Created in COMSOL Multiphysics 5.6

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, 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” are analyzed. 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 listening environment is fitted with absorbers and diffusers; their location is not particularly optimized and does probably not follow design rules. The aim of this tutorial is to describe the important modeling steps to perform a room acoustics simulation using ray tracing. The geometry of the concert hall is depicted in Figure 1.

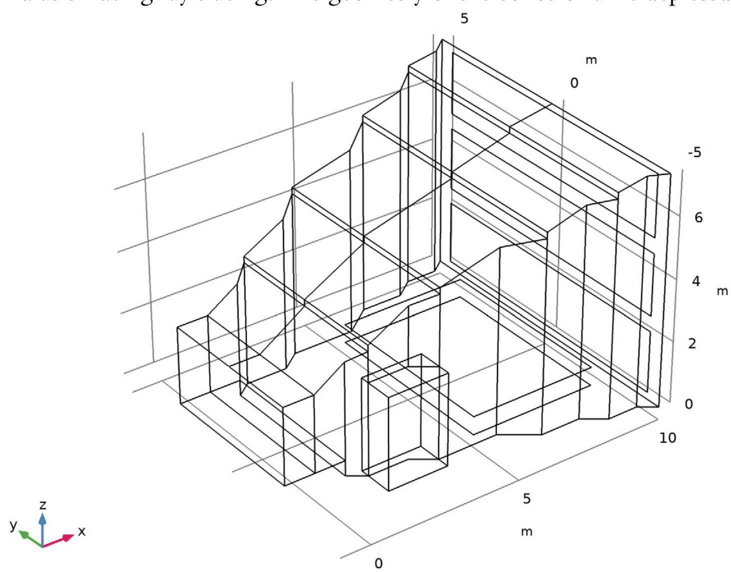


Figure 1: Geometry of the small concert hall.

An omnidirectional source is located at the coordinates (x_s, y_s, z_s) near 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_r, y_r, z_r). These are parameters found under **Global Definitions > Parameters 1**. 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 absorption properties of the various surfaces (windows, seats, diffusers, floor, entrance, walls, and absorbers) are generic values taken from Ref. 1 and 2. The data is given in octave band values and imported from the file `small_concert_hall_absorption_parameters.txt` file into an interpolation function (lookup table). Moreover, the (intensity) attenuation of air is imported from the file `small_concert_hall_volume_absorption.txt`. Note that when the attenuation coefficient m (loaded from the file) is entered in the **Material Properties of Exterior and Unmeshed Domains** section, it is the amplitude attenuation $\alpha_{ext} = 0.5 \cdot m$ that should be used.

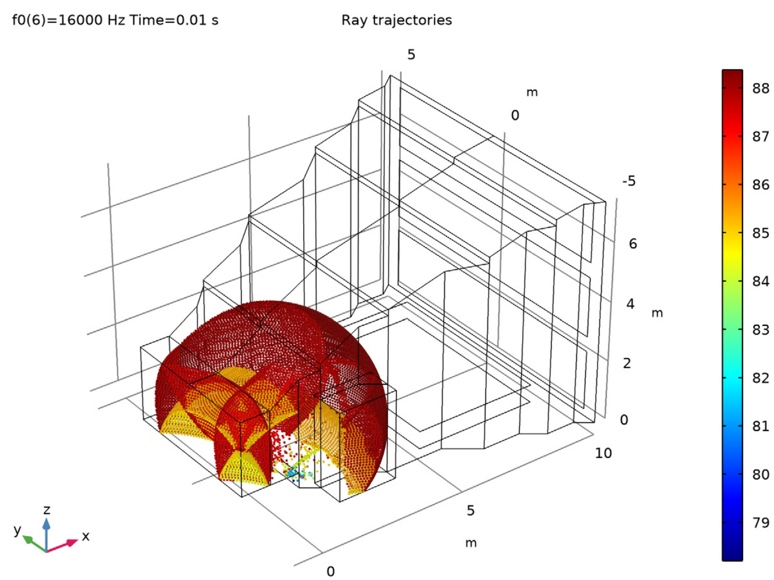


Figure 2: Ray location and SPL after 10 ms.

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 16 kHz frequency band. At this frequency the volume attention is the largest. 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 make the model run slightly faster and reduce the number of degrees of freedom (DOFs) solved for. The **Count reflections** option is also necessary when analyzing the IR.

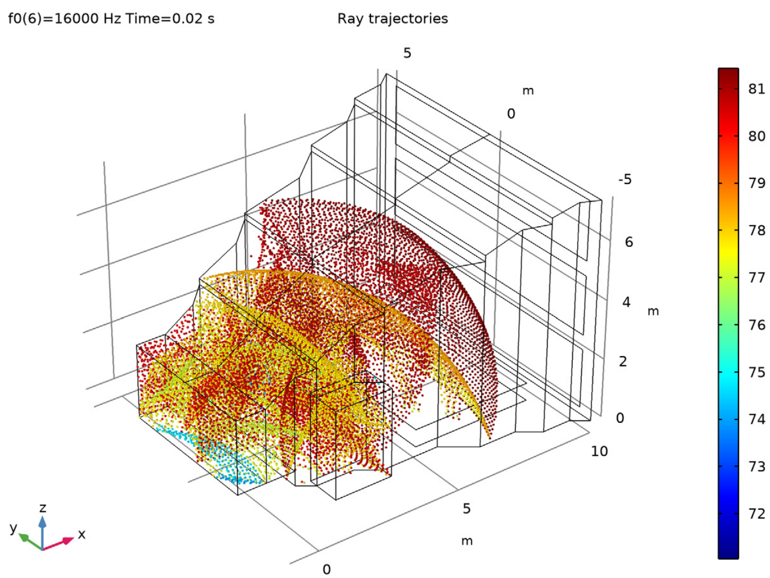


Figure 3: Ray location and field SPL after 20 ms.

The temporal impulse response (IR) for the default source location configuration used in the model is depicted in Figure 4. The frequency domain (FFT) of the IR is depicted in Figure 5. No smoothing nor windowing is used in the plot. 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, definition D, early decay time EDT, center time t_s, reverberation times T_{20}, T_{30}, T_{60}, and the STI. The level decay curves for the 6 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 > Tabels**). The values are depicted graphically in Figure 9 and Figure 10.

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 (this model uses 20,000) 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.

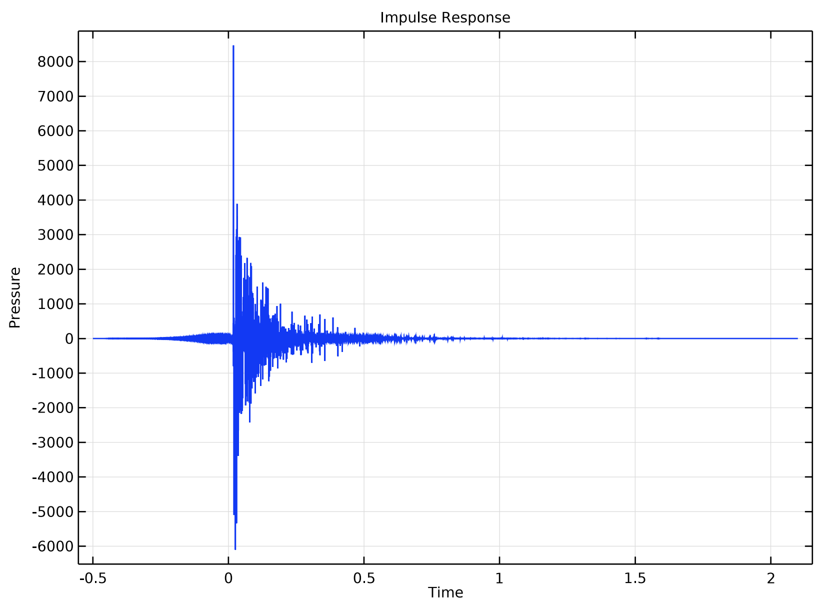


Figure 4: Temporal impulse response computed at the receiver location.

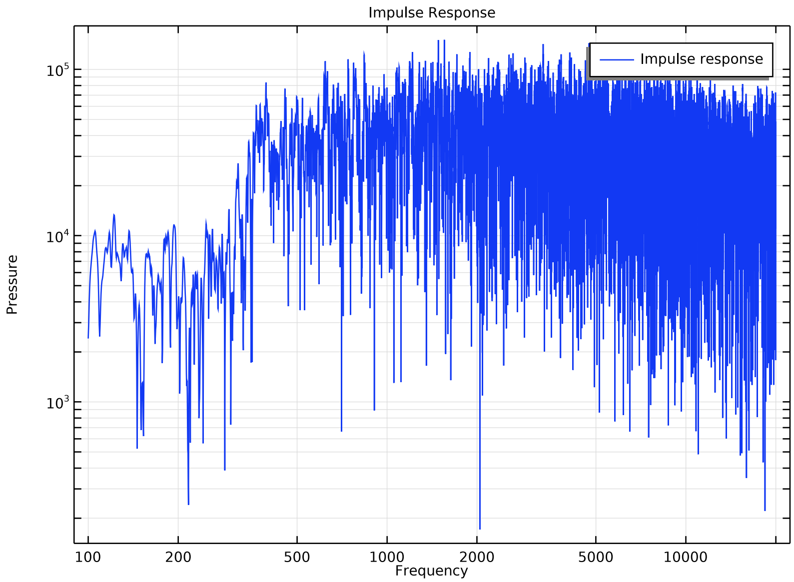


Figure 5: FFT of the impulse response (no smoothing/windowing is used).

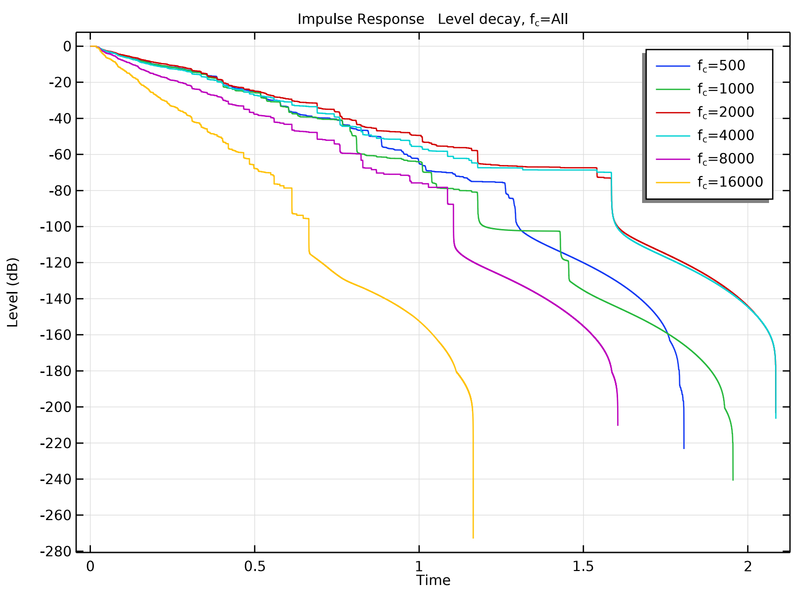


Figure 6: Level decay curves for the 6 octave bands used in the model.

The sound pressure level in a cross section located above the seating section is depicted in Figure 7 for the 16 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 a transparent surface (**Pass through** used as **Wall condition**). The feature can be added to all other walls to postprocess the SPL distribution there if necessary.

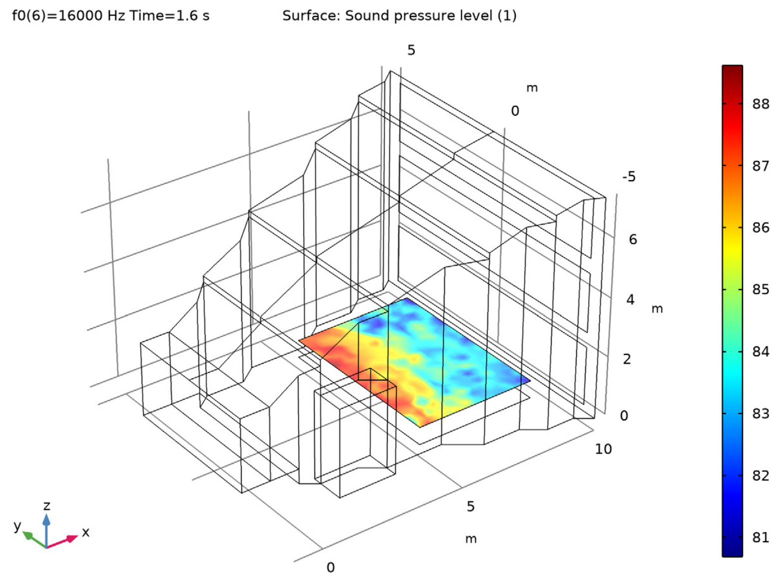


Figure 7: SPL in a cross section 60 cm above the ground at the location of the audience.

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, for example, Ref. 3). The intensity is evaluated using the expression `re1dist*rac.Q/re1vol`. Plotting this information in a **Ray** plot as function of the arrival time yields the (discrete time) energy impulse response or reflectogram. It is plotted for the 500 Hz and the 16 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 (60 dB down which is 6 decades for $\log_{10}(I_{\mathrm{n}})$) gives an estimate of the T_{60} reverberation time. In this case about 0.5 s for the 16 kHz band and 1 s for the 500 Hz band. These values are seen to fit well with the computed values below.

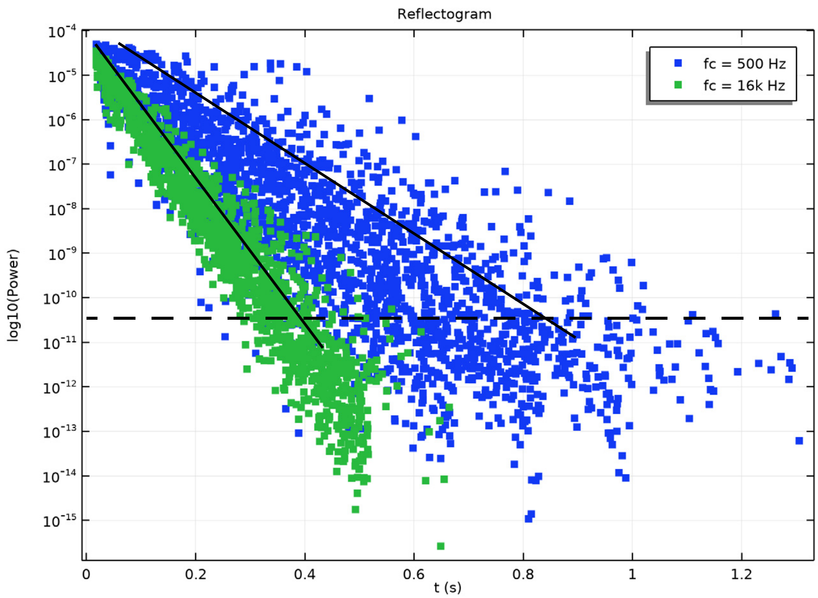


Figure 8: The raw data of the energetic impulse response or reflectogram. The slope represents the reverberation time in the given octave band.

A comparison between the computed value of T_{60} 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

$$T_{60,S} = 0.161[\mathrm{s/m}]\frac{V}{S\bar{\alpha} + 4mV}$$

$$T_{60,E} = 0.161[\mathrm{s/m}]\frac{V}{-S\ln(1-\bar{\alpha}) + 4mV}$$

where V is the room volume, S is the total surface area, m is the volume attenuation, and $\bar{\alpha}$ is the average wall absorption (see Ref. 2). The results show quantitative agreement. It is not expected that the Sabine and Eyring predictions match the more detailed ray tracing results exactly.

Selected room acoustic metrics are plotted as function of the octave band center frequency in Figure 10. The definition, the clarity, and the center time 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**.

Definition (D or D_{50}) gives a metric for syllable intelligibility. In this room it is above 50% for all bands which is acceptable. The clarity metric C_{80} is used to characterize the transparency of music, for concert halls typical values lie between -5 to +3 dB. In this case the design is not optimal for the higher octave bands. The center time is another metric that correlates to speech intelligibility. All metrics should be estimated taking their just noticeable difference (JND) into account.

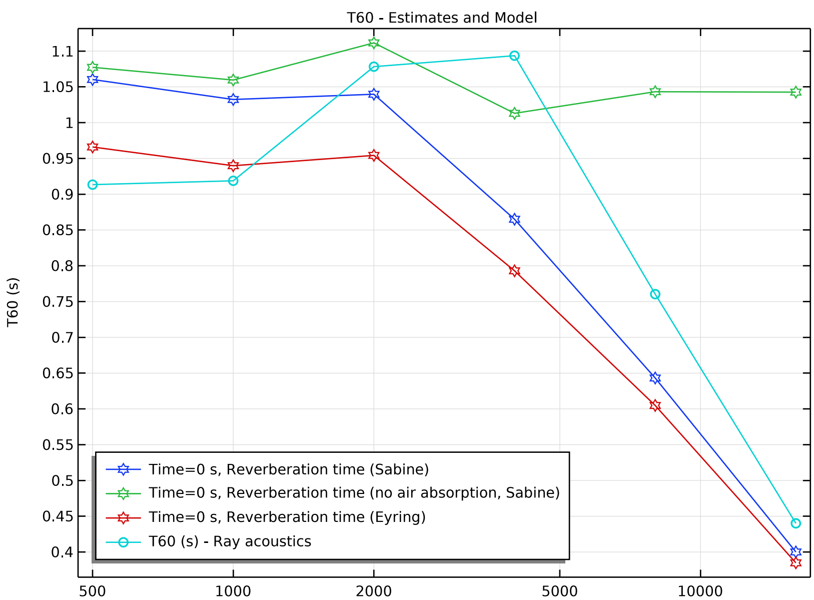


Figure 9: Reverberation time estimates based on the Sabine and Eyring formula compared to the computed reverberation time.

The speech transmission index STI is a single valued metric for speech intelligibility. It is based on modulation transfer function values (14 frequencies) and 7 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 7 bands. To get the single metric, change the **Band type** to **Broadband**. Making these changes this gives a STI value of 0.63 (this indicates good intelligibility). Note that the standard does specify using also the 125 and 250 Hz octave bands (they are not included in this model). The STI values plotted as 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 each band contribute with the appropriate weighting.

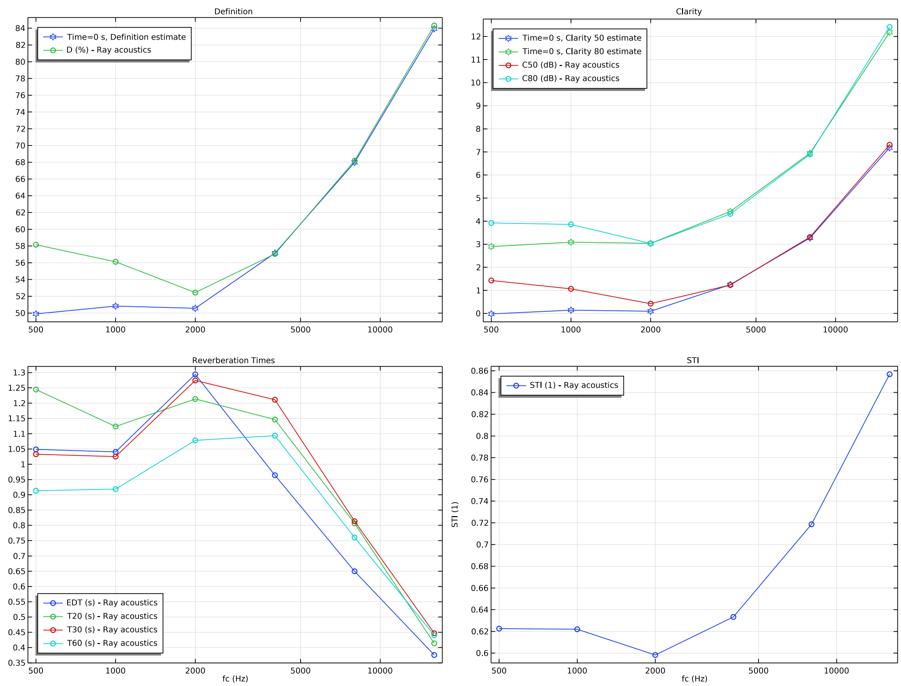


Figure 10: Objective room acoustic metrics clarity, definition, reverberation times, and STI plotted as function of octave band center frequency. The clarity and definition metrics are compared to analytical estimates. The center time (not shown here) can be seen in the plots in the model.

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.

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. 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 Absorptive Muffler model. They are followed by the Geometry Sequence 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

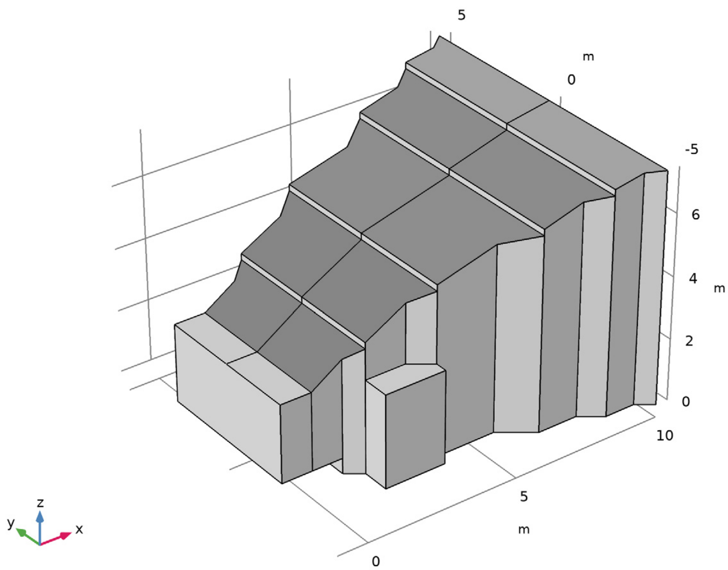
The geometry is set up by importing a geometry sequence. The sequence imports the small concert hall geometry and sets up several selections. The predefined selections simplify the rest of the model setup.

1 In the **Geometry** toolbar, click **Insert Sequence**.

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 **Zoom Extents** button in the **Graphics** toolbar.



Import the model parameters form a file. 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

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.

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

3 Click **Load from File**.

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

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 intensity attenuation of air (given at 50 % relative humidity and 20 deg. C).

Interpolation 1 (int1)

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 **Arguments** text field, type `Hz`.

11 In the **Function** text field, type `1`.

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_volume_absorption.txt`.

6 Click **Import**.

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

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

9 Locate the **Units** section. In the **Arguments** text field, type `Hz`.

10 In the **Function** text field, type `1/m`.

Now 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, definition, and center time. This also requires setting up integration operators for all the surfaces.

DEFINITIONS

Variables: Quality Metric Estimates

1 In the **Model Builder** window, expand the **Component 1 (comp1)>Definitions** node.

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

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

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

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

Integration 1 (intop1)

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

2 In the **Settings** window for **Integration**, type `intop_windows` 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 **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**.

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 (boundaries).

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 `0.5*m_air(f0)`.

Multiplication by 0.5 is necessary as the input in COMSOL is defined for the amplitude attenuation and not the intensity attenuation (as given in the interpolation data).

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 **Specular reflection**.

5 Locate the **Reflection Coefficient Model** section. In the α 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 **Specular reflection**.

5 Locate the **Reflection Coefficient Model** section. In the α 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 **Specular reflection**.

5 Locate the **Reflection Coefficient Model** section. In the α 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 **Specular reflection**.

5 Locate the **Reflection Coefficient Model** section. In the α 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: Seats

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

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

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

4 Locate the **Wall Condition** section. From the **Wall condition** list, choose **Specular reflection**.

5 Locate the **Reflection Coefficient Model** section. In the α text field, type `a_seats(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 **Specular reflection**.

5 Locate the **Reflection Coefficient Model** section. In the α text field, type `a_absorbers(f0)`.

Wall: SPL cross section

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

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

3 Locate the **Wall Condition** section. From the **Wall condition** list, choose **Pass through**.

The **Pass through** option is used here as this surface only is meant for visualizing the SPL in a cross section. Use **Wireframe** rendering to select the surface that is located inside the concert hall.

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

5 Select Boundary 40 only.

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.

Release from Grid 1

1 In the **Physics** toolbar, click **Global** and choose **Release from Grid**.

2 In the **Settings** window for **Release from Grid**, locate the **Initial Coordinates** section.

3 In the $q_{x,0}$ text field, type `x_s`.

4 In the $q_{y,0}$ text field, type `y_s`.

5 In the $q_{z,0}$ text field, type `z_s`.

6 Locate the **Ray Direction Vector** section. From the **Ray direction vector** list, choose **Spherical**.

7 In the N_w text field, type `Nrays`.

8 Locate the **Total Source Power** section. In the P_{src} text field, type `P0`.

Ray Termination 1

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

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 **Intensity**.

5 In the I_{th} text field, type `1e-14[W/m^2]`.

MESH 1

Free Triangular 1

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

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

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

Size

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

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

3 From the **Predefined** list, choose **Finer**.

Size 1

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

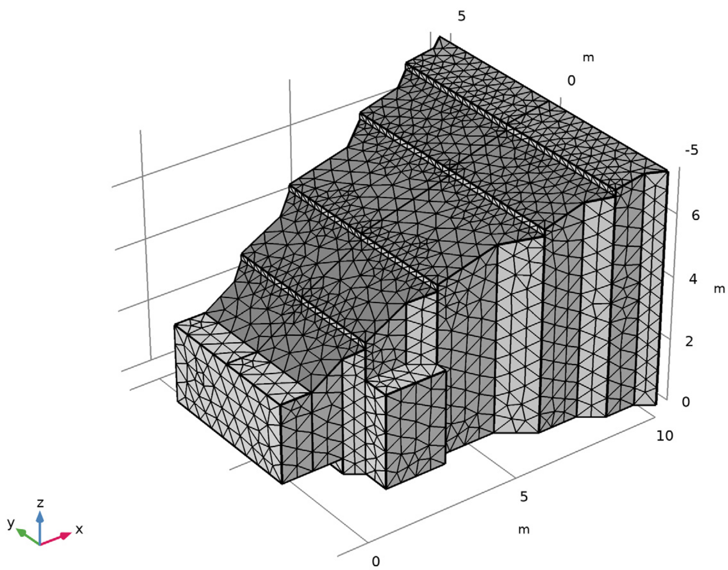
4 Select Boundary 40 only.

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

6 Locate the **Element Size Parameters** section. Select the **Maximum element size** check box.

7 In the associated text field, type `0.3`.

8 Click **Build All**.



Proceed and solve the model 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

Step 1: Ray Tracing

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

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 Click **Range**.

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

6 In the **Start frequency** text field, type `500`.

7 In the **Stop frequency** text field, type `20000`.

8 Click **Replace**.

   Solving the model takes a couple of minutes and uses less than 2 GB of RAM (depending on your hardware). This will increase for an increasing number of rays.

9 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, 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.

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.

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

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

7 Select the **Only plot when requested** check box.

8 Locate the **Save Data in the Model** section. From the **Save plot data** list, choose **On**.

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 **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_r`.

5 In the **y** text field, type `y_r`.

6 In the **z** text field, type `z_r`.

7 Find the **Radius** subsection. In the **Number of rays** text field, type `Nrays`.

8 In the **Room volume** text field, type `Vol`.

9 In the **Source-receiver distance** text field, type `dsr`.

The default **Expression** option for the receiver radius is good for classical room acoustics applications (like in this example). If ray tracing is used in smaller spaces, like a car cabin, it is recommended to switch to a user defined radius.

Receiver 3D - 500 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 - 500 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 **500**.

Receiver 3D - 16 kHz Band

1 In the **Model Builder** window, right-click **Receiver 3D - 500 Hz Band** and choose **Duplicate**.

2 In the **Settings** window for **Receiver 3D**, type `Receiver 3D - 16 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 **16000**.

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.

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 **Quantization level** 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**.
6. From the **Plot** list, choose **Level decay**.
7. Right-click **Energy Decay 1** and choose **Show Legends**.
8. In the **Impulse Response** toolbar, click **Plot**.

   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 **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. Select the **y-axis log scale** check box.

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 **Frequency spectrum**.
4. Select the **Frequency range** check box.
5. In the **Minimum** text field, type `100`.

6 In the **Maximum** text field, type 20000.

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

This should reproduce the image in Figure 5.

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

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

10 Clear the **Only plot when requested** check box.

Cross Section 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 Cross Section SPL in the **Label** text field.

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

Surface 1

1 Right-click **Cross Section 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.wall9.spl1.Iw>rac.wall9.spl1.Lp - Sound pressure level - dB**.

3 In the **Cross Section SPL** toolbar, click **Plot**.

This should reproduce the image in Figure 7. The 16 kHz band is chosen per default. A smoothed variable for the SPL also exists rac.wall9.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. Select the **x-axis label** check box.

5 In the associated text field, type t (s).

6 Select the **y-axis label** check box.

7 In the associated text field, type log10(Power).

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

9 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 - 500 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 From the **Positioning** list, choose **In data points**.

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

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

10 In the table, enter the following settings:

Legends
fc = 500 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 - 16 kHz Band**.

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

Legends
fc = 16k 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/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 **Axis** section. Select the **x-axis log scale** check box.

7 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 (no air absorption, Sabine)
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**.

6 From the **Positioning** list, choose **In data points**.

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 From the **Positioning** list, choose **In data points**.

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

9 In the **Suffix** text field, type `- Ray acoustics`.

10 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/ 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 **Axis** section. Select the **x-axis log scale** check box.

7 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**.

6 From the **Positioning** list, choose **In data points**.

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 From the **Positioning** list, choose **In data points**.

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

9 In the **Suffix** text field, type `- Ray acoustics`.

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

Clarity

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

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

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
C50		Clarity 50 estimate
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, choose **C50 (dB)** and **C80 (dB)**.

4 In the **Clarity** toolbar, click **Plot**.

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

Global 1

1. In the **Model Builder** window, expand the **Reverberation Times** node.
2. Right-click **Global 1** and choose **Delete**.

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, choose **EDT (s)**, **T20 (s)**, **T30 (s)**, and **T60 (s)**.
4. In the **Reverberation Times** toolbar, click **Plot**.

STI

1. In the **Model Builder** window, right-click **Reverberation Times** and choose **Duplicate**.
2. In the **Settings** window for **1D Plot Group**, type `STI` in the **Label** text field.
3. Locate the **Legend** section. From the **Position** list, choose **Upper left**.

Table Graph 1

1. In the **Model Builder** window, expand the **STI** 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 **STI** toolbar, click **Plot**.

Center Time, Clarity, Definition, Reverberation Times, STI

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

Geometry Sequence 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.

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 **imp1**, select Boundaries 60–62 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 **imp1**, select Boundary 39 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 **imp1**, select Boundaries 13, 15, 29, 30, 41, 42, 49, and 50 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 **imp1**, 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 **imp1**, 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 **imp1**, select Boundaries 7, 9–11, 17, 22, 24–28, 34–37, 43–48, and 51–59 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 **imp1**, select Boundaries 1, 2, 4–6, 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**.