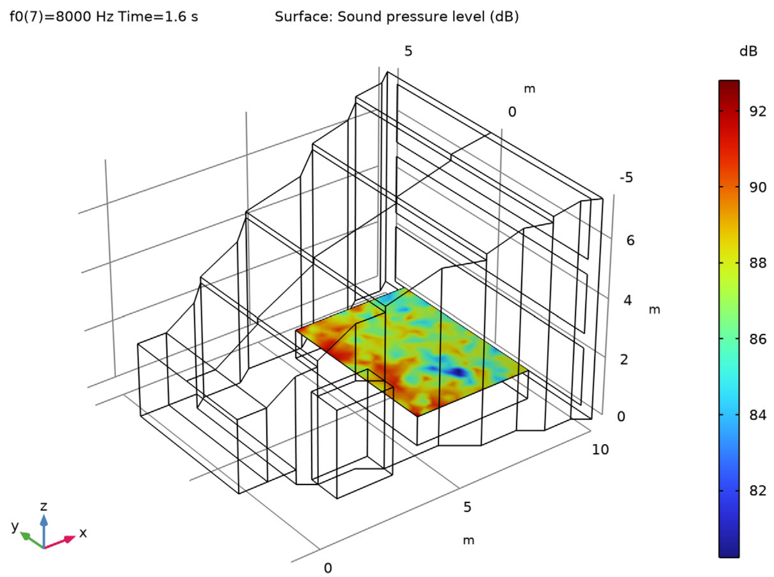


Figure 7: SPL from the omnidirectional source at the location of the audience.

In the ray tracing method, the intensity I and RMS pressure p_{rms} of the n^{th} ray detected by the receiver sphere is expressed as

$$I_n = \frac{L_{\mathrm{r}} Q_n}{V_{\mathrm{r}}} \qquad (p_{\mathrm{rms}}^2)_n = \rho c I_n$$

where V_r is the receiver volume, L_r is the distance traveled by the ray inside the receiver, and Q_n is the power carried by the ray (see Ref. 4). The intensity is evaluated using the expression `re1dist*rac.Q/re1vol`. Plotting this information in a **Ray** plot as a function of the arrival time yields the (discrete time) energy impulse response, or reflectogram. It is plotted for the 125 Hz and the 8 kHz octave bands in Figure 8. The slope of the curves (point data) gives a visual indication of the reverberation time of the room. In Figure 8 approximate trend lines have been added manually; their slope (from −5 dB to −65 dB which is six decades for $\log_{10}(I_n)$) gives an estimate of the T_{60} reverberation time. In this case about 0.5 s for the 8 kHz band and 1 s for the 125 Hz band. These values are seen to fit well with the computed values below.

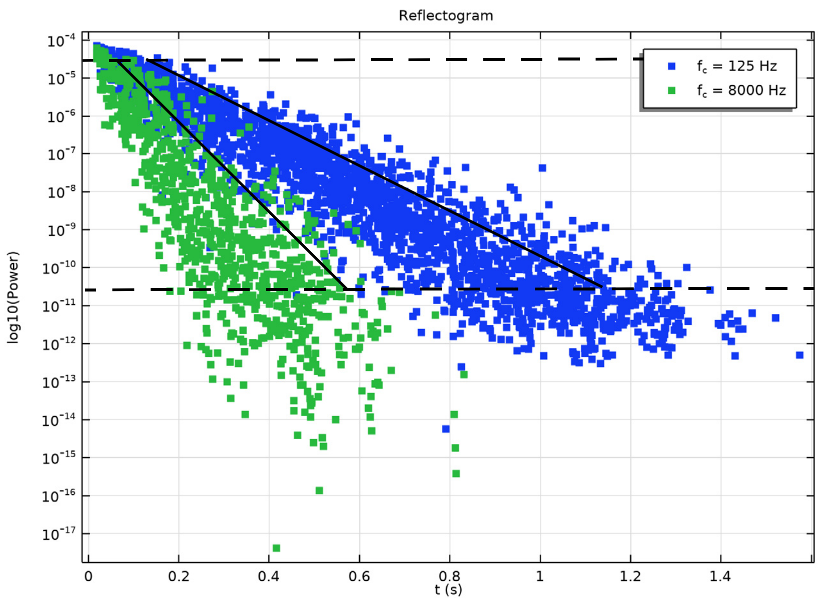


Figure 8: The raw data of the energetic impulse response or reflectogram. The slope represents the reverberation time in the given octave band.

A comparison between the computed value of reverberation time and simple statistical estimates is shown in Figure 9. To plot the data from the results table the **Table Graph** plot is used. The estimated values are calculated using the Sabine and Eyring equations used in statistical room acoustics

$$T_{60,S} = 0.161\ \mathrm{s/m}\ \frac{V}{S\bar{\alpha} + 8a_{\mathrm{air}}V}$$

$$T_{60,E} = 0.161\ \mathrm{s/m}\ \frac{V}{-S\ln(1-\bar{\alpha}) + 8a_{\mathrm{air}}V}$$

where V is the room volume, S is the total surface area, a_{air} is the atmospheric amplitude attenuation, and $\bar{\alpha}$ is the average wall absorption (see Ref. 2). The results show a good agreement in this case. However, it is not expected that the Sabine and Eyring predictions always match simulation results closely, especially in rooms where the diffuse sound field assumption does not hold.

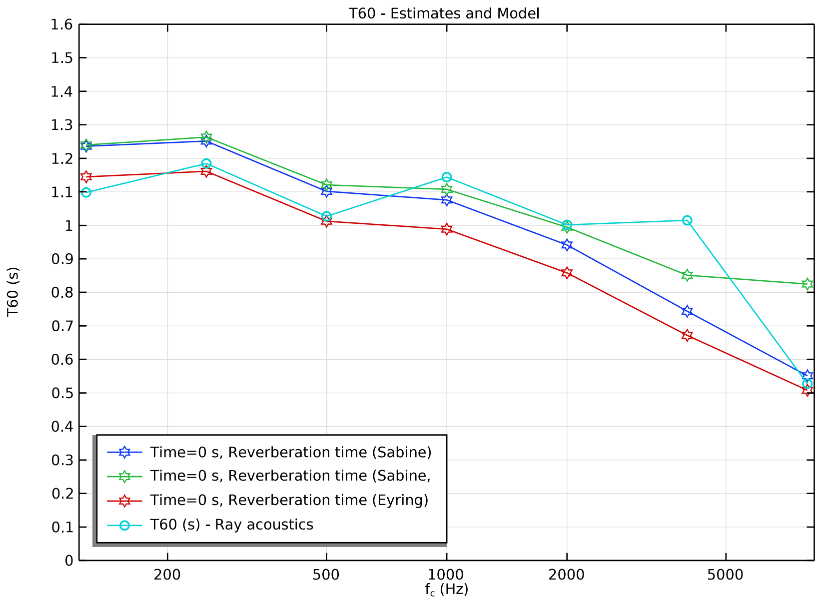


Figure 9: Reverberation time estimates based on the Sabine and Eyring formulas compared to the computed reverberation time.

Selected room acoustic metrics are plotted as functions of the octave band center frequency in Figure 10. The definition and clarity metrics are also compared to analytical estimates in the figures. The estimates are based on analytical models of the direct energy, early energy, and late energy (see Ref. 1). They are defined in the **Definitions>Variables: Quality Metric Estimates**. All metrics should be estimated taking their just noticeable difference (JND) into account when investigating a study case.

Definition D (or D_{50}) gives a metric for syllable intelligibility. In this room it is around 40% to 50% for most bands which is acceptable for a space with a purpose focused on music. The center time t_s is another metric that correlates to speech intelligibility, it is not shown here but can be found in the model. The clarity metric C_{80} is used to characterize the transparency of music, for concert halls typical values lie between –5 dB to +3 dB. In this case the design is not optimal for the higher octave bands.

Several definitions of the reverberation time exist, each using a different decay range to quantify the reverberance of a room, or in other words the rate at which acoustic energy is dissipated. In this case the four variables EDT, T_{20}, T_{30}, and T_{60} return similar values; this indicates that the room exhibits a rather steady decay over time, a sign that the sound field is close to diffuse conditions.

The speech transmission index STI is a single valued metric for speech intelligibility. It is based on modulation transfer function values (14 frequencies) and seven octave bands. The **Modulation transfer function** can be plotted using the **Energy Decay** subfeature. The STI is computed as a single value that combines the information in the seven bands. To get the single metric, change the **Band type** to **Broadband** in the **Energy Decay** plot. Making these changes gives an STI value of 0.61 (this indicates good intelligibility). The STI values plotted as a function of octave band center frequency in Figure 10 are computed based on the apparent signal to noise ratio in each band. When **Broadband** is selected the values in the different bands contribute with the appropriate weighting.

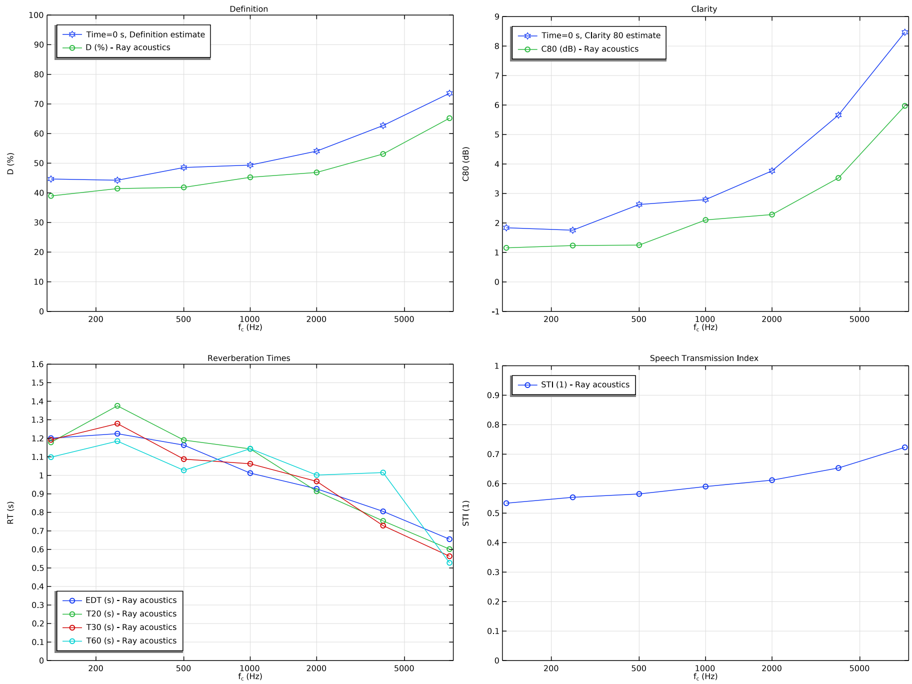


Figure 10: Objective room acoustic metrics clarity, definition, reverberation times, and speech transmission index plotted as functions of octave band center frequency. The clarity and definition metrics are compared to analytical estimates. The center time can be seen in the step-by-step instructions and in the model.

The second study investigates the sound field resulting from the directional loudspeaker. Its orientation is defined with a rotated coordinate system as depicted in Figure 11. It was set to point towards the audience area in this example. The directivity of the loudspeaker is also shown in Figure 12 with the SPL of the rays at 4 kHz after 5 ms.

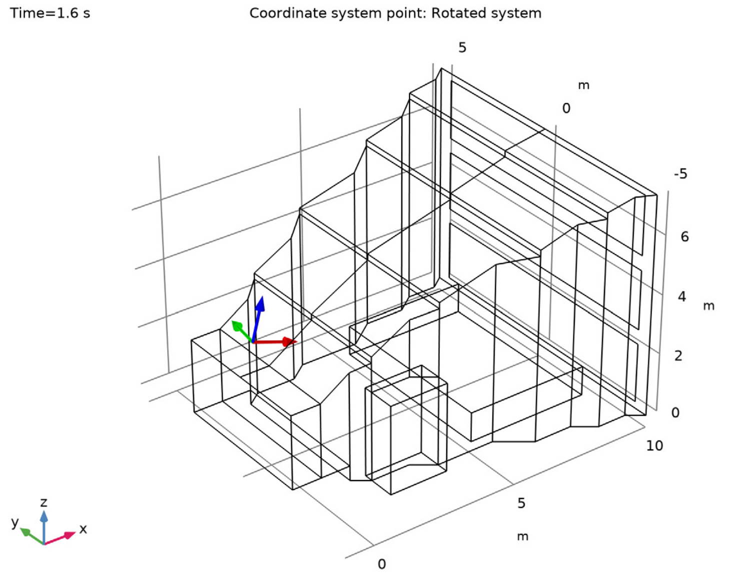


Figure 11: Orientation of the directional loudspeaker.

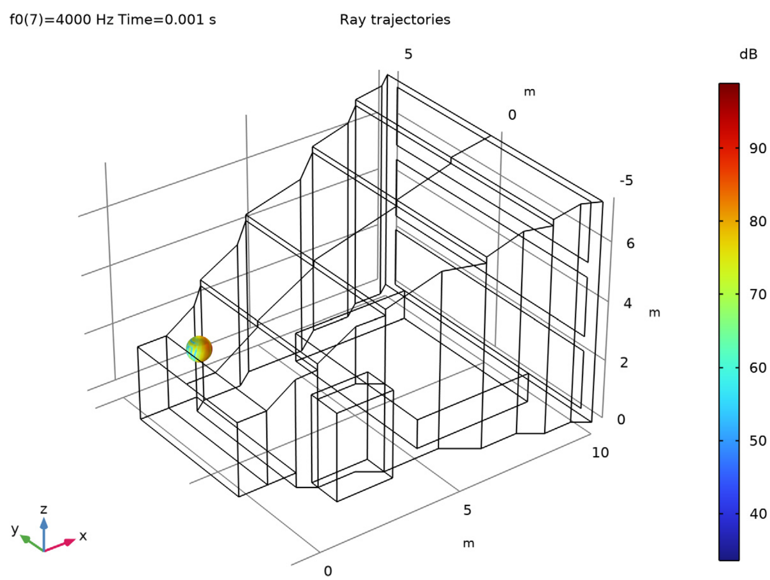


Figure 12: Ray location and SPL after 1 ms with the directional loudspeaker.

The SPL on the top surface of the seats is now considered. As seen in Figure 13, the highest levels are found at the front seats on the side of the loudspeaker and at the back seats thanks to the close wall reflection. A different loudspeaker location or a combination of several loudspeakers should therefore be investigated if the target was to uniformly cover the audience area.

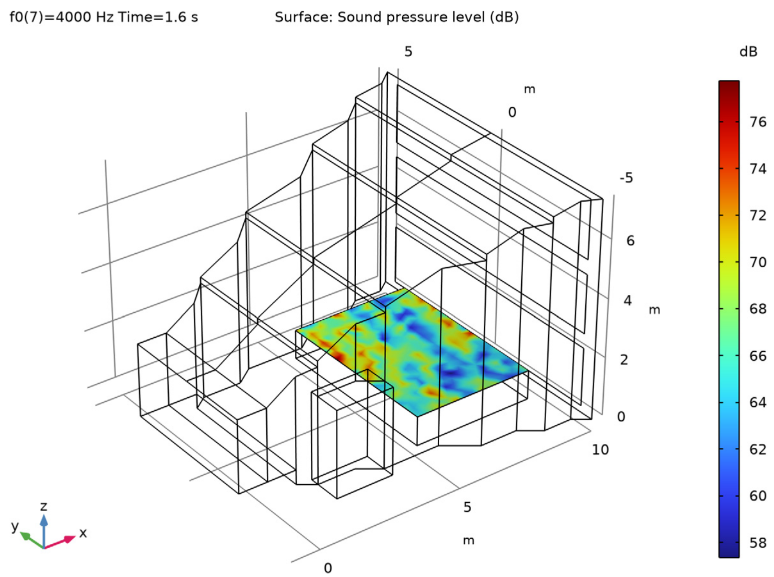


Figure 13: SPL from the directional loudspeaker at the location of the audience.

Notes About the COMSOL Implementation

There are several options that can be selected on the **Results** node that are useful when working with ray acoustic models and especially when evaluating the impulse response.

- When first setting up plots, it is useful to select the **Only plot when requested** option as some plots take a long time to render. Another trick is to use only a few rays initially.
- Once the plots are set up, then before running the model (with a large number of rays), select the **Recompute all plot data after solving** option. Once the model has solved the plots will be rendered. This is very useful when running the model over lunch break or over night since rendering the IR plot often takes longer time than solving the model.
- Before saving the model, remember to set the **Save plot data** list to **On**. Then all plots do not need to be re-rendered once the model is opened again.

The radiation directivity used in the second study was calculated and imported from a separate loudspeaker model. See the Loudspeaker Driver in a Vented Enclosure model in the *Acoustics Module Application Library* to learn how to create and export such data.

References

1. M. Vorländer, *Auralization, Fundamentals of Acoustics, Modeling, Simulation, Algorithms and Acoustic Virtual Reality*, Springer, 2008.

2. H. Kuttruff, *Room Acoustics*, CRC Press, 2009.

3. T.J. Cox and P. D'Antonio, *Acoustic Absorbers and Diffusers: Theory, design and application*, Taylor & Francis, 2009.

4. Z. Xiangyang, C. Ke'an, and S. Jincai, "On the accuracy of the ray-tracing algorithms based on various sound receiver models," *Appl. Acoust.*, vol. 64, pp. 433–441, 2003.

Application Library path: `Acoustics_Module/Building_and_Room_Acoustics/small_concert_hall`

Modeling Instructions

This section contains the modeling instructions for the Small Concert Hall model. They are followed by the Geometry Modeling Instructions section.

From the **File** menu, choose **New**.

NEW

In the **New** window, click **Model Wizard**.

MODEL WIZARD

1 In the **Model Wizard** window, click **3D**.

2 In the **Select Physics** tree, select **Acoustics>Geometrical Acoustics>Ray Acoustics (rac)**.

3 Click **Add**.

4 Click **Study**.

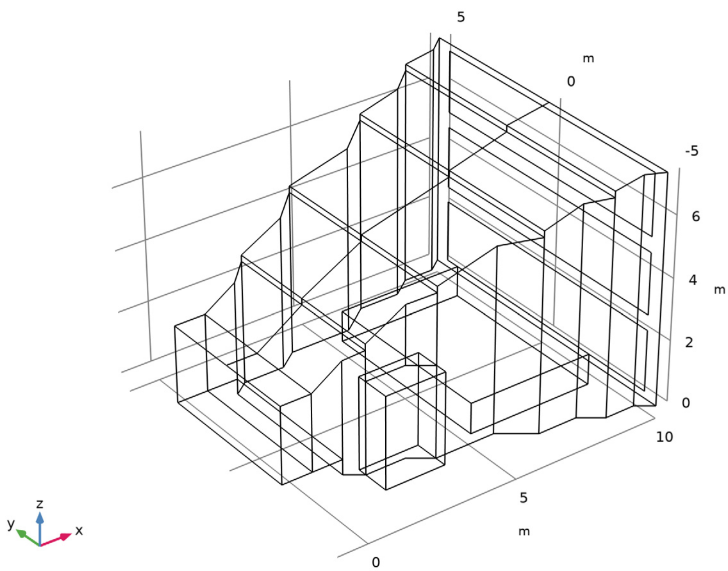
5 In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces>Ray Tracing**.

6 Click **Done**.

GEOMETRY 1

The geometry is set up by importing a geometry sequence. The sequence imports the small concert hall geometry and sets up several selections. The predefined selections simplify the rest of the model setup.

1 In the **Geometry** toolbar, click **Insert Sequence** and choose **Insert Sequence**.
2 Browse to the model's Application Libraries folder and double-click the file `small_concert_hall_geom_sequence.mph`.
3 In the **Geometry** toolbar, click **Build All**.
4 Click the **Wireframe Rendering** button in the **Graphics** toolbar.
5 Click the **Zoom Extents** button in the **Graphics** toolbar.



Import the model parameters from the files. The parameters include the band center frequency `f0`, the location of the source and receiver, as well as the room volume.

GLOBAL DEFINITIONS

Parameters 1 - Model

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.
2 In the **Settings** window for **Parameters**, type `Parameters 1 - Model` in the **Label** text field.

3 Locate the **Parameters** section. Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `small_concert_hall_parameters_model.txt`.

Parameters 2 - Source and Receiver Positions

1 In the **Home** toolbar, click **Parameters** and choose **Add>Parameters**.

2 In the **Settings** window for **Parameters**, type `Parameters 2 - Source and Receiver Positions` in the **Label** text field.

3 Locate the **Parameters** section. Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `small_concert_hall_parameters_source_positions.txt`.

Parameters 3 - Source and Receiver Settings

1 In the **Home** toolbar, click **Parameters** and choose **Add>Parameters**.

2 In the **Settings** window for **Parameters**, type `Parameters 3 - Source and Receiver Settings` in the **Label** text field.

3 Locate the **Parameters** section. Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `small_concert_hall_parameters_source_settings.txt`.

Create an interpolation function to import the loudspeaker directivity data.

Interpolation 1 (int1)

1 In the **Home** toolbar, click **Functions** and choose **Global>Interpolation**.

2 In the **Settings** window for **Interpolation**, locate the **Definition** section.

3 From the **Data source** list, choose **File**.

4 Click **Browse**.

5 Browse to the model's Application Libraries folder and double-click the file `small_concert_hall_radiation_balloon.txt`.

6 In the **Number of arguments** text field, type `3`.

7 Click **Import**.

8 Find the **Functions** subsection. In the table, enter the following settings:

Function name	Position in file
preal	1
pimag	2

9 Locate the **Units** section. In the **Function** table, enter the following settings:

Function	Unit
preal	Pa
pimag	Pa

10 In the **Argument** table, enter the following settings:

Argument	Unit
Column 1	Hz
Column 2	rad
Column 3	rad

Proceed and set up interpolation functions for the absorption coefficients of the different surfaces in the concert hall. The data is easily stored in one `.txt` file. Also define an interpolation function for the amplitude attenuation of air (given at 50% relative humidity and 20°C).

Interpolation 2 (int2)

1 In the **Home** toolbar, click f(X) **Functions** and choose **Global>Interpolation**.

2 In the **Settings** window for **Interpolation**, locate the **Definition** section.

3 From the **Data source** list, choose **File**.

4 Click **Browse**.

5 Browse to the model's Application Libraries folder and double-click the file `small_concert_hall_absorption_parameters.txt`.

6 In the **Number of arguments** text field, type `1`.

7 Click **Import**.

8 Find the **Functions** subsection. In the table, enter the following settings:

Function name	Position in file
a_walls	1
a_entrance	2
a_windows	3
a_floor	4
a_diffuser	5
a_seats	6
a_absorbers	7

9 Locate the **Interpolation and Extrapolation** section. From the **Interpolation** list, choose **Nearest neighbor**.

10 Locate the **Units** section. In the **Function** table, enter the following settings:

Function	Unit
a_walls	1
a_entrance	1
a_windows	1
a_floor	1
a_diffuser	1
a_seats	1
a_absorbers	1

11 In the **Argument** table, enter the following settings:

Argument	Unit
Column 1	Hz

Interpolation 3 (int3)

1 In the **Home** toolbar, click f(X) **Functions** and choose **Global>Interpolation**.

2 In the **Settings** window for **Interpolation**, locate the **Definition** section.

3 From the **Data source** list, choose **File**.

4 Click **Browse**.

5 Browse to the model's Application Libraries folder and double-click the file `small_concert_hall_air_attenuation.txt`.

6 Click **Import**.

7 In the **Function name** text field, type `a_air`.

8 Locate the **Interpolation and Extrapolation** section. From the **Interpolation** list, choose **Nearest neighbor**.

9 Locate the **Units** section. In the **Argument** table, enter the following settings:

Argument	Unit
t	Hz

10 In the **Function** table, enter the following settings:

Function	Unit
a_air	1/m

Now create the rotated coordinate system that will represent the orientation of the directional loudspeaker. When working on your own model, it is recommended to run a quick study to visualize the coordinate system and ensure that the correct angles are entered.

DEFINITIONS

Rotated System 2 (sys2)

1 In the **Definitions** toolbar, click **Coordinate Systems** and choose **Rotated System**.

2 In the **Settings** window for **Rotated System**, locate the **Rotation** section.

3 Find the **Euler angles (Z-X-Z)** subsection. In the α text field, type `alpha0`.

4 In the β text field, type `beta0`.

5 In the γ text field, type `gamma0`.

Add a point to the geometry to represent the loudspeaker position. This will allow to later plot the rotated coordinate system.

GEOMETRY 1

Point 1 (pt1)

1 In the **Geometry** toolbar, click **More Primitives** and choose **Point**.

2 In the **Settings** window for **Point**, locate the **Point** section.

3 In the **x** text field, type `x_spk`.

4 In the **y** text field, type `y_spk`.

5 In the **z** text field, type `z_spk`.

6 In the **Geometry** toolbar, click **Build All**.

Import the variables that define the room acoustic quality metric estimates. They include the reverberation time (`T60`), based on the Sabine and Eyring estimation equations, clarity (`C80`), definition (`D`), and center time (`ts`). This also requires setting up integration operators for all the surfaces.

DEFINITIONS

Integration 1 (intop1)

1. In the **Model Builder** window, expand the **Component 1 (comp1)>Definitions** node.
2. Right-click **Definitions** and choose **Nonlocal Couplings>Integration**.
3. In the **Settings** window for **Integration**, type `intop_windows` in the **Operator name** text field.
4. Locate the **Source Selection** section. From the **Geometric entity level** list, choose **Boundary**.
5. From the **Selection** list, choose **Windows**.

Integration 2 (intop2)

1. In the **Definitions** toolbar, click **Nonlocal Couplings** and choose **Integration**.
2. In the **Settings** window for **Integration**, type `intop_seats` in the **Operator name** text field.
3. Locate the **Source Selection** section. From the **Geometric entity level** list, choose **Boundary**.
4. From the **Selection** list, choose **Seats**.

Integration 3 (intop3)

1. In the **Definitions** toolbar, click **Nonlocal Couplings** and choose **Integration**.
2. In the **Settings** window for **Integration**, type `intop_diffusers` in the **Operator name** text field.
3. Locate the **Source Selection** section. From the **Geometric entity level** list, choose **Boundary**.
4. From the **Selection** list, choose **Diffusers**.

Integration 4 (intop4)

1. In the **Definitions** toolbar, click **Nonlocal Couplings** and choose **Integration**.
2. In the **Settings** window for **Integration**, type `intop_floor` in the **Operator name** text field.
3. Locate the **Source Selection** section. From the **Geometric entity level** list, choose **Boundary**.
4. From the **Selection** list, choose **Floor**.

Integration 5 (intop5)

1. In the **Definitions** toolbar, click **Nonlocal Couplings** and choose **Integration**.

2 In the **Settings** window for **Integration**, type `intop_entrance` in the **Operator name** text field.

3 Locate the **Source Selection** section. From the **Geometric entity level** list, choose **Boundary**.

4 From the **Selection** list, choose **Entrance**.

Integration 6 (intop6)

1 In the **Definitions** toolbar, click **Nonlocal Couplings** and choose **Integration**.

2 In the **Settings** window for **Integration**, type `intop_walls` in the **Operator name** text field.

3 Locate the **Source Selection** section. From the **Geometric entity level** list, choose **Boundary**.

4 From the **Selection** list, choose **Walls**.

Integration 7 (intop7)

1 In the **Definitions** toolbar, click **Nonlocal Couplings** and choose **Integration**.

2 In the **Settings** window for **Integration**, type `intop_absorbers` in the **Operator name** text field.

3 Locate the **Source Selection** section. From the **Geometric entity level** list, choose **Boundary**.

4 From the **Selection** list, choose **Absorbers**.

Variables: Quality Metric Estimates

1 Right-click **Definitions** and choose **Variables**.

2 In the **Settings** window for **Variables**, type `Variables: Quality Metric Estimates` in the **Label** text field.

3 Locate the **Variables** section. Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `small_concert_hall_variables.txt`.

Proceed to set up and define the physics and boundary conditions of the model. To compute the impulse response, it is necessary to model the power along the rays and count the reflections. In the model the intensity is also computed along the rays. The intensity represents spatially local properties of the acoustic field approximated by the rays. The model only uses a surface mesh. Propagation in the unmeshed domains requires the definition of material properties at the interface level (in the section **Material Properties of Exterior and Unmeshed Domains**). Set up boundary conditions for the different walls. All the boundary conditions are defined as **Mixed diffuse and specular reflection**, with either a default or specific scattering coefficient.

RAY ACOUSTICS (RAC)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Ray Acoustics (rac)**.

2 In the **Settings** window for **Ray Acoustics**, locate the **Intensity Computation** section.

3 From the **Intensity computation** list, choose **Compute intensity and power**.

4 Locate the **Material Properties of Exterior and Unmeshed Domains** section. In the c_{ext} text field, type `c0`.

5 In the ρ_{ext} text field, type `rho0`.

6 In the α_{ext} text field, type `a_air(f0)`.

7 Locate the **Additional Variables** section. Select the **Count reflections** check box.

Ray Properties 1

1 In the **Model Builder** window, under **Component 1 (comp1)>Ray Acoustics (rac)** click **Ray Properties 1**.

2 In the **Settings** window for **Ray Properties**, locate the **Ray Properties** section.

3 In the f text field, type `f0`.

Wall: Walls

1 In the **Physics** toolbar, click **Boundaries** and choose **Wall**.

2 In the **Settings** window for **Wall**, type `Wall: Walls` in the **Label** text field.

3 Locate the **Boundary Selection** section. From the **Selection** list, choose **Walls**.

4 Locate the **Wall Condition** section. From the **Wall condition** list, choose **Mixed diffuse and specular reflection**.

5 In the γ_{s} text field, type `1-s_default`.

6 Locate the **Reflection Coefficients Model** section. In the α_s text field, type `a_walls(f0)`.

7 In the α_d text field, type `a_walls(f0)`.

Wall: Entrance

1 In the **Physics** toolbar, click **Boundaries** and choose **Wall**.

2 In the **Settings** window for **Wall**, type `Wall: Entrance` in the **Label** text field.

3 Locate the **Boundary Selection** section. From the **Selection** list, choose **Entrance**.

4 Locate the **Wall Condition** section. From the **Wall condition** list, choose **Mixed diffuse and specular reflection**.

5 In the γ_{s} text field, type `1-s_default`.

6 Locate the **Reflection Coefficients Model** section. In the α_s text field, type `a_entrance(f0)`.

7 In the α_d text field, type `a_entrance(f0)`.

Wall: Windows

1 In the **Physics** toolbar, click **Boundaries** and choose **Wall**.

2 In the **Settings** window for **Wall**, type `Wall: Windows` in the **Label** text field.

3 Locate the **Boundary Selection** section. From the **Selection** list, choose **Windows**.

4 Locate the **Wall Condition** section. From the **Wall condition** list, choose **Mixed diffuse and specular reflection**.

5 In the γ_s text field, type `1-s_default`.

6 Locate the **Reflection Coefficients Model** section. In the α_s text field, type `a_windows(f0)`.

7 In the α_d text field, type `a_windows(f0)`.

Wall: Floor

1 In the **Physics** toolbar, click **Boundaries** and choose **Wall**.

2 In the **Settings** window for **Wall**, type `Wall: Floor` in the **Label** text field.

3 Locate the **Boundary Selection** section. From the **Selection** list, choose **Floor**.

4 Locate the **Wall Condition** section. From the **Wall condition** list, choose **Mixed diffuse and specular reflection**.

5 In the γ_s text field, type `1-s_default`.

6 Locate the **Reflection Coefficients Model** section. In the α_s text field, type `a_floor(f0)`.

7 In the α_d text field, type `a_floor(f0)`.

Wall: Diffusers

1 In the **Physics** toolbar, click **Boundaries** and choose **Wall**.

2 In the **Settings** window for **Wall**, type `Wall: Diffusers` in the **Label** text field.

3 Locate the **Boundary Selection** section. From the **Selection** list, choose **Diffusers**.

4 Locate the **Wall Condition** section. From the **Wall condition** list, choose **Mixed diffuse and specular reflection**.

5 In the γ_s text field, type `1-s_diffuser`.

6 Locate the **Reflection Coefficients Model** section. In the α_s text field, type `a_diffuser(f0)`.

7 In the α_d text field, type `a_diffuser(f0)`.

In this model the scattering coefficient s_diffuser is constant across the frequency bands. It can of course also be defined as an interpolation function that depends on f0.

Wall: Absorbers

1 In the **Physics** toolbar, click **Boundaries** and choose **Wall**.

2 In the **Settings** window for **Wall**, type Wall: Absorbers in the **Label** text field.

3 Locate the **Boundary Selection** section. From the **Selection** list, choose **Absorbers**.

4 Locate the **Wall Condition** section. From the **Wall condition** list, choose **Mixed diffuse and specular reflection**.

5 In the γ_s text field, type 1-s_default.

6 Locate the **Reflection Coefficients Model** section. In the α_s text field, type a_absorbers(f0).

7 In the α_d text field, type a_absorbers(f0).

Wall: Seats (Top)

1 In the **Physics** toolbar, click **Boundaries** and choose **Wall**.

2 In the **Settings** window for **Wall**, type Wall: Seats (Top) in the **Label** text field.

3 Locate the **Boundary Selection** section. From the **Selection** list, choose **Manual**.

4 Select Boundary 41 only.

5 Locate the **Wall Condition** section. From the **Wall condition** list, choose **Mixed diffuse and specular reflection**.

6 In the γ_s text field, type 1-s_seats.

7 Locate the **Reflection Coefficients Model** section. In the α_s text field, type a_seats(f0).

8 In the α_d text field, type a_seats(f0).

Sound Pressure Level Calculation 1

1 In the **Physics** toolbar, click **Attributes** and choose **Sound Pressure Level Calculation**.

2 In the **Settings** window for **Sound Pressure Level Calculation**, locate the **Smoothing** section.

3 Select the **Compute smoothed accumulated variable** check box.

Wall: Seats (Around)

1 In the **Physics** toolbar, click **Boundaries** and choose **Wall**.

2 In the **Settings** window for **Wall**, type Wall: Seats (Around) in the **Label** text field.

3 Locate the **Boundary Selection** section. From the **Selection** list, choose **Manual**.

4 Select Boundaries 39, 40, 42, and 59 only.

5 Locate the **Wall Condition** section. From the **Wall condition** list, choose **Mixed diffuse and specular reflection**.

6 In the γ_s text field, type `1-s_seats`.

7 Locate the **Reflection Coefficients Model** section. In the α_s text field, type `a_seats(f0)`.

8 In the α_d text field, type `a_seats(f0)`.

The source is defined here with its reference level and distance. The spatial directivity is set to 0 to obtain an omnidirectional point source.

Source with Directivity 1

1 In the **Physics** toolbar, click **Global** and choose **Source with Directivity**.

2 In the **Settings** window for **Source with Directivity**, locate the **Initial Position** section.

3 Specify the $\mathbf{q}_0$ vector as

x_src	x
y_src	y
z_src	z

4 Locate the **Ray Direction Vector** section. In the N_w text field, type `Nrays`.

5 Locate the **Intensity and Power** section. In the L_{ref} text field, type `L0_src`.

6 In the R_{ref} text field, type `R0_src`.

A second source is included in the model to demonstrate the case of a directional loudspeaker source. In this case, the radiation data is given as the sound pressure measured one meter away from the source; it therefore needs to be converted to sound pressure level.

Source with Directivity 2

1 In the **Physics** toolbar, click **Global** and choose **Source with Directivity**.

2 In the **Settings** window for **Source with Directivity**, locate the **Coordinate System Selection** section.

3 From the **Coordinate system** list, choose **Rotated System 2 (sys2)**.

4 Locate the **Initial Position** section. Specify the $\mathbf{q}_0$ vector as

x_spk	x
y_spk	y
z_spk	z

5 Locate the **Ray Direction Vector** section. In the N_w text field, type `Nrays`.

6 Locate the **Intensity and Power** section. In the $D(\varphi\theta,)$ text field, type `20*log10(abs(preal(f0,rac.swd2.phi,rac.swd2.theta)+i*pimag(f0,rac.swd2.phi,rac.swd2.theta))/sqrt(2)/20e-6[Pa])`.

7 In the L_{ref} text field, type `L0_spk`.

8 In the R_{ref} text field, type `R0_spk`.

Ray Termination 1

1 In the **Physics** toolbar, click **Global** and choose **Ray Termination**.

Add a termination condition to end the propagation of rays once their energy drops below a certain threshold. This allows for faster computations by removing rays which do not have a significant contribution anymore.

2 In the **Settings** window for **Ray Termination**, locate the **Termination Criteria** section.

3 From the **Spatial extents of ray propagation** list, choose **Bounding box, from geometry**.

4 From the **Additional termination criteria** list, choose **Power**.

5 In the Q_{th} text field, type `rac.swd1.Q0*1e-7`.

Now create the mesh. In ray tracing simulations for room acoustics, the mesh is used to detect the collisions between rays and boundaries. Therefore, only the boundaries need to be meshed and the element size can be set to a coarse value without compromising accuracy.

MESH 1

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Mesh 1**.

2 In the **Settings** window for **Mesh**, locate the **Sequence Type** section.

3 From the list, choose **User-controlled mesh**.

Size

1 In the **Model Builder** window, under **Component 1 (comp1)>Mesh 1** click **Size**.

2 In the **Settings** window for **Size**, locate the **Element Size** section.

3 From the **Predefined** list, choose **Extra coarse**.

Free Triangular 1

1 In the **Model Builder** window, click **Free Triangular 1**.

2 In the **Settings** window for **Free Triangular**, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **All boundaries**.

Size 1

1 Right-click **Free Triangular 1** and choose **Size**.

Add a finer mesh on the surface where the SPL is computed.

2 In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.

3 Click **Clear Selection**.

4 Select Boundary 41 only.

5 Locate the **Element Size** section. Click the **Custom** button.

6 Locate the **Element Size Parameters** section.

7 Select the **Maximum element size** check box. In the associated text field, type `0.3`.

Mesh the vertices that are not part of the model boundaries.

Vertex 1

1 In the **Mesh** toolbar, click **Boundary** and choose **Vertex**.

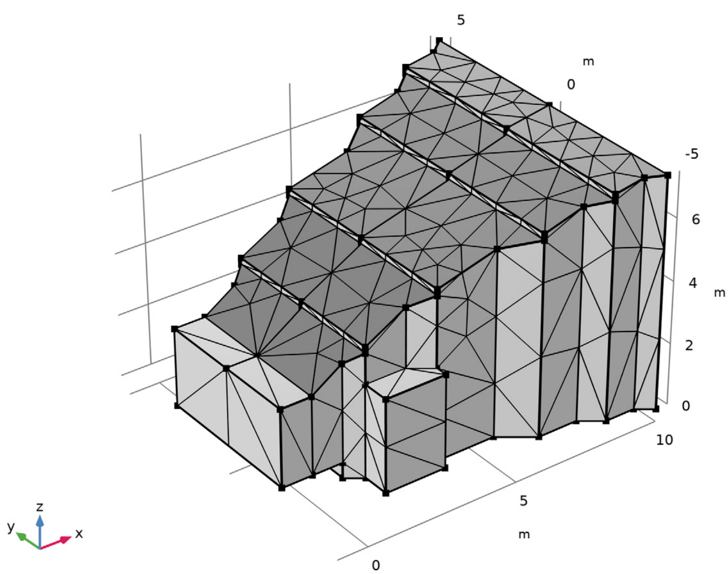
2 In the **Settings** window for **Vertex**, locate the **Point Selection** section.

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog box, type `11` in the **Selection** text field.

5 Click **OK**.

6 In the **Settings** window for **Vertex**, click **Build All**.



Proceed and solve the model with the omnidirectional source by adding a parametric sweep over the center frequency variable `f0`. This represents the center frequency of the octave bands analyzed in this model, in order to get a broadband response. The first time you set up and solve the model it can be useful to reduce the number of rays by changing the value of the parameter `Nrays` to, for example, 1000. This will make solving and postprocessing faster. Remember that the quality of the results in acoustic ray tracing increase for an increasing number of rays and more narrow frequency bands (you need to have wall absorption data with the desired resolution). In the Ray Acoustics interface the impulse response plot can handle octave, 1/3-octave, and 1/6-octave data.

STUDY 1 - OMNIDIRECTIONAL SOURCE

1 In the **Model Builder** window, click **Study 1**.

2 In the **Settings** window for **Study**, type `Study 1 - Omnidirectional Source` in the **Label** text field.

Step 1: Ray Tracing

1 In the **Model Builder** window, under **Study 1 - Omnidirectional Source** click **Step 1: Ray Tracing**.

2 In the **Settings** window for **Ray Tracing**, locate the **Study Settings** section.

3 From the **Time unit** list, choose **s**.

4 In the **Output times** text field, type `0 1.6`.

For optimal performance only enter 0 and the end time for the simulation. In postprocessing, when reconstructing the impulse response, additional exact time steps for all the wall reflections are used and rendered.

5 Locate the **Physics and Variables Selection** section. Select the **Modify model configuration for study step** check box.

6 In the tree, select **Component 1 (comp1)>Ray Acoustics (rac)>Source with Directivity 2**.

7 Click **Disable**.

Parametric Sweep

1 In the **Study** toolbar, click **Parametric Sweep**.

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 postprocessing, by the receiver dataset and the impulse response plot, to generate the broadband impulse response.

2 In the **Settings** window for **Parametric Sweep**, locate the **Study Settings** section.

3 Click **Add**.

4 In the table, click to select the cell at row number 1 and column number 2.

5 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
f0 (Band center frequency)		Hz

6 Click **Range**.

7 In the **Range** dialog box, choose **ISO preferred frequencies** from the **Entry method** list.

8 In the **Start frequency** text field, type `125`.

9 In the **Stop frequency** text field, type `8000`.

10 Click **Replace**.

Solving the model takes a couple of minutes and uses less than 4 GB of RAM (depending on your hardware). This will increase for an increasing number of rays.

11 In the **Study** toolbar, click **Compute**.

RESULTS

Ray Trajectories (rac)

1 In the **Settings** window for **3D Plot Group**, locate the **Data** section.

2 From the **Time (s)** list, choose **Interpolation**.

3 In the **Time** text field, type `10[ms]`.

4 In the **Ray Trajectories (rac)** toolbar, click **Plot**.

Ray Trajectories 1

1 In the **Model Builder** window, expand the **Ray Trajectories (rac)** node, then click **Ray Trajectories 1**.

2 In the **Settings** window for **Ray Trajectories**, locate the **Coloring and Style** section.

3 Find the **Line style** subsection. From the **Type** list, choose **None**.

4 Find the **Point style** subsection. From the **Type** list, choose **Point**.

Color Expression 1

1 In the **Model Builder** window, expand the **Ray Trajectories 1** node, then click **Color Expression 1**.

2 In the **Settings** window for **Color Expression**, locate the **Expression** section.

3 In the **Expression** text field, type `rac.Lp`.

4 In the **Ray Trajectories (rac)** toolbar, click **Plot**.

This should reproduce the image in Figure 2.

Ray Trajectories (rac)

1 In the **Model Builder** window, under **Results** click **Ray Trajectories (rac)**.

2 In the **Settings** window for **3D Plot Group**, locate the **Data** section.

3 In the **Time** text field, type `20[ms]`.

4 In the **Ray Trajectories (rac)** toolbar, click **Plot**.

This should reproduce the image in Figure 3.

Create an animation to visualize early reflections and wave patterns.

Animation 1

1 In the **Results** toolbar, click **Animation** and choose **Player**.

2 In the **Settings** window for **Animation**, locate the **Animation Editing** section.

3 From the **Time selection** list, choose **Interpolated**.

4 Click **Range**.

5 In the **Range** dialog box, type `3[ms]` in the **Start** text field.

6 In the **Step** text field, type `1[ms]`.

7 In the **Stop** text field, type `50[ms]`.

8 Click **Replace**.

9 In the **Settings** window for **Animation**, locate the **Frames** section.

10 In the **Number of frames** text field, type `48`.

11 Click the **Play** button in the **Graphics** toolbar.

On the **Results** node you have several options that are useful when postprocessing ray tracing simulations, where rendering plots can be time consuming. This is especially true for the impulse response plots. While setting up plots, it is useful to select **Only plot when requested** such that the plots are not generated every time you change an option. It is also good practice to save the plots in the model such that they are already rendered when you open your model at a later stage. Finally, once you have set up all the plots and you are ready to run the model again, it can be useful to enable **Recompute all plot data after solving**. All plots will then be recomputed after the model is solved, for example, running over lunch.

12 In the **Model Builder** window, click **Results**.

13 In the **Settings** window for **Results**, locate the **Update of Results** section.

14. Select the **Only plot when requested** check box.
15. Select the **Recompute all plot data after solving** check box.
16. Locate the **Save Data in the Model** section. From the **Save plot data** list, choose **On**.

    Also turn on the **Plot Information Section** to display rendering time and other useful information. This option applies to the whole COMSOL installation; if selected, the **Plot Information Section** will also appear in other models opened at a later stage.
17. Click the **Show More Options** button in the **Model Builder** toolbar.
18. In the **Show More Options** dialog box, select **Results>Plot Information Section** in the tree.
19. In the tree, select the check box for the node **Results>Plot Information Section**.
20. Click **OK**.

Now set up the **Receiver** dataset used for creating the impulse response and subsequent analysis.

Receiver 3D - All Bands

1. In the **Model Builder** window, expand the **Results>Datasets** node.
2. Right-click **Results>Datasets** and choose **More 3D Datasets>Receiver 3D**.
3. In the **Settings** window for **Receiver 3D**, type `Receiver 3D - All Bands` in the **Label** text field.
4. Locate the **Receiver** section. Find the **Center** subsection. In the **x** text field, type `x_rec`.
5. In the **y** text field, type `y_rec`.
6. In the **z** text field, type `z_rec`.
7. Find the **Radius** subsection. From the **Radius input** list, choose **Fixed size**.
8. In the **Radius** text field, type `r_rec`.

The default recommendation is to use a receiver radius of 0.3 m, which corresponds to the standard width of a seat. For different applications, especially smaller spaces like a car cabin, it is recommended to decrease the value of the receiver radius.

Receiver 3D - 125 Hz Band

1. In the **Model Builder** window, right-click **Receiver 3D - All Bands** and choose **Duplicate**.
2. In the **Settings** window for **Receiver 3D**, type `Receiver 3D - 125 Hz Band` in the **Label** text field.
3. Locate the **Data** section. From the **Parameter selection (f0)** list, choose **From list**.
4. In the **Parameter values (f0 (Hz))** list, select **125**.

Receiver 3D - 8 kHz Band

1 In the **Model Builder** window, right-click **Receiver 3D - 125 Hz Band** and choose **Duplicate**.
2 In the **Settings** window for **Receiver 3D**, type `Receiver 3D - 8 kHz Band` in the **Label** text field.
3 Locate the **Data** section. From the **Parameter selection (f0)** list, choose **From list**.
4 In the **Parameter values (f0 (Hz))** list, select **8000**.

Impulse Response

1 In the **Results** toolbar, click **1D Plot Group**.
2 In the **Settings** window for **1D Plot Group**, type `Impulse Response` in the **Label** text field.
3 Locate the **Data** section. From the **Dataset** list, choose **Receiver 3D - All Bands**.

Impulse Response 1

1 In the **Impulse Response** toolbar, click **More Plots** and choose **Impulse Response**.

To get sharper filters you can modify some settings in the **Advanced** section.

2 In the **Settings** window for **Impulse Response**, click to expand the **Advanced** section.
3 In the N_p text field, type `22050`.
4 In the δ text field, type `0.001`.

Rendering the impulse response will typically take one or two minutes (depending on hardware, number of rays, and frequency band resolution). Once the plot has been generated (the first time) the necessary ray data is cached and any subsequent changes/ updates of the plot is faster. The rendering time for the last time a figure was plotted can be found in the first subnode of its plot group, under **Information** in the **Settings** window.

5 In the **Impulse Response** toolbar, click **Plot**.

This should reproduce the impulse response shown in Figure 4. The impulse response is the most important result of this model. The signal can be exported under the **Export** node and used for further analysis in an external signal processing tool. The response is reconstructed from the ray data detected by the **Receiver** dataset (arrival time, power, and band center frequency). It has a default sampling frequency of 44100 Hz. This can also be changed under the **Advanced** section in the plot settings window.

Plot 1

1 Right-click **Impulse Response 1** and choose **Add Plot Data to Export**.
2 In the **Settings** window for **Plot**, locate the **Output** section.
3 From the **File type** list, choose **WAVE audio file (*.wav)**.

4 In the **Filename** text field, type `small_concert_hall_impulse_response.wav`.

5 Click to expand the **Advanced** section. From the **Encoding** list, choose **16-bit**.

Click **Export** to produce a wav file with the impulse response. This file could be used for auralization or analysis with other tools. Remember to disable any **Energy Decay** subfeature before exporting.

Proceed to analyze the impulse response with the **Energy Decay** subfeature. This will create a plot of the level/energy decay and a table with the objective quality metrics.

Energy Decay 1

1 In the **Model Builder** window, expand the **Results>Impulse Response** node.

2 Right-click **Impulse Response 1** and choose **Energy Decay**.

3 In the **Settings** window for **Energy Decay**, locate the **Display** section.

4 From the **Band type** list, choose **Individual bands**.

5 From the **Band frequency** list, choose **All frequencies**.

6 From the **Plot** list, choose **Level decay**.

7 Locate the **Table** section. Find the **Early energy** subsection. Clear the **C_{50}, Clarity** check box.

8 Clear the **t_r, First ray arrival time** check box.

9 Find the **Speech intelligibility** subsection. Clear the **SNR, Apparent SNR** check box.

10 Click the **Show Legends** button in the **Graphics** toolbar.

11 In the **Impulse Response** toolbar, click **Plot**.

This should reproduce the image in Figure 6.

To show the impulse response signal again, simply disable the **Energy Decay** subfeature and click **Plot** again.

For the sake of this tutorial, the impulse response is generated again and an FFT of the transient signal is performed (duplicate the plot and disable the **Energy Decay** subfeature). Since a new plot is now generated, the IR data has to be computed again. Creating the plot based on the existing IR plot would have been faster as the data is cached.

Impulse Response 1

1 In the **Model Builder** window, right-click **Impulse Response** and choose **Duplicate**.

2 Expand the **Impulse Response 1** node.

Energy Decay 1

1 In the **Model Builder** window, expand the **Results>Impulse Response 1> Impulse Response 1** node.

2 Right-click **Energy Decay 1** and choose **Disable**.

Impulse Response FFT

1 In the **Model Builder** window, under **Results** click **Impulse Response 1**.

2 In the **Settings** window for **1D Plot Group**, type `Impulse Response FFT` in the **Label** text field.

3 Locate the **Axis** section. Select the **x-axis log scale** check box.

4 Locate the **Legend** section. Clear the **Show legends** check box.

When performing an FFT, the energy contained in the time signal is split between positive and negative frequencies. The **Show > Frequency spectrum** option with **Scale > Multiply by sampling period** applies the correct scaling factors to obtain physically meaningful results in dB for positive frequencies.

Impulse Response 1

1 In the **Model Builder** window, expand the **Impulse Response FFT** node, then click **Impulse Response 1**.

2 In the **Settings** window for **Impulse Response**, locate the **x-Axis Data** section.

3 From the **Transformation** list, choose **Discrete Fourier transform**.

4 From the **Show** list, choose **Frequency spectrum**.

5 From the **Scale** list, choose **Multiply by sampling period**.

6 Select the **Frequency range** check box.

7 In the **Minimum** text field, type `100`.

8 In the **Maximum** text field, type `10000`.

9 Select the **In dB** check box.

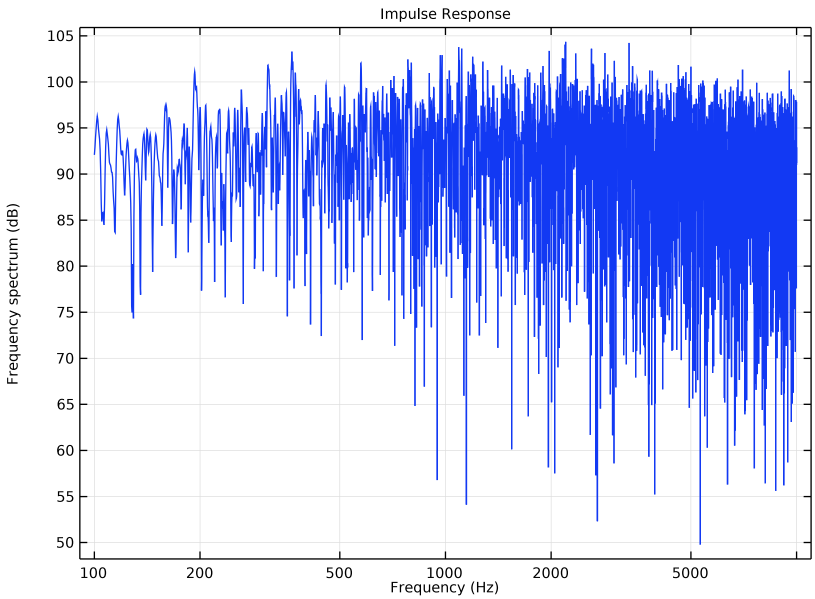
10 From the **dB type** list, choose **20log**.

11 From the **dB reference** list, choose **Manual**.

12 In the **Reference value** text field, type `rac.pref_SPL`.

13 In the **Impulse Response FFT** toolbar, click **Plot**.

This is the raw transfer function of the room (no smoothing).



14 In the **Model Builder** window, click **Impulse Response 1**.

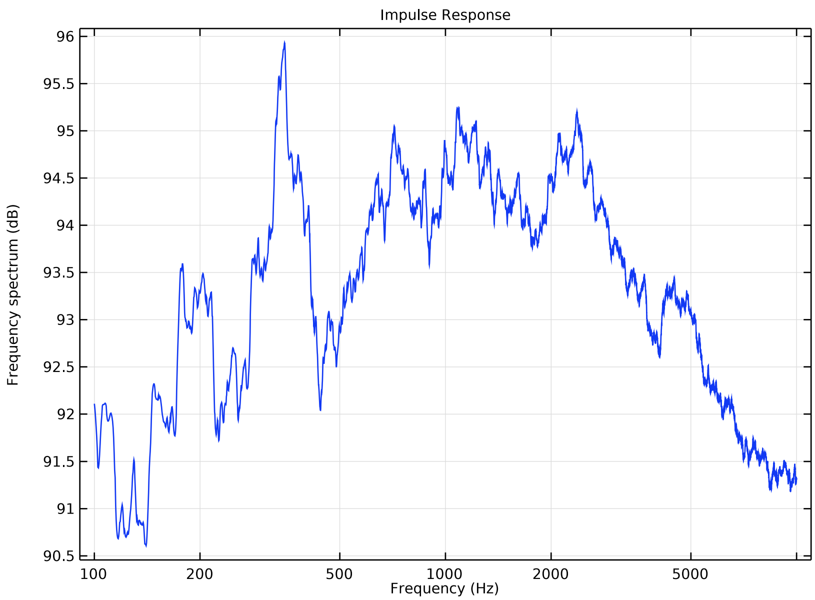
15 Locate the **Smoothing** section. Select the **Moving average** check box.

16 From the **Type** list, choose **1/n octave**.

17 In the **n** text field, type 3.

18 In the **Impulse Response FFT** toolbar, click **Plot**.

This should reproduce the image in Figure 5.



Seats SPL

1 In the **Home** toolbar, click **Add Plot Group** and choose **3D Plot Group**.

2 In the **Settings** window for **3D Plot Group**, type `Seats SPL` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study 1 - Omnidirectional Source/ Parametric Solutions 1 (sol2)**.

4 Locate the **Color Legend** section. Select the **Show units** check box.

Surface 1

1 Right-click **Seats SPL** and choose **Surface**.

2 In the **Settings** window for **Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Ray Acoustics> Accumulated variables>Wall intensity comp1.rac.wall8.spl1.Iw>rac.wall8.spl1.Lp - Sound pressure level - dB**.

3 Locate the **Expression** section. From the **Unit** list, choose **dB**.

4 In the **Seats SPL** toolbar, click **Plot**.

This should reproduce the image in Figure 7. The 8 kHz band is chosen per default. A smoothed variable for the SPL also exists `rac.wall8.spl1.Lp_sm`.

Reflectogram

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, type `Reflectogram` in the **Label** text field.

3 Click to expand the **Title** section. From the **Title type** list, choose **Label**.

4 Locate the **Plot Settings** section.

5 Select the **x-axis label** check box. In the associated text field, type `t (s)`.

6 Select the **y-axis label** check box. In the associated text field, type `log10(Power)`.

7 Locate the **Data** section. From the **Dataset** list, choose **None**.

8 Locate the **Axis** section. Select the **y-axis log scale** check box.

Ray 1

1 In the **Reflectogram** toolbar, click **More Plots** and choose **Ray**.

2 In the **Settings** window for **Ray**, locate the **Data** section.

3 From the **Dataset** list, choose **Receiver 3D - 125 Hz Band**.

4 Locate the **y-Axis Data** section. In the **Expression** text field, type `re1dist*rac.Q/re1vol`.

5 Click to expand the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **None**.

6 Find the **Line markers** subsection. From the **Marker** list, choose **Point**.

7 Click to expand the **Legends** section. From the **Legends** list, choose **Manual**.

8 Select the **Show legends** check box.

9 In the table, enter the following settings:

Legends
f_c = 125 Hz

Ray 2

1 Right-click **Ray 1** and choose **Duplicate**.

2 In the **Settings** window for **Ray**, locate the **Data** section.

3 From the **Dataset** list, choose **Receiver 3D - 8 kHz Band**.

4 Locate the **Legends** section. In the table, enter the following settings:

Legends
f_c = 8000 Hz

5 In the **Reflectogram** toolbar, click **Plot**.

This should reproduce the image in Figure 8.

T60 - Estimates and Model

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, type `T60 - Estimates and Model` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study 1 - Omnidirectional Source/ Parametric Solutions 1 (sol2)**.

4 From the **Time selection** list, choose **First**.

5 Click to expand the **Title** section. From the **Title type** list, choose **Label**.

6 Locate the **Plot Settings** section.

7 Select the **x-axis label** check box. In the associated text field, type f_c (Hz).

8 Locate the **Axis** section. Select the **Manual axis limits** check box.

9 In the **x minimum** text field, type `120`.

10 In the **x maximum** text field, type `8322`.

11 In the **y minimum** text field, type `0`.

12 In the **y maximum** text field, type `1.6`.

13 Select the **x-axis log scale** check box.

14 Locate the **Legend** section. From the **Position** list, choose **Lower left**.

Global 1

1 Right-click **T60 - Estimates and Model** and choose **Global**.

2 In the **Settings** window for **Global**, locate the **y-Axis Data** section.

3 In the table, enter the following settings:

Expression	Unit	Description
T60_S	s	Reverberation time (Sabine)
T60_Sna	s	Reverberation time (Sabine, no air absorption)
T60_E	s	Reverberation time (Eyring)

4 Locate the **x-Axis Data** section. From the **Axis source data** list, choose **f0**.

5 Click to expand the **Coloring and Style** section. Find the **Line markers** subsection. From the **Marker** list, choose **Star**.

Table Graph 1

1 In the **Model Builder** window, right-click **T60 - Estimates and Model** and choose **Table Graph**.

2 In the **Settings** window for **Table Graph**, locate the **Data** section.

3 From the **x-axis data** list, choose **fc (Hz)**.

4 From the **Plot columns** list, choose **Manual**.

5 In the **Columns** list, select **T60 (s)**.

6 Locate the **Coloring and Style** section. Find the **Line markers** subsection. From the **Marker** list, choose **Circle**.

7 Click to expand the **Legends** section. Select the **Show legends** check box.

8 Find the **Prefix and suffix** subsection. In the **Suffix** text field, type - Ray acoustics.

9 In the **T60 - Estimates and Model** toolbar, click **Plot**.

This should reproduce the image in Figure 9.

Definition

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, type Definition in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study 1 - Omnidirectional Source/ Parametric Solutions 1 (sol2)**.

4 From the **Time selection** list, choose **First**.

5 Click to expand the **Title** section. From the **Title type** list, choose **Label**.

6 Locate the **Plot Settings** section.

7 Select the **x-axis label** check box. In the associated text field, type f_c (Hz).

8 Select the **y-axis label** check box. In the associated text field, type D (%).

9 Locate the **Axis** section. Select the **Manual axis limits** check box.

10 In the **x minimum** text field, type 120.

11 In the **x maximum** text field, type 8322.

12 In the **y minimum** text field, type 0.

13 In the **y maximum** text field, type 100.

14 Select the **x-axis log scale** check box.

15 Locate the **Legend** section. From the **Position** list, choose **Upper left**.

Global 1

1 Right-click **Definition** and choose **Global**.

2 In the **Settings** window for **Global**, locate the **y-Axis Data** section.

3 In the table, enter the following settings:

Expression	Unit	Description
D	s	Definition estimate

4 Locate the **x-Axis Data** section. From the **Axis source data** list, choose **f0**.

5 Click to expand the **Coloring and Style** section. Find the **Line markers** subsection. From the **Marker** list, choose **Star**.

Table Graph 1

1 In the **Model Builder** window, right-click **Definition** and choose **Table Graph**.

2 In the **Settings** window for **Table Graph**, locate the **Data** section.

3 From the **x-axis data** list, choose **fc (Hz)**.

4 From the **Plot columns** list, choose **Manual**.

5 In the **Columns** list, select **D (%)**.

6 Locate the **Coloring and Style** section. Find the **Line markers** subsection. From the **Marker** list, choose **Circle**.

7 Click to expand the **Legends** section. Select the **Show legends** check box.

8 Find the **Prefix and suffix** subsection. In the **Suffix** text field, type `- Ray acoustics`.

9 In the **Definition** toolbar, click **Plot**.

This should reproduce the first image in .

Clarity

1 Right-click **Definition** and choose **Duplicate**.

2 In the **Settings** window for **1D Plot Group**, type `Clarity` in the **Label** text field.

3 Locate the **Plot Settings** section. In the **y-axis label** text field, type `C80 (dB)`.

4 Locate the **Axis** section. In the **x minimum** text field, type `120`.

5 In the **x maximum** text field, type `8322`.

6 In the **y minimum** text field, type `-1`.

7 In the **y maximum** text field, type `9`.

Global 1

1. In the **Model Builder** window, expand the **Clarity** node, then click **Global 1**.
2. In the **Settings** window for **Global**, locate the **y-Axis Data** section.
3. In the table, enter the following settings:

Expression	Unit	Description
`C80`		`Clarity 80 estimate`

Table Graph 1

1. In the **Model Builder** window, click **Table Graph 1**.
2. In the **Settings** window for **Table Graph**, locate the **Data** section.
3. In the **Columns** list, select **C80 (dB)**.
4. In the **Clarity** toolbar, click **Plot**.

   This should reproduce the second image in .

Center Time

1. In the **Model Builder** window, right-click **Clarity** and choose **Duplicate**.
2. In the **Settings** window for **1D Plot Group**, type `Center Time` in the **Label** text field.
3. Locate the **Plot Settings** section. In the **y-axis label** text field, type `ts (s)`.
4. Locate the **Axis** section. In the **x minimum** text field, type `120`.
5. In the **x maximum** text field, type `8322`.
6. In the **y minimum** text field, type `0`.
7. In the **y maximum** text field, type `0.2`.
8. Locate the **Legend** section. From the **Position** list, choose **Lower left**.

Global 1

1. In the **Model Builder** window, expand the **Center Time** node, then click **Global 1**.
2. In the **Settings** window for **Global**, locate the **y-Axis Data** section.
3. In the table, enter the following settings:

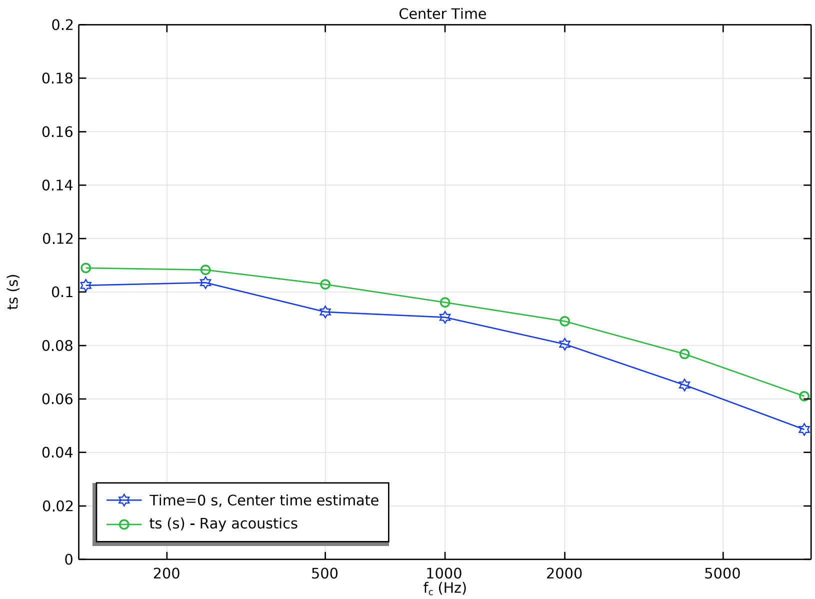
Expression	Unit	Description
`ts`		`Center time estimate`

Table Graph 1

1. In the **Model Builder** window, click **Table Graph 1**.
2. In the **Settings** window for **Table Graph**, locate the **Data** section.

3 In the **Columns** list, select **ts (s)**.

4 In the **Center Time** toolbar, click **Plot**.



Reverberation Times

1 In the **Model Builder** window, right-click **Center Time** and choose **Duplicate**.

2 In the **Settings** window for **1D Plot Group**, type `Reverberation Times` in the **Label** text field.

3 Locate the **Plot Settings** section. In the **y-axis label** text field, type `RT (s)`.

4 Locate the **Axis** section. In the **x minimum** text field, type `120`.

5 In the **x maximum** text field, type `8322`.

6 In the **y minimum** text field, type `0`.

7 In the **y maximum** text field, type `1.6`.

Global 1

1 In the **Model Builder** window, expand the **Reverberation Times** node.

2 Right-click **Results>Reverberation Times>Global 1** and choose **Delete**.

Table Graph 1

1 In the **Model Builder** window, under **Results>Reverberation Times** click **Table Graph 1**.

2 In the **Settings** window for **Table Graph**, locate the **Data** section.

3 In the **Columns** list, choose **EDT (s)**, **T20 (s)**, **T30 (s)**, and **T60 (s)**.

4 In the **Reverberation Times** toolbar, click **Plot**.

This should reproduce the third image in .

Speech Transmission Index

1 In the **Model Builder** window, right-click **Reverberation Times** and choose **Duplicate**.

2 In the **Settings** window for **1D Plot Group**, type `Speech Transmission Index` in the **Label** text field.

3 Locate the **Plot Settings** section. In the **y-axis label** text field, type `STI (1)`.

4 Locate the **Axis** section. In the **x minimum** text field, type `120`.

5 In the **x maximum** text field, type `8322`.

6 In the **y minimum** text field, type `0`.

7 In the **y maximum** text field, type `1`.

8 Locate the **Legend** section. From the **Position** list, choose **Upper left**.

Table Graph 1

1 In the **Model Builder** window, expand the **Speech Transmission Index** node, then click **Table Graph 1**.

2 In the **Settings** window for **Table Graph**, locate the **Data** section.

3 In the **Columns** list, select **STI (1)**.

4 In the **Speech Transmission Index** toolbar, click **Plot**.

This should reproduce the fourth image in .

Center Time, Clarity, Definition, Reverberation Times, Speech Transmission Index

1 In the **Model Builder** window, under **Results**, Ctrl-click to select **Definition**, **Clarity**, **Center Time**, **Reverberation Times**, and **Speech Transmission Index**.

2 Right-click and choose **Group**.

Objective Quality Metric Plots

In the **Settings** window for **Group**, type `Objective Quality Metric Plots` in the **Label** text field.

Next, solve the model with the directional loudspeaker using a parametric sweep that fits the frequency range of the speaker data. The criterion value for ray termination should also be updated to match the source variable.

RAY ACOUSTICS (RAC)

Ray Termination 1

1 In the **Model Builder** window, under **Component 1 (comp1)>Ray Acoustics (rac)** click **Ray Termination 1**.

2 In the **Settings** window for **Ray Termination**, locate the **Termination Criteria** section.

3 In the Q_{th} text field, type `rac.swd2.Q0*1e-7`.

ADD STUDY

1 In the **Home** toolbar, click **Add Study** to open the **Add Study** window.

2 Go to the **Add Study** window.

3 Find the **Studies** subsection. In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces>Ray Tracing**.

4 Click **Add Study** in the window toolbar.

5 In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

STUDY 2 - DIRECTIONAL LOUDSPEAKER

1 In the **Model Builder** window, click **Study 2**.

2 In the **Settings** window for **Study**, type `Study 2 - Directional Loudspeaker` in the **Label** text field.

Step 1: Ray Tracing

1 In the **Model Builder** window, under **Study 2 - Directional Loudspeaker** click **Step 1: Ray Tracing**.

2 In the **Settings** window for **Ray Tracing**, locate the **Study Settings** section.

3 From the **Time unit** list, choose **s**.

4 In the **Output times** text field, type `0 1.6`.

5 Locate the **Physics and Variables Selection** section. Select the **Modify model configuration for study step** check box.

6 In the tree, select **Component 1 (comp1)>Ray Acoustics (rac)>Source with Directivity 1**.

7 Click **Disable**.

Parametric Sweep

1 In the **Study** toolbar, click **Parametric Sweep**.

2 In the **Settings** window for **Parametric Sweep**, locate the **Study Settings** section.

3 Click **Add**.

4 In the table, click to select the cell at row number 1 and column number 2.

5 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
f0 (Band center frequency)		Hz

6 Click **Range**.

7 In the **Range** dialog box, choose **ISO preferred frequencies** from the **Entry method** list.

8 In the **Start frequency** text field, type `63`.

9 In the **Stop frequency** text field, type `4000`.

10 Click **Replace**.

11 In the **Study** toolbar, click **Compute**.

RESULTS

Ray Trajectories (rac) 1

1 In the **Settings** window for **3D Plot Group**, locate the **Data** section.

2 From the **Time (s)** list, choose **Interpolation**.

3 In the **Time** text field, type `1[ms]`.

Ray Trajectories 1

1 In the **Model Builder** window, expand the **Ray Trajectories (rac) 1** node, then click **Ray Trajectories 1**.

2 In the **Settings** window for **Ray Trajectories**, locate the **Coloring and Style** section.

3 Find the **Line style** subsection. From the **Type** list, choose **None**.

4 Find the **Point style** subsection. From the **Type** list, choose **Point**.

Color Expression 1

1 In the **Model Builder** window, expand the **Ray Trajectories 1** node, then click **Color Expression 1**.

2 In the **Settings** window for **Color Expression**, locate the **Expression** section.

3 In the **Expression** text field, type `rac.Lp`.

4 In the **Ray Trajectories (rac) 1** toolbar, click **Plot**.

This should reproduce the image in Figure 12.

Loudspeaker Orientation

1 In the **Home** toolbar, click **Add Plot Group** and choose **3D Plot Group**.

2 In the **Settings** window for **3D Plot Group**, type `Loudspeaker Orientation` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study 2 - Directional Loudspeaker/ Solution 10 (sol10)**.

4 Click to expand the **Selection** section. From the **Geometric entity level** list, choose **Point**.

5 Select Point 11 only.

Coordinate System Point 1

1 Right-click **Loudspeaker Orientation** and choose **More Plots>Coordinate System Point**.

2 In the **Settings** window for **Coordinate System Point**, locate the **Coordinate System** section.

3 From the **Coordinate system** list, choose **Rotated System 2 (sys2)**.

4 Locate the **Coloring and Style** section.

5 Select the **Scale factor** check box. In the associated text field, type `2`.

6 In the **Loudspeaker Orientation** toolbar, click **Plot**.

This should reproduce the image in .

Seats SPL 1

1 In the **Model Builder** window, right-click **Seats SPL** and choose **Duplicate**.

2 In the **Settings** window for **3D Plot Group**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 2 - Directional Loudspeaker/ Parametric Solutions 2 (sol11)**.

4 In the **Seats SPL 1** toolbar, click **Plot**.

This should reproduce the image in Figure 13.

Geometry Modeling Instructions

From the **File** menu, choose **New**.

NEW

In the **New** window, click **Blank Model**.

ADD COMPONENT

In the **Home** toolbar, click **Add Component** and choose **3D**.

GEOMETRY 1

Import 1 (imp1)

1 In the **Home** toolbar, click **Import**.

2 In the **Settings** window for **Import**, locate the **Import** section.

3 Click **Browse**.

4 Browse to the model's Application Libraries folder and double-click the file `small_concert_hall.mphbin`.

5 Click **Import**.

6 Click the **Wireframe Rendering** button in the **Graphics** toolbar.

Delete Entities 1 (del1)

1 In the **Model Builder** window, right-click **Geometry 1** and choose **Delete Entities**.

2 On the object **imp1**, select Boundary 40 only.

Extrude 1 (ext1)

1 In the **Geometry** toolbar, click **Extrude**.

2 On the object **del1**, select Boundary 39 only.

3 In the **Settings** window for **Extrude**, locate the **Distances** section.

4 Select the **Reverse direction** check box.

5 Click **Build Selected**.

Delete Entities 2 (del2)

1 Right-click **Geometry 1** and choose **Delete Entities**.

2 On the object **ext1**, select Boundary 41 only.

Windows

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, type `Windows` in the **Label** text field.

3 Locate the **Entities to Select** section. From the **Geometric entity level** list, choose **Boundary**.

4 On the object **del2**, select Boundaries 63–65 only.

Seats

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, type `Seats` in the **Label** text field.

3 Locate the **Entities to Select** section. From the **Geometric entity level** list, choose **Boundary**.

4 On the object **del2**, select Boundaries 39–42 and 59 only.

Diffusers

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, type `Diffusers` in the **Label** text field.

3 Locate the **Entities to Select** section. From the **Geometric entity level** list, choose **Boundary**.

4 On the object **del2**, select Boundaries 13, 15, 29, 30, 43, 44, 51, and 52 only.

Floor

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, type `Floor` in the **Label** text field.

3 Locate the **Entities to Select** section. From the **Geometric entity level** list, choose **Boundary**.

4 On the object **del2**, select Boundaries 3, 8, 12, 14, 18, and 21 only.

Entrance

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, type `Entrance` in the **Label** text field.

3 Locate the **Entities to Select** section. From the **Geometric entity level** list, choose **Boundary**.

4 On the object **del2**, select Boundaries 16, 19, 20, 23, 31, and 32 only.

Walls

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, type `Walls` in the **Label** text field.

3 Locate the **Entities to Select** section. From the **Geometric entity level** list, choose **Boundary**.

4 On the object **del2**, select Boundaries 1, 2, 4–7, 9–11, 17, 22, 24–28, 34–37, 45–50, 53–58, and 60–62 only.

Absorbers

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, type `Absorbers` in the **Label** text field.

3 Locate the **Entities to Select** section. From the **Geometric entity level** list, choose **Boundary**.

4 On the object **del2**, select Boundaries 33 and 38 only.

Form Union (fin)

1 In the **Model Builder** window, click **Form Union (fin)**.

2 In the **Settings** window for **Form Union/Assembly**, click **Build Selected**.