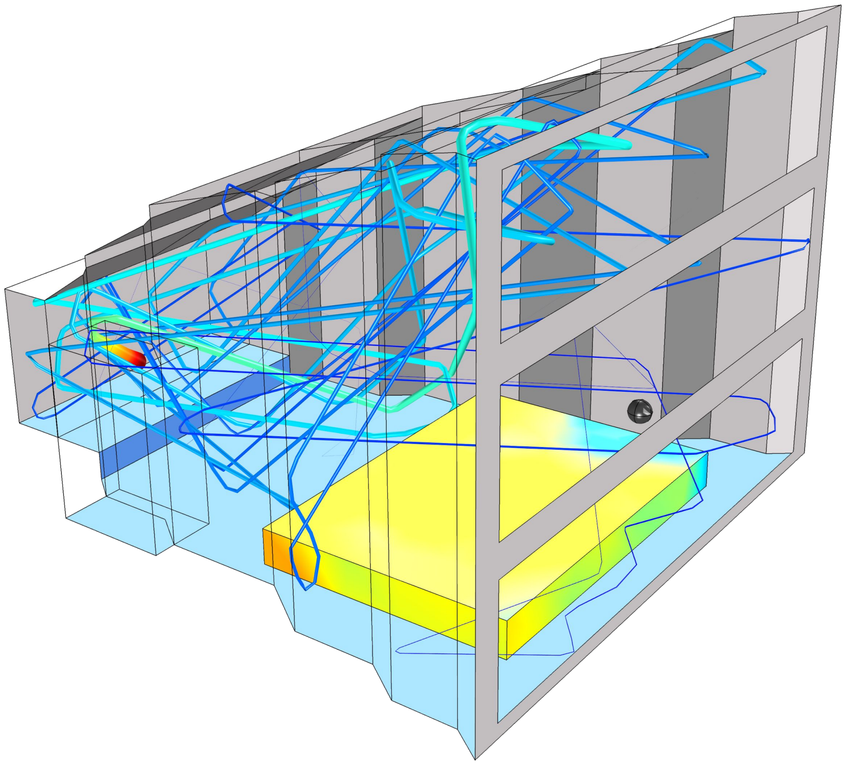
Small Concert Hall Acoustics

Application Gallery #20145



Abstract

- In this model the acoustics of a small concert hall, with a volume of 422.5 m^3, are analyzed using the Ray Acoustics physics interface. The model shows how to:
  - Set up a “microphone” in order to calculate the pressure impulse response and energy impulse response. (Physics Setup 1 slide)
  - Set up an omnidirectional sound source containing one Fourier component (one frequency f_0). (Source slide)
  - And an omnidirectional source containing a frequency distribution (20 frequencies in the 1000 Hz octave band). (Source slide 2)
  - Set up the basic boundary conditions for specular and diffuse scattering including absorption (Wall slides)
  - Use the Sound Pressure Level Calculation feature (sub feature to the Wall) to determine the sound pressure level distribution at the seating area.
  - Compare the energy response to simple room acoustics measures. (Results slides)
  - Set up variables to sum and analyze the impulse response of the source emitting a frequency distribution.

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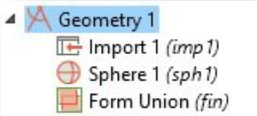
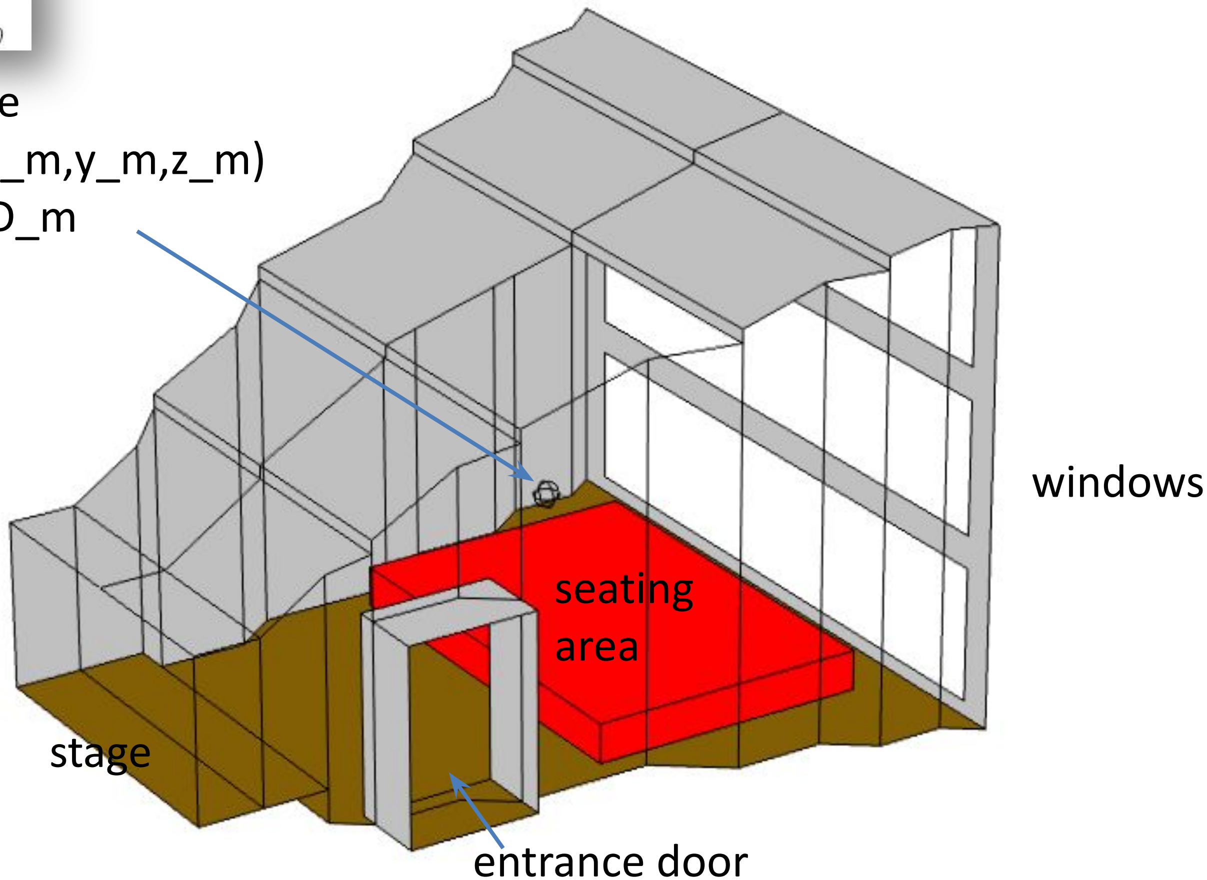
Ray Acoustics Interface

- The Ray Acoustics physics interface is used to compute the trajectories, phase, and intensity of acoustic rays. Ray acoustics is valid in the high-frequency limit where the acoustic wavelength is smaller than the characteristic geometric features. The interface can be used to model acoustics in rooms, concert halls, and many outdoor environments.
- The properties of the media in which the rays propagate can change continuously within domains or discontinuously at boundaries. At exterior boundaries it is possible to assign a variety of wall conditions, including combinations of specular and diffuse reflection. Impedance and absorption can depend on the frequency, intensity, and direction of incident rays. Transmission and reflection are also modeled at material discontinuities. A background velocity may also be assigned to any medium.

Geometry

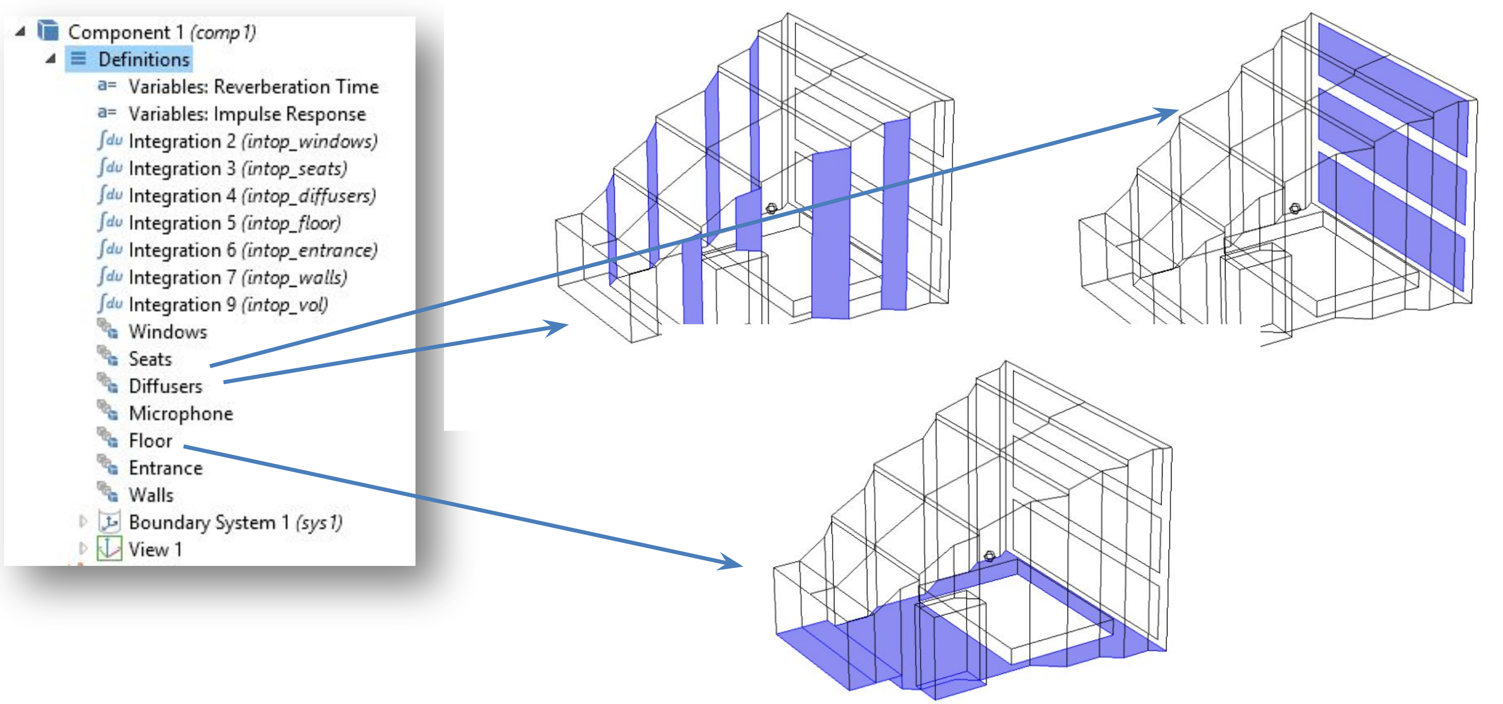


microphone
location: (x_m,y_m,z_m)
diameter: D_m



Definitions: Selections

- Set up selections for the different boundaries



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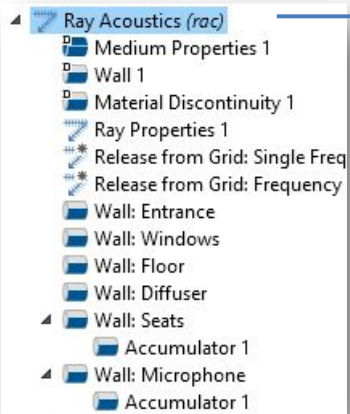
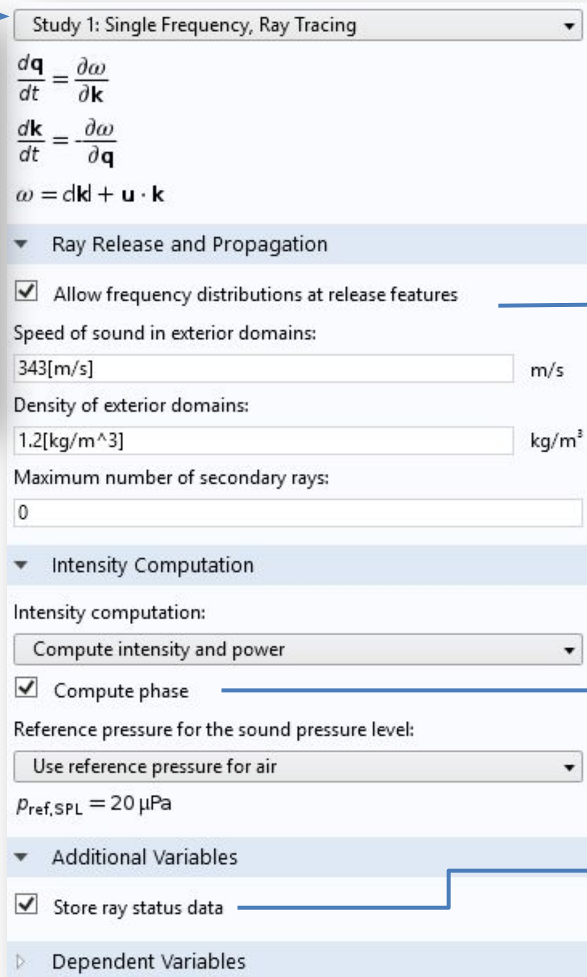
Physics Setup 1





Equation view of the solved Hamiltonian for the ray position **q** and wave vector **k**.

Enable the use of a frequency distribution at the release features, for example, frequency components of an octave band.

Set the number of secondary rays to 0 if the *Material Discontinuity* conditions is not used.

Enable computation of intensity and power along rays.

Compute the phase along rays – essential for correct impulse response evaluation.

Records information about the status and stop time of the rays.

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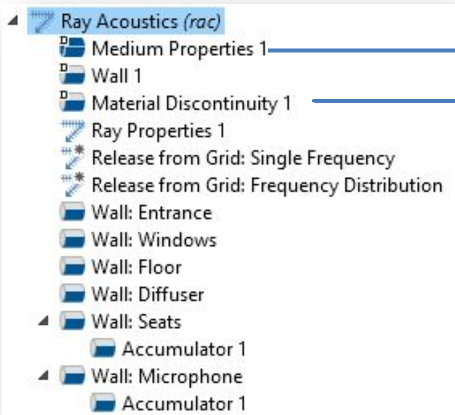
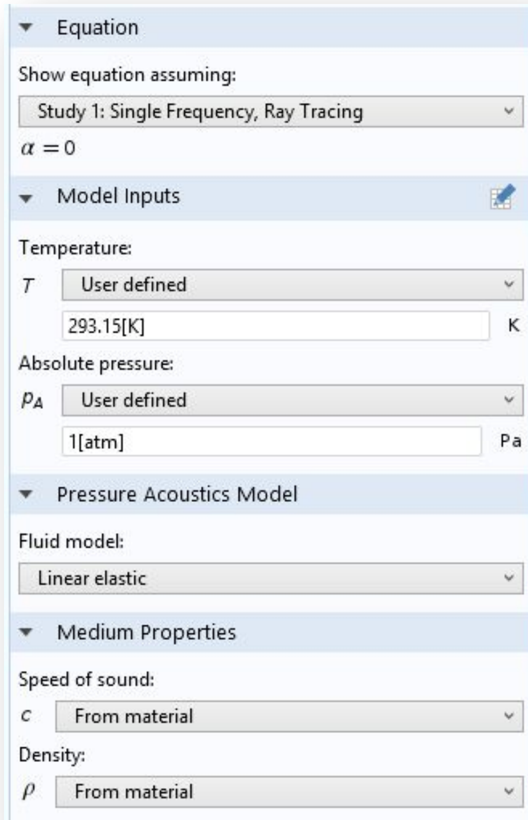
Physics Setup 2



The *Material Discontinuity* condition can be used on interior boundaries between domains with different material properties. The condition will calculate the properties of reflected and refracted rays including phase shifts. Upon arrival a ray is divided into a reflected and a transmitted ray. The condition is not used in this model.



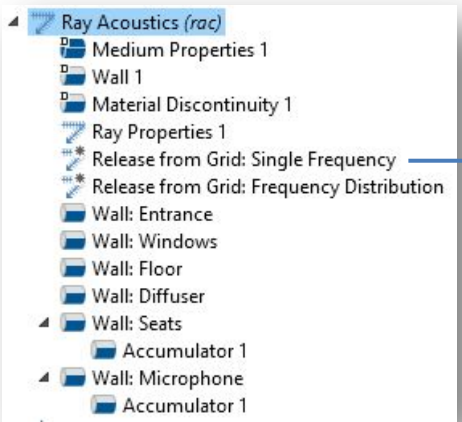
Here the fluid model is set to linear elastic, meaning that there is no bulk attenuation.

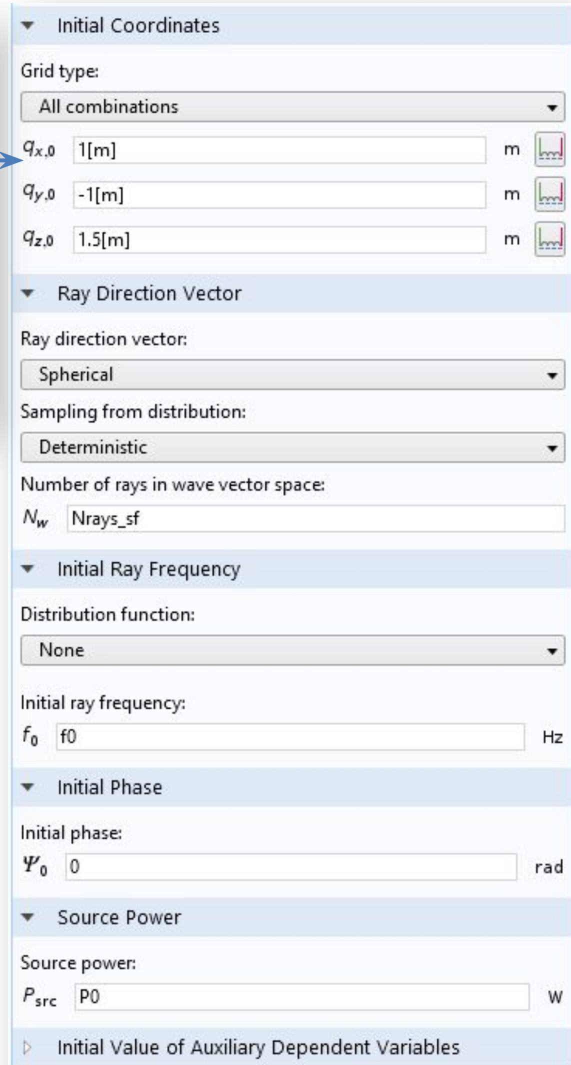
Select *Linear elastic with attenuation* to enter a user defined attenuation (can be a imported interpolation function and can depend on the frequency rac.f).

Or select the predefined loss model for thermal and viscous losses.

Set the medium properties

Source 1: Release from Grid





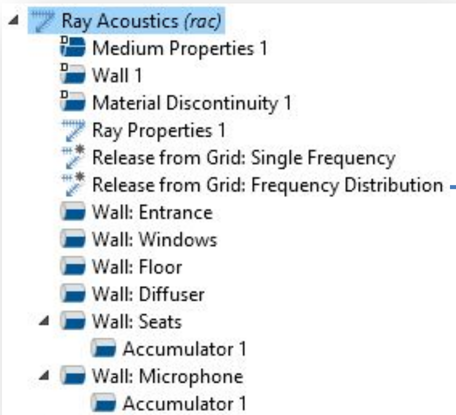
Select the source location or locations (several can be entered)

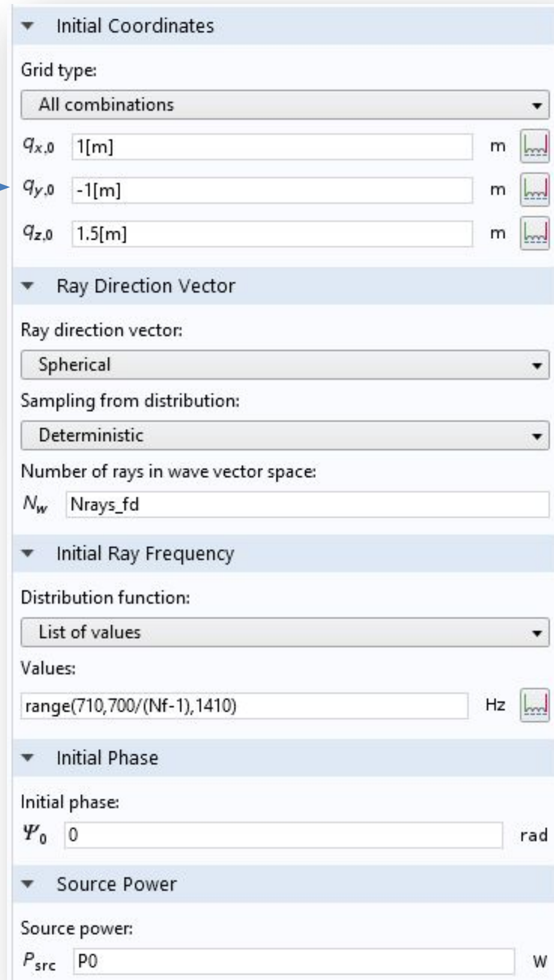
Select the source type: Spherical, Hemisphere , Conical, or Expression. The latter can be used to define complex sources.

Select the frequency content of the released signal. Here only one Fourier component. The frequency f0 is released. Adding a distribution will result in the release of more rays – one for each frequency in each direction (next slide).

Set the initial phase (= 0) and total source power (P0 = 1 W).

Source 2: Release from Grid



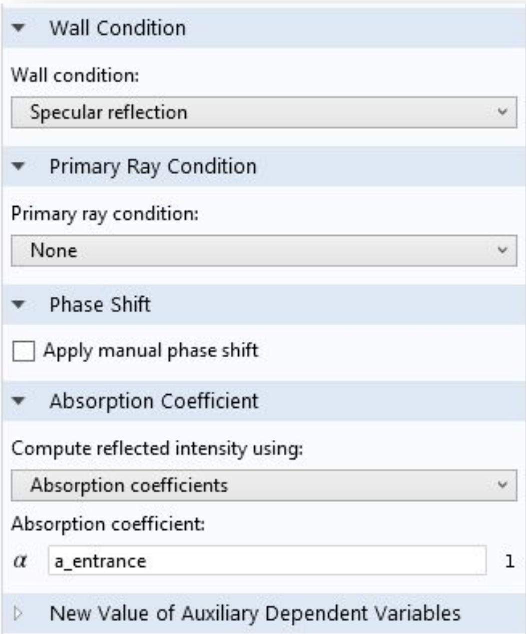


In this second release feature the source is assumed to contain several frequencies. Here 20 values (given by the parameter Nf) between 710 Hz and 1410 Hz. this corresponds to the octave band centered at 1000 Hz.

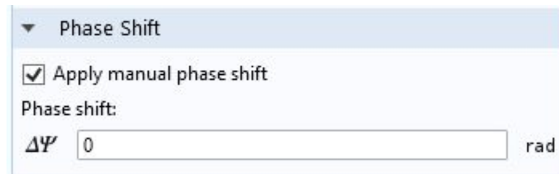
The two sources are used independently in two separate studies.

The total power of the emitted signal remains the same.

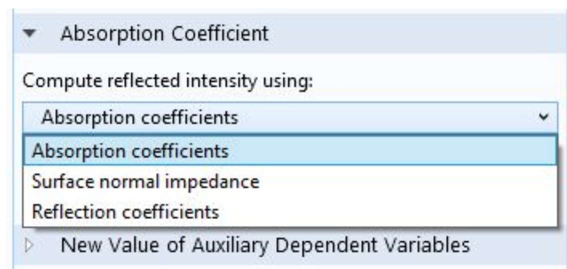
Wall: Specular Reflection



- Specular reflection wall condition
- Optionally manually control the phase shift at a boundary by selecting *Apply manual phase shift*



- Select how to calculate the reflected intensity (defining the absorbed energy)



- The *Absorption coefficient* option (real number) yields a default 0 phase shift
- Impedance or reflection coefficient can be complex valued with corresponding correct phase shift.

All material properties can depend on both the angle of incidence **rac.wall1.thetai** and the ray frequency **rac.f**

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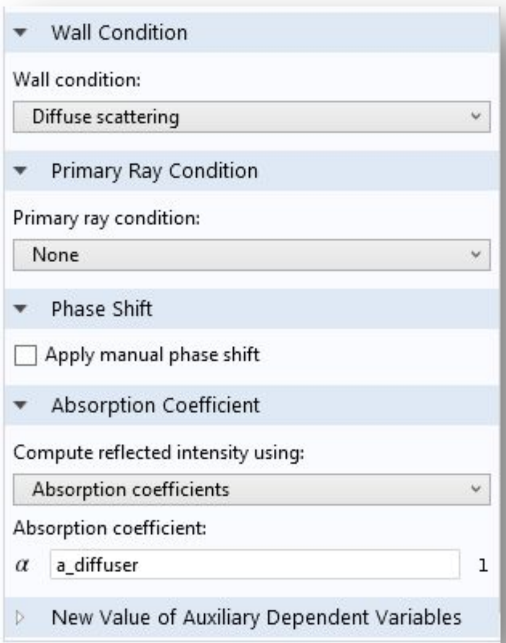
Wall: Diffuse Scattering



- The *Diffuse scattering* wall condition causes the wave to leave the surface in a random direction with a probability given by Lambert's cosine law.

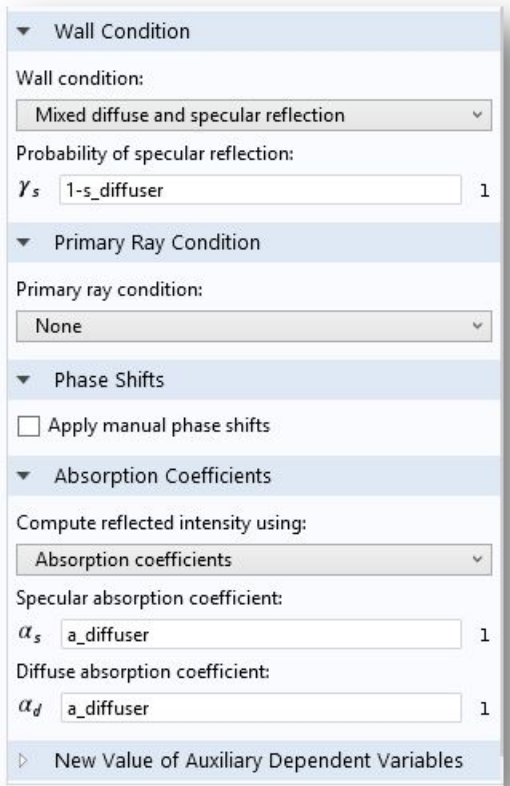
- The intensity of the reflected wave I_r is defined by the absorption coefficient α and the incident intensity I_i such that:

$$I_r = (1 - \alpha) I_i$$

- This is assuming that the scattering coefficient *s* for this purely diffuse reflection is equal to 1.

- This condition is not used in the current model.

Wall: Mixed Specular and Diffuse



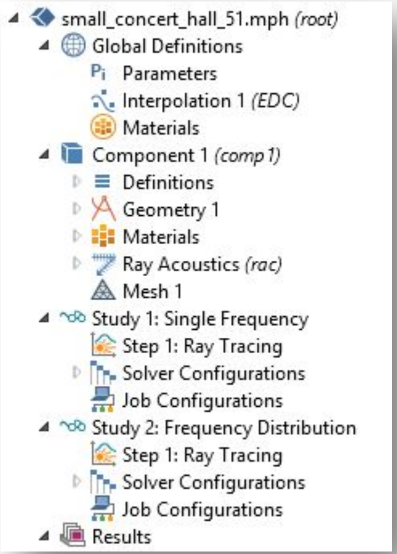
- For a *Mixed diffuse and specular reflection* condition enter the *Probability of specular reflection*. The ray behaves either according to the *Specular reflection condition* or the *Diffuse scattering* condition, based on the *Probability of specular reflection*.
- The intensity of the two reflected wave I_{rs} (specular) and I_{rd} (diffuse) is defined by the two absorption coefficient α_s and α_d, and the incident intensity I_i such that:

$$I_{rs} = (1 - \alpha_s) I_i \text{ and } I_{rd} = (1 - \alpha_d) I_i$$

- If you know the more common absorption coefficient α and the scattering coefficient *s* enter them as:

  - Set the probability of specular reflection to 1-*s*
  - Set both absorption coefficients equal to α

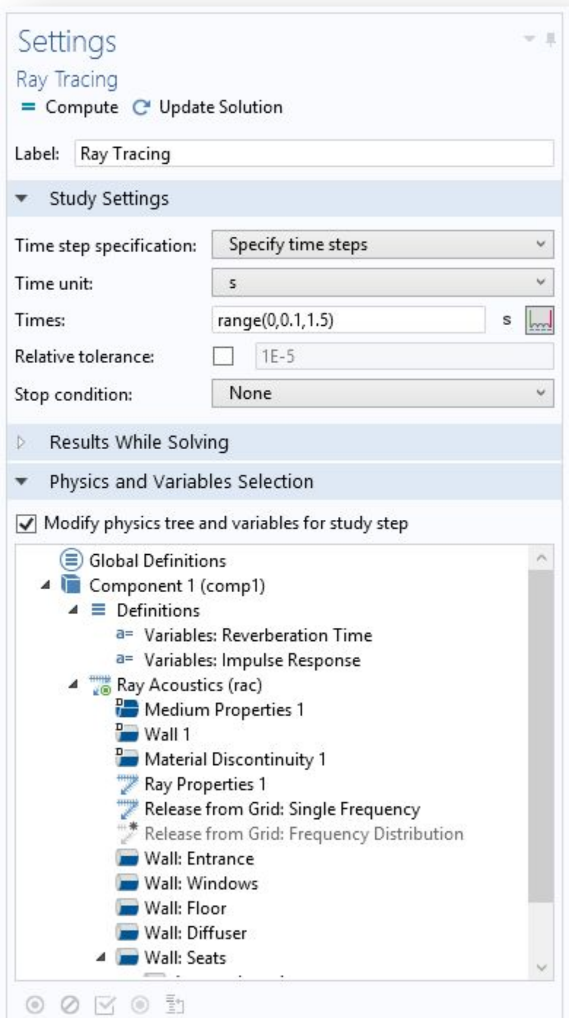
Study 1 and 2



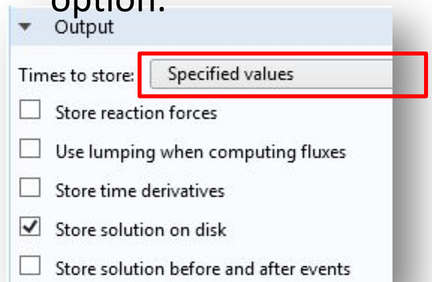
- Two studies are set up:
  - Study 1: Single Frequency: Rays with a singe frequency are emitted by the source (the other release feature is deactivated).
  - Study 2: Frequency Distribution: Rays are emitted with the given frequency content (the single frequency source is deactivated(

- The parameter defining the number of rays release Nrays_sf is set equal to 10000 for the single frequency case. Fir the frequency distribution the parameter Nrays_fd is set equal to 3000 (to decrease the model file size). Increase these number to get a more detailed response.
- In the case of the frequency distribution the nuber of rays emitted is equal to Nrays_fd times the number of frequencies Nf so Nrays_fd*Nf.

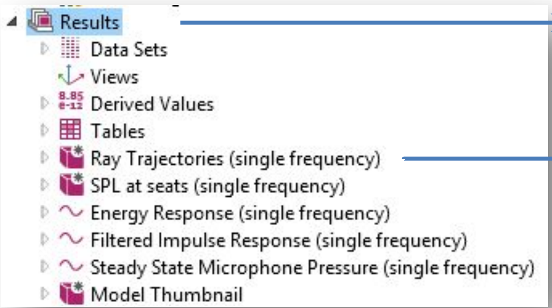
Study: Ray Tracing

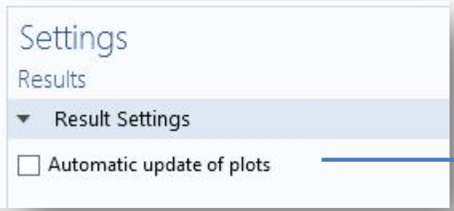


- Solve the model for 1.5 s in steps of 0.1 s. This will not affect the accuracy of the solution (within limits). The drawback is that the Ray Trajectories Plot will not look as good. That is, the setting is effectively only important for rendering purposes. The arrival time of rays at the microphone or the interaction of rays with walls is solved with very accurate time steps (internally).
- It is possible to give stop conditions for the solver. Either if there are no rays left or if the remaining rays have an intensity below a certain threshold.
- To reduce the file size when saving go to the Output section under Solver Configurations > Solution 1 > Time-Dependent Solver 1 and set the Times to store option.

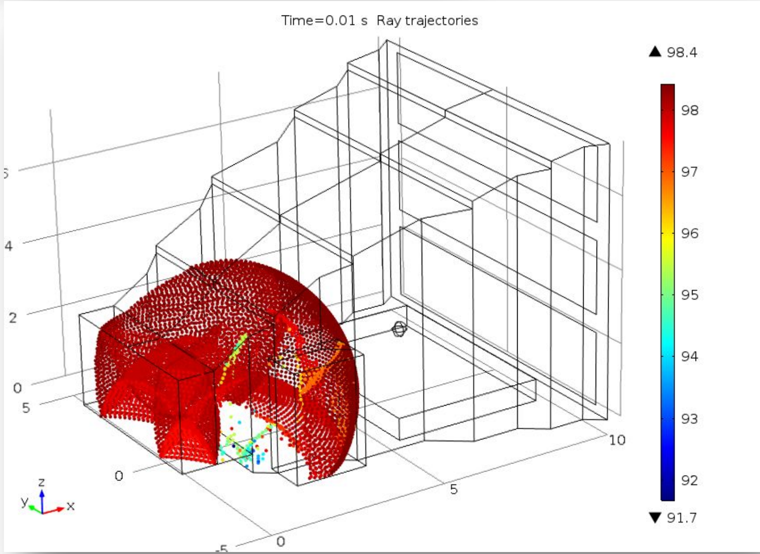


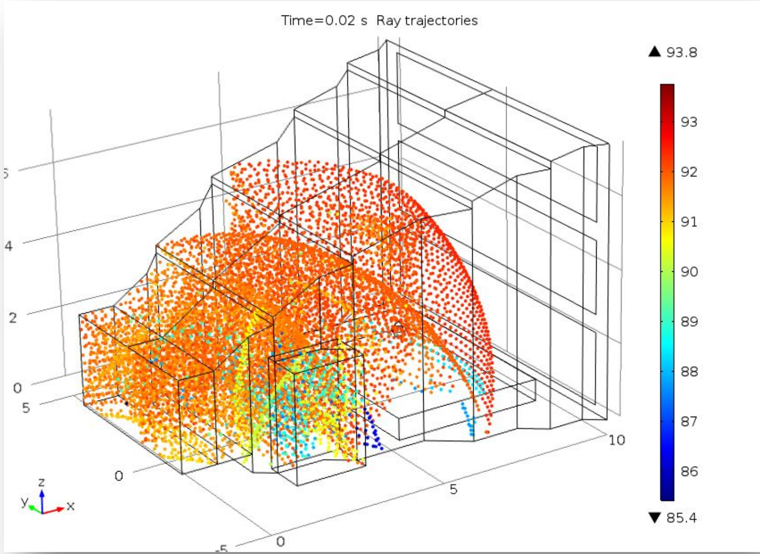
Results 1 (Single Frequency)





Start by deselecting the Automatic update of plots option under the Results node. Some of the plots may take a long time to plot, for example, if they are rendered for all rays at all times.





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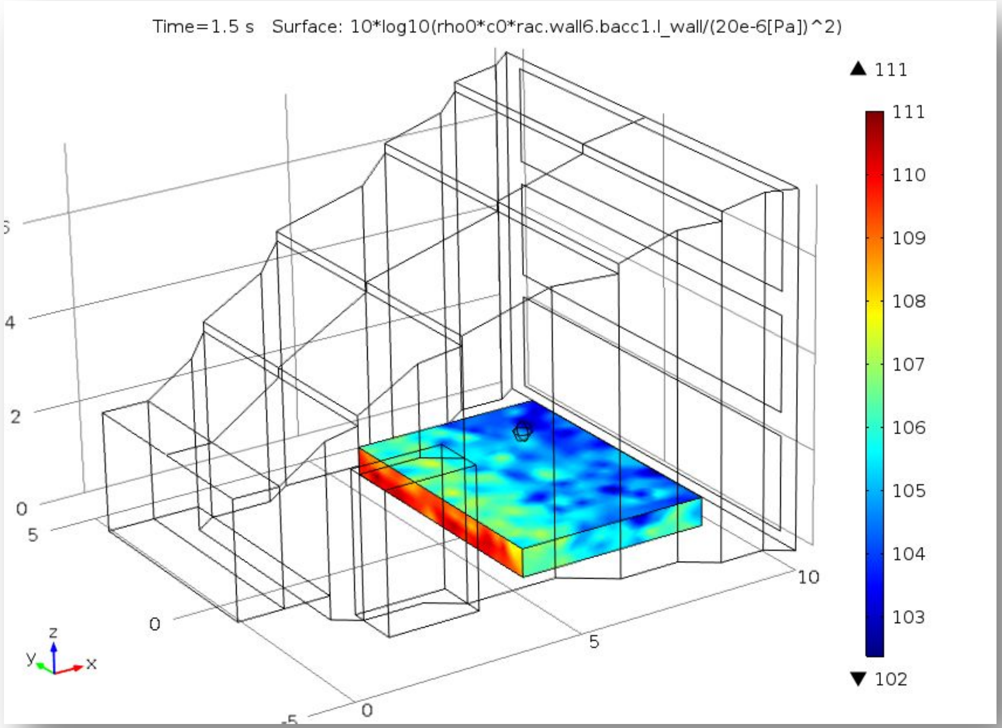
Results 2 (Single Frequency)



- SPL at the seats surface found by plotting the accumulator variable.
- The results can be improved using more rays or fiddling with the smoothing options of the accumulator.

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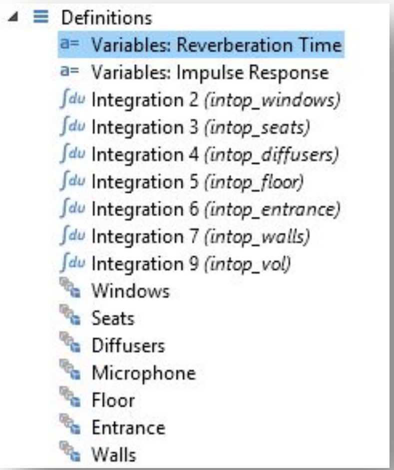
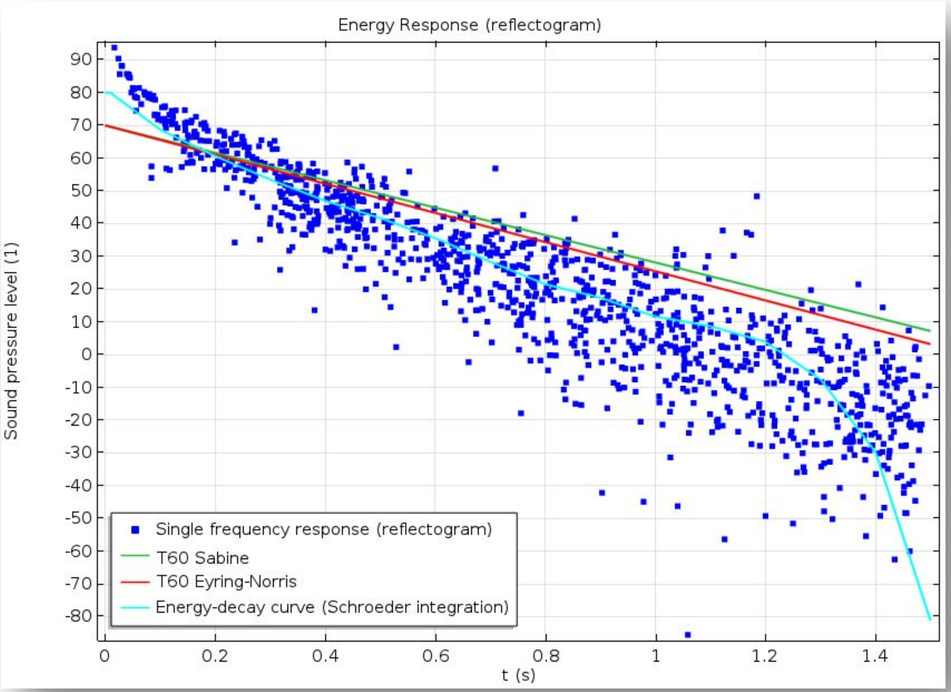
Results 3 (Single Frequency)



- The Sabine and Eyring-Norris reverberation times T_{60} as well as the Schroeder frequency f_s are calculated based on the absorption coefficients.
- $T_{60} = \dfrac{55.3\,V}{cA}$ $\qquad T_{60} = \dfrac{55.3\,V}{-c\,S\,log(1-A/S)}$ $\qquad f_s = 2000\sqrt{T_{60}/V}$
- These and the total absorption A, total surface area S, and room volume V are defined under **Definitions > Variables: Reverberation Time**.
- Results are, see **Results > Derived Values** :
    - Sabine reverberation time: 1.43 s
    - Eyring-Norris reverberation time: 1.35 s
    - Schroeder frequency: 116 Hz

Results 4 (Single Frequency)



- NB: Before plotting set the Time selection to Last!

- The energy response as measured at the microphone surface. Plot the SPL variable rac.Lp as function of the ray arrival time (the stop time) rac.st.

- Comparing to a Schroeder integrated energy-decay curve (cyan), and the two simple decay curves based on the Sabine and Eyring-Norris reverberation metrics (green and red).

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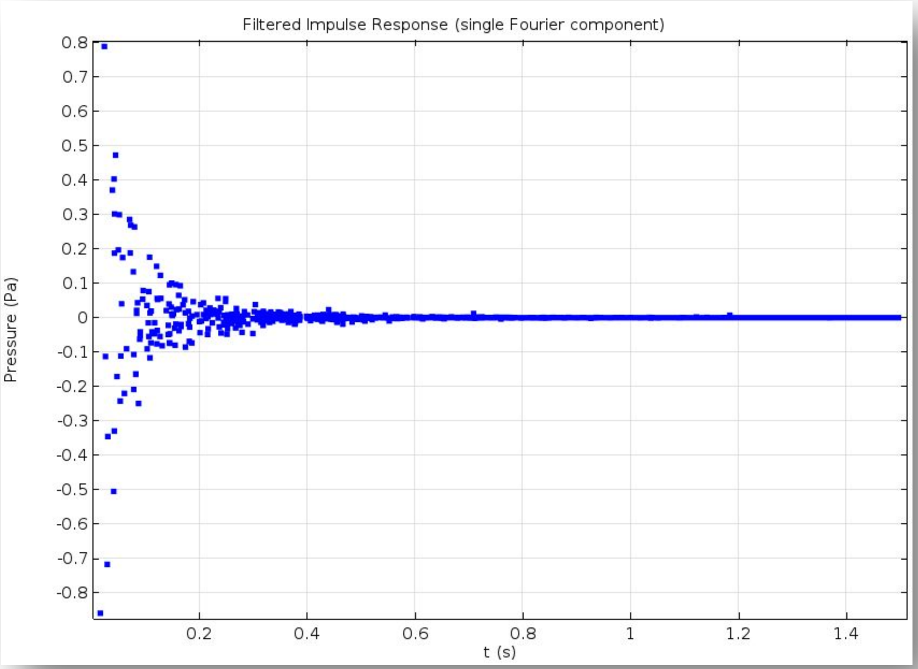
Results 5 (Single Frequency)

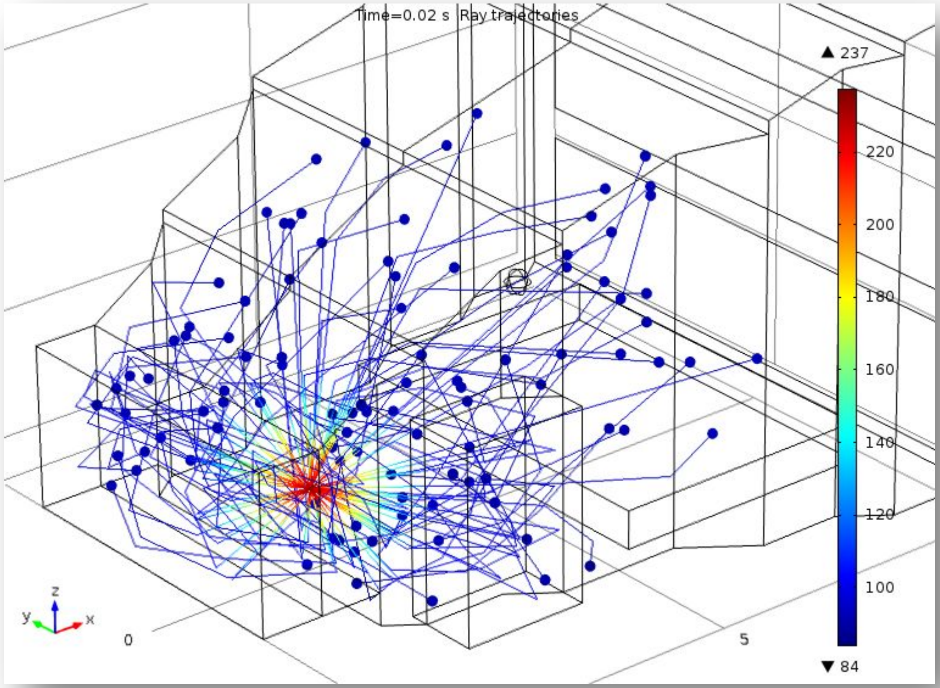


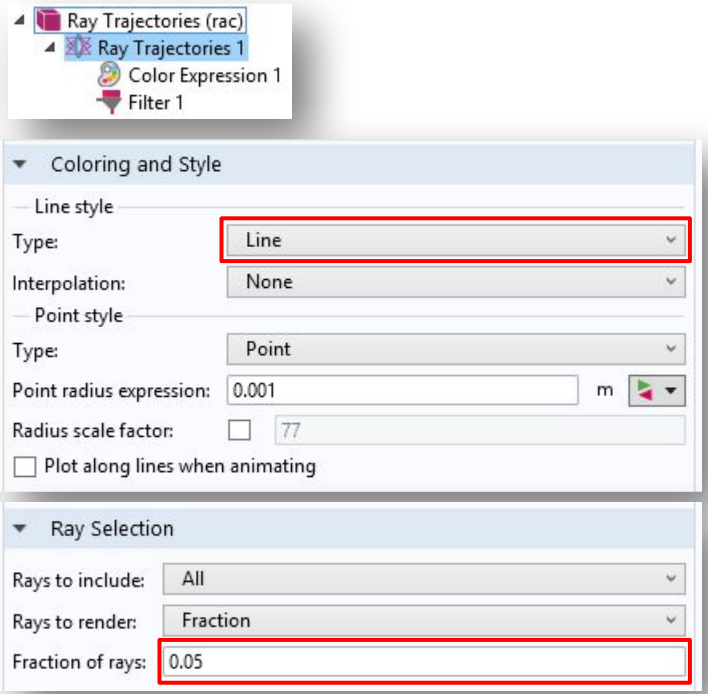
- NB: Before plotting set the Time selection to Last!

- Impulse response as measured at the microphone surface. Plot the pressure variable rac.p (it includes the phase) as function of the ray arrival time (the stop time) rac.st.

- Note that this is the filtered (discrete time) impulse response for the single Fourier component, with frequency f0, of an impulse modeled here.

Results 5 (Single Frequency)





Plot the ray trajectories as lines. Filter out the number of rays using the Filter feature.

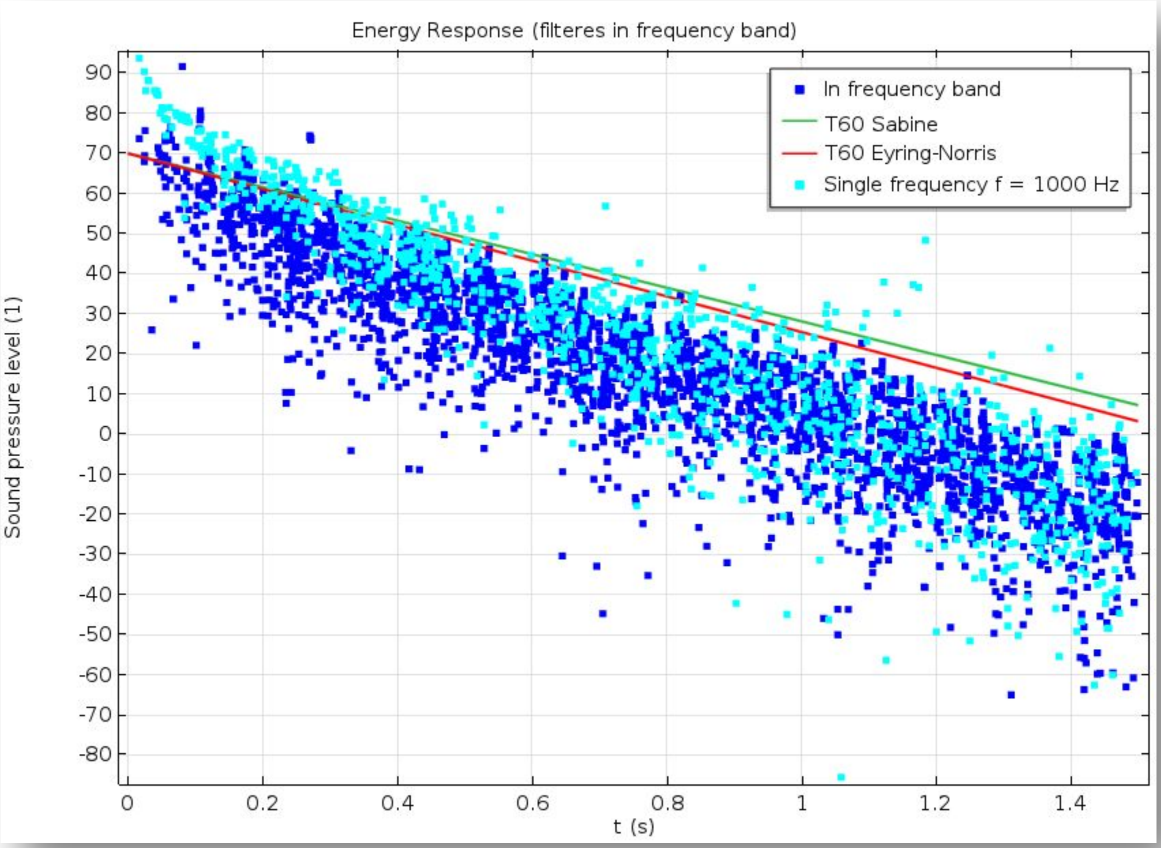
Results 1 (Frequency Distribution)

- Analyze the impulse response of an emitted frequency distribution by summing (over frequencies) the pressure contributions at the microphone.
- This can be done using the *rac.racop1()* operator (sum over rays), the *dest()* operator, and the logic *if()* operator.
- Basically the defined variables sum all rays that arrive at the microphone within the "sampling time" *dt_samp*. Here it se set to 1 ms.
- Alternatively, export the data and analyze the impulse response data in a dedicated software.

Variables

Name	Expression	Unit	Description
dt_samp	1[ms]	s	Sampling time
dt	dest(rac.st)-rac.st	s	Time difference
ptot	rac.racop1(if(abs(dt)<dt_samp, rac.p, 0))	Pa	Total pressure summed over sampling time
Lptot	10*log10(0.5*abs(ptot)^2/rac.pref_SPL^2)[dB]	dB	Total sound pressure level

Results 2 (Frequency Distribution)



COMSOL Ray Tracing Formulation

- The Ray Acoustics interface uses a mixed time and frequency formulation. This means that each ray has a specific frequency, it represents one Fourier component of the source signal. The propagation of each component is modeled in time. In the present model we only solve for one frequency. You can release multiple frequencies at once defined in different ways.
- The ray propagation is modeled by solving a set of ordinary differential equations (ODEs). Hamilton's equation in the high frequency limit for wave propagation.
- This formulation of the ray problem allows for a detailed description of boundary conditions. The boundary absorption (impedance or reflection coefficient) can be dependent on both frequency and angle of incidence.
- The following auxiliary dependent variables are computed along each ray: the intensity, the phase, and the frequency.