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Generation of synthetic room impulse responses from image sources

Using the ray tracing method

Basic idea explanation

The goal of this program is to obtain a simulation of the impulse response corresponding to the input-output transfer function of a system formed by the elements: loudspeaker-room-microphone. This can be accomplished in several ways; the one chosen here corresponds to assuming that the sound propagates as rays, and that the objects (boundaries) produce pure specular reflections **[1]**.

These rays will bounce on the room, and eventually may reach the microphone. In such case, they are said to correspond to "image sources" (in so far as they are not real sources) that are placed at a distance corresponding to the total traveled path, and located in the direction that they approach the microphone from.

Under these assumptions, the simulated IR is obtained by adding the contributions of all image sources, with their distance and amplitude, as if the whole environment was anechoic but containing many sources (instead of a single one).

Image source formation

The obtained image sources produce a signal that is a copy of the original but delayed on time and filtered in frequency.

The reasons for the change in the spectrum of the signal on each image source come from:

- Spherical propagation law:

  As the wave propagates, the energy is distributed on a larger area, therefore the intensity (watts per unit of area) gets lower. The reduction of the sound pressure amplitude is then inversely proportional to the distance **[2]**:

$$A \sim \frac{1}{r}$$

- Absorption on reflective boundaries:

  Each time a ray bounces on a boundary, only a part of the energy is reflected. This effect is frequency dependent **[3]**. Therefore, depending on which boundaries the ray bounces on, the final result will vary, as it is formed from all partial contributions (all individual frequency dependent-reflections).

  Different materials are commonly used to finish a room, such as painted plaster walls, carpets and wood. The presence of furniture or objects such as doors and windows also introduce an important contribution. The behaviour of some of these has been taken into account in the simulations conducted. The following plot offers a general idea of the absorption of some of them as a function of frequency.

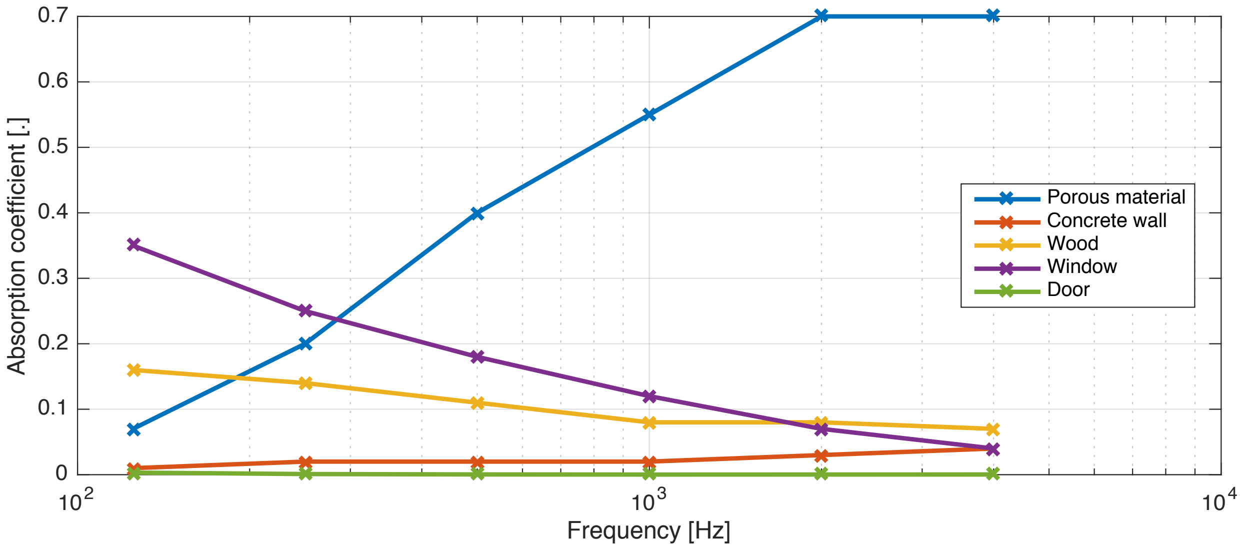


Fig. 1: frequency dependent absorption of some typical materials found on most rooms. Data extracted from **[4]**. Corresponds to diffuse incidence (average over all incident angles).

- Air absorption phenomena:

  It has a considerably smaller contribution to the final result than the previous two effects, but it is also included in the program to allow for better results in big low-absorbent spaces. It mainly results in a loss of high frequency (specially above 4 kHz) **[5]**. It's magnitude depends on the traveled distance **[5]**, and for a typical room such as the one studied here, its effect is mostly shadowed by the absorption of the boundaries.

Parts of the program

1. Knowing the geometry of the space (placement of boundaries and their frequency-dependent absorption), and the placement of source and receiver, a series of rays are "launched" from the source.

2. They are launched in equally spaced angle intervals. A complete simulation system should work on 4π steradians. The current developed software considers only a plane, instead of a volume, therefore they cover 2π radians.

3. Following the Snell's law, they bounce if a boundary is found. The absorption of the boundary is then applied to the ray.

4. If a ray reaches the receiver before a maximum amount of reflections has been reached, it is saved as a "contributing ray". The informations that characterise each ray are the total traveled distance and the cumulative frequency response. This is handled by:

    1. Producing a sinc function with a group delay corresponding to the total traveled distance.
    2. Filtering the sinc function in frequency every time a boundary is reached.
    3. Applying the correction for the air absorption on the total traveled distance.

5. After all possible rays have been launched, a reflectogram is constructed by adding all contributing rays. This will represent the effect of the room alone. To include the loudspeaker and microphone, it is convolved with their anechoic impulse responses.

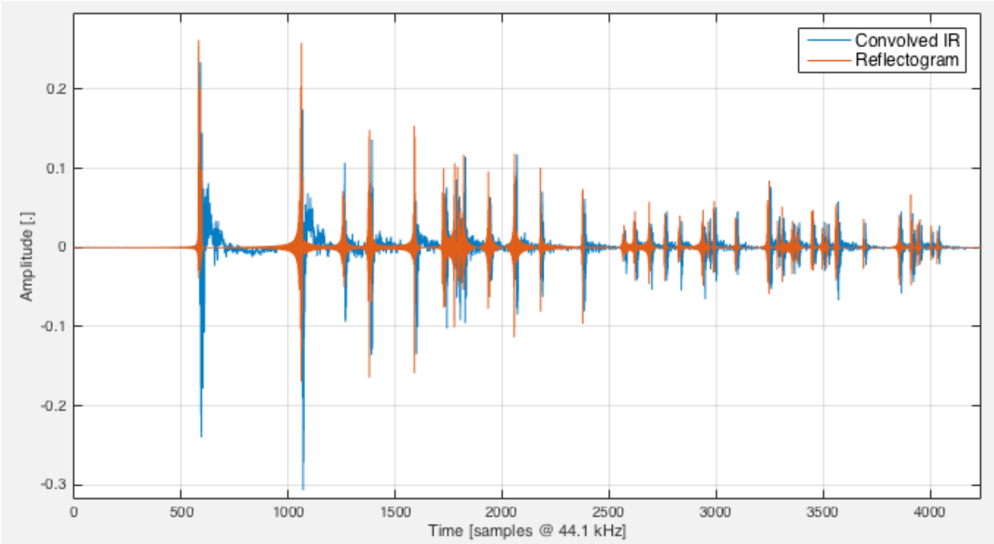
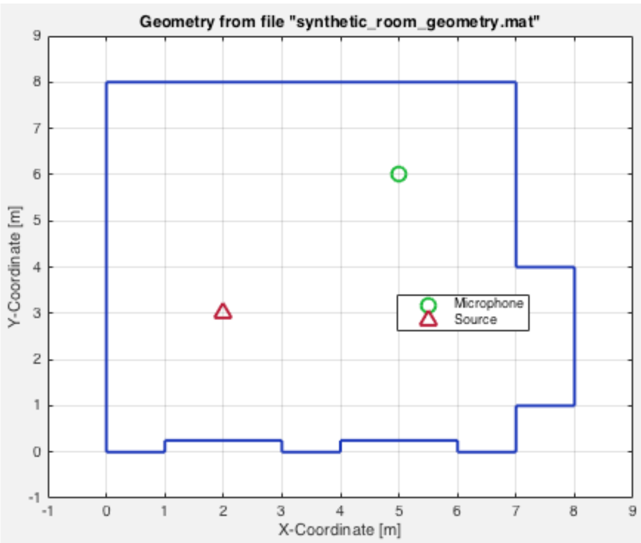


Fig. 2: Comparison of obtained synthetic impulse response and its corresponding reflectogram.

Note:

Step 5 introduces the assumption that the loudspeaker response is homogeneous across all radiating angles. For a better approximation, each ray should be processed with a different frequency response of the loudspeaker depending of the angle it was launched on. The main defect of the method used in this software is that it will include a higher amount of energy radiated in high frequency for all directions that are not the frontal.

Conducted example simulations



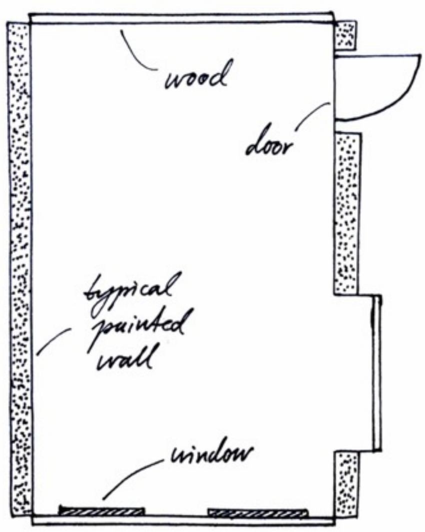
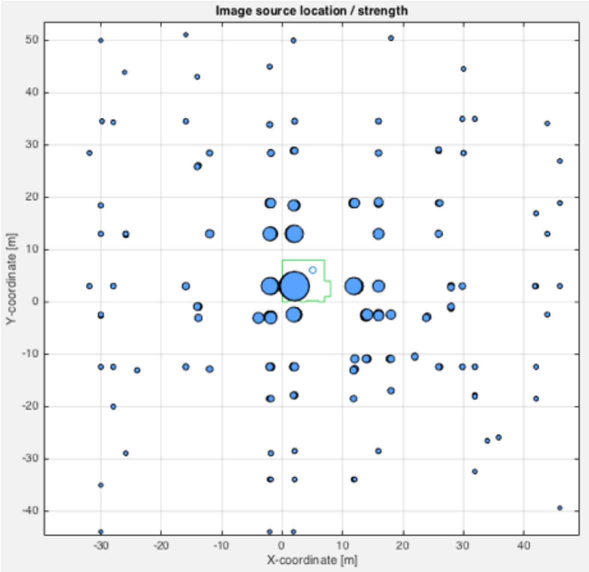


Fig. 3: designed room used for simulations (left). Fig. 4: hand drawn design, specifying materials used (right).

The main simulation results come from a room with a geometry as given by the figure 3. The simulation was conducted launching a ray every 0.5 degrees from the source position, and limiting the number of reflections to 50. The results are shown below in different formats.

All found image sources (346 in this example case, being the latest of order 49) are displayed in figures 5 and 6.



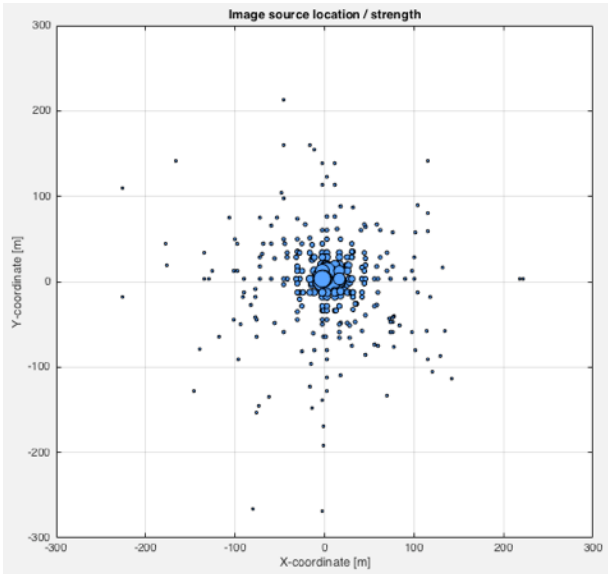


Fig. 5: image sources found, zoom (left). Fig. 6: complete set of image sources found (right). Each image source is presented with a circle whose radius gives a qualitative idea of the amplitude of the source.

All image sources are used to generate a reflectogram, according to their amplitude and frequency response, as shown in figure 7.

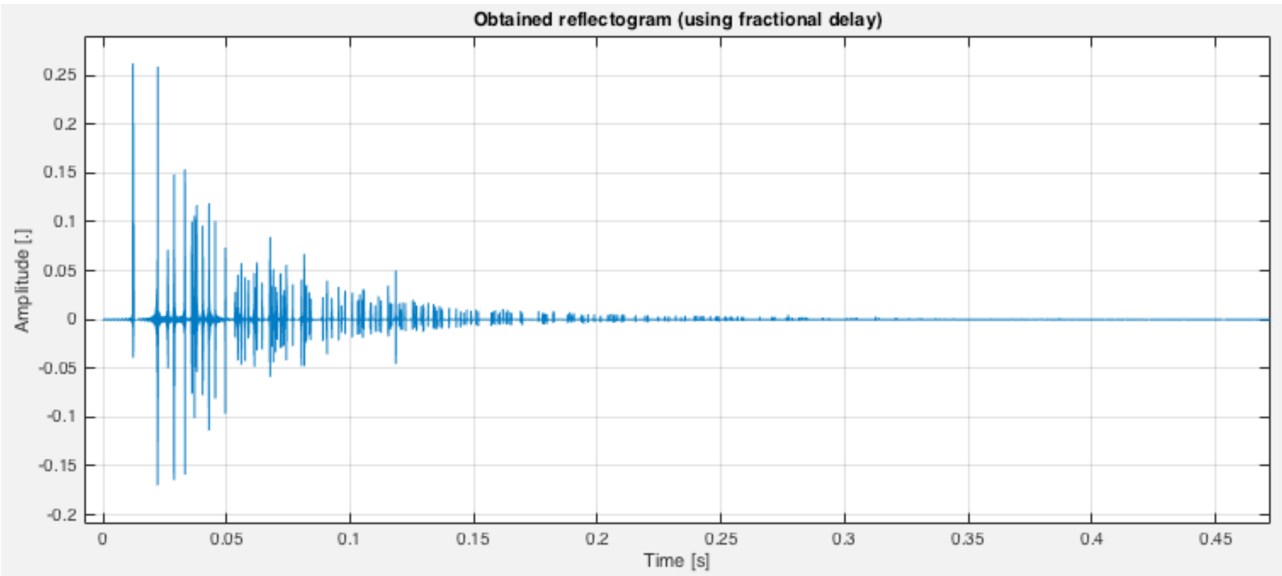


Fig. 7: reflectogram composed from all found image sources. Each of them produces a “peak” of different amplitude (distance) and shape (frequency response).

Convolving the reflectogram with the impulse response of a Genelec 1031A (figure 8, frontal radiation, anechoic conditions) leads to the final synthetic IR, shown in figure 9.

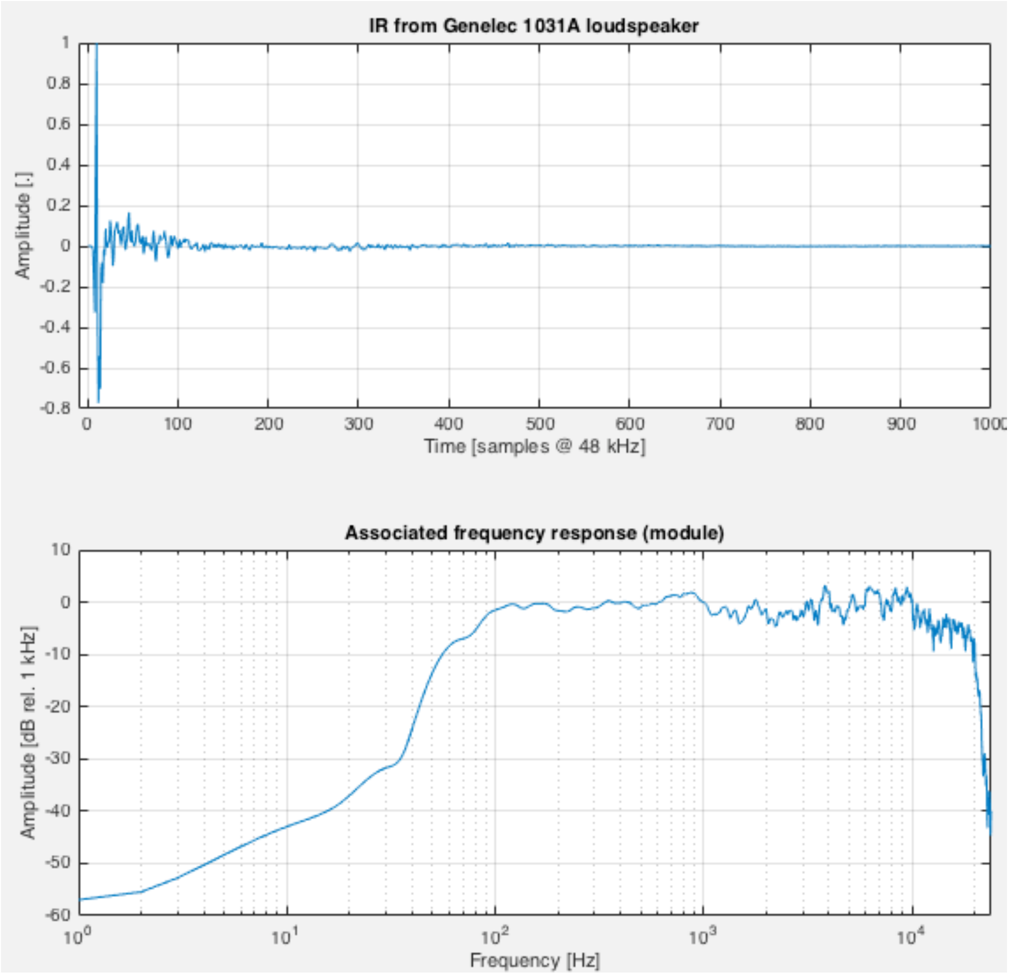


Fig. 8: measured response of a Genelec 1031A. Anechoic conditions, frontal radiation.

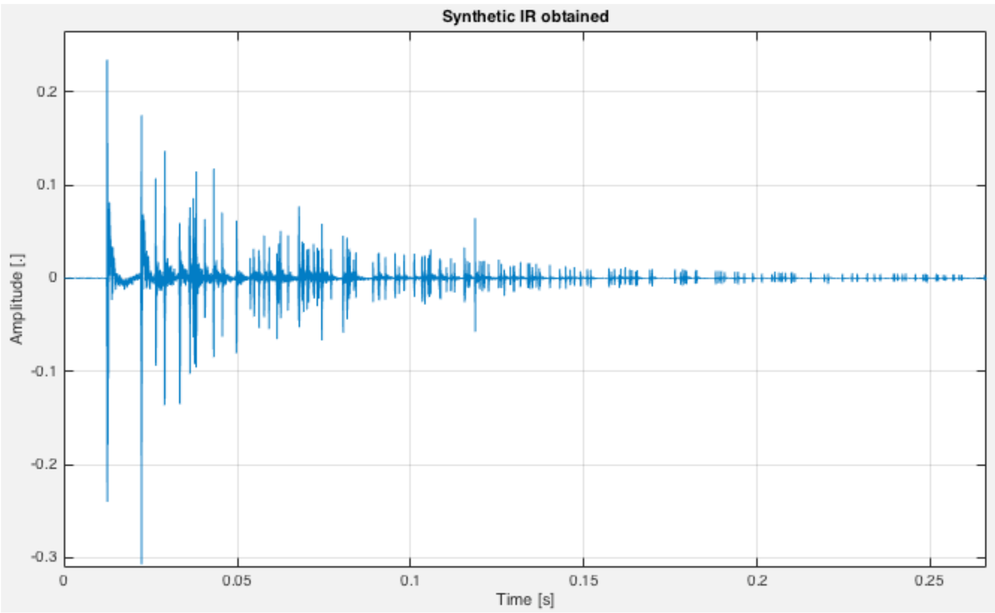


Fig. 9: final IR obtained.

Lastly, the obtained IR can be used to process a dry audio sample and “listen” to the room.

The spectrum of the final impulse response was also computed, and is displayed on figure 10.

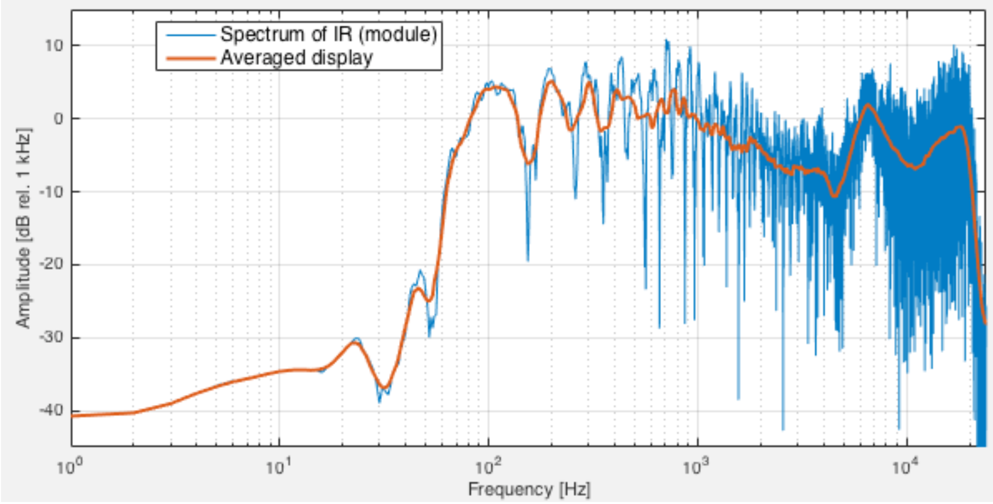


Fig. 10: spectrum of the obtained synthetic IR. Some clear comb filter effect appears, as a result of the addition of the strong early reflections. Some loss is also observed in high frequency, as some materials are more absorbent in that range. An averaged version is also plotted to help the reader visualise the behavior.

References

[1] Environmental and architectural acoustics, page 261, Z. Maekawa and P. Lord. 1994.
[2] Fundamentals of acoustics, page 160, Lawrence E. Kinsler and Austin R. Frey. 2nd ed, 1962.
[3] Room acoustics, page 133, Heinrich Kuttruff. 3rd ed, 1991.
[4] Environmental and architectural acoustics, table A.2, Z. Maekawa and P. Lord. 1994.
[5] Attenuation of sound during propagation outdoors ISO-9613-2, ISO, 1996.