3D Printed Modular Acoustic Panel

Vasil B. Botev

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Abstract

The demand for cost-effective, customizable acoustic solutions has led to innovative approaches in material design and manufacturing. This study investigates the development and performance of 3D printed modular acoustic panels using Fused Deposition Modeling (FDM) technology. Our focus is on creating a low-cost, easily customizable solution that is accessible to anyone with a 3D printer and basic tools.

I designed and fabricated panels with varying geometric patterns to optimize sound absorption and diffusion. Technical drawings and STL files of the designs are provided to enable replication and customization. Acoustic measurements were conducted using a calibrated measurement microphone in a previously untreated room to assess the effectiveness of the panels.

The results demonstrate significant improvements in acoustic performance in terms of reducing reverberation times and room distortion, improving sound clarity and sound absorption. This research highlights the potential of 3D printed acoustic panels as a viable and affordable alternative for achieving effective acoustic treatment in various settings.

Introduction

Acoustic panels are crucial components in managing sound within various environments, ranging from recording studios and home theaters to office spaces and classrooms. They are designed to absorb or diffuse sound waves, thereby reducing noise, controlling reverberation, and improving overall sound clarity. Proper acoustic treatment can significantly enhance auditory experiences, making environments more conducive to communication, productivity, and media enjoyment. Traditionally, acoustic panels are constructed from materials such as fiberglass, mineral wool, and foam, which are known for their sound-absorbing properties. These materials are typically encased in fabric and mounted on walls or ceilings. Manufacturing methods vary but often involve cutting, shaping, and assembling these materials into panels of different sizes and thicknesses to target specific frequency ranges.

While effective, these conventional methods and materials come with certain limitations. They can be costly, especially for high-performance products, and offer limited customization options in terms of aesthetics and specific acoustic properties. Additionally, the installation process can be labor-intensive, requiring professional assistance, which further increases the overall cost and accessibility of acoustic treatment solutions. The advent of 3D printing technology presents a promising alternative to traditional acoustic panel manufacturing. 3D printing, particularly Fused Deposition Modeling (FDM), allows for the creation of complex geometric shapes and patterns that can be optimized for sound absorption and diffusion. This technology enables the production of highly customizable acoustic panels that can be tailored to specific aesthetic preferences and acoustic requirements.

3D printing offers several advantages over conventional methods. It reduces material waste, lowers production costs, and accelerates the manufacturing process. Moreover, it democratizes the production, making it possible for individuals with access to a 3D printer and basic tools **to create their own custom acoustic treatments**. This opens up new possibilities for **personalized** and **affordable** acoustic solutions in various settings.

This research aims to explore the potential of 3D printed modular acoustic panels as a low-cost, customizable, and effective solution for acoustic treatment. The specific objectives are to develop 3D printed modular acoustic panels optimized for sound absorption and to measure the acoustic performance of the 3D printed panels in a previously untreated room using a calibrated measurement

Methods

The primary intention behind the design of the 3D printed modular acoustic panels was to combine the functions of sound reflection and absorption into a single, cohesive structure.

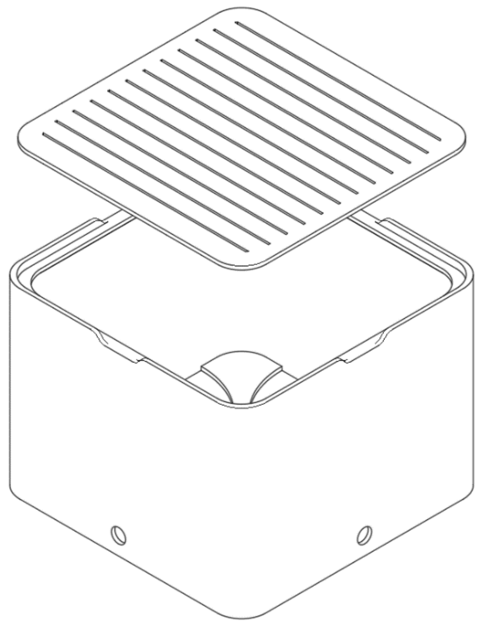

Figure 1 – Cell design

To achieve this, a parametric cell design was developed, serving as the fundamental building block for the panel. Each cell is square-shaped with rounded corners, providing a blend of aesthetic appeal and functional integrity. The cell is hollow, allowing it to house acoustic filling material that enhances its sound-absorbing properties. The dimensions of each cell are 70x70 mm, with a variable height ranging from 12 mm to 120 mm. These dimensions are defining the effective frequency range of the diffuser:

$$f_{low} = \frac{c}{2d_{\max}} = \frac{343}{2 \times 0.12} \approx 143 Hz$$

$$f_{high} = \frac{c}{\lambda_{\min}} = \frac{343}{0.07} \approx 4900 Hz$$

Since the lower cutoff frequency is determined by the deepest well and the upper cutoff frequency is determined by the smallest dimension, which is the width of the cell, in theory the effective frequency response range of the panel will be from **143 Hz to 4.9 kHz**.

A cap tops each cell, sealing it and forming the front reflective surface. It also implements acoustic metasurface-based perfect absorber with deep subwavelength thickness[1] without coiled coplanar air chamber, only featuring micro-openings - 500 microns in size, which facilitate good sound absorption with very thin size.

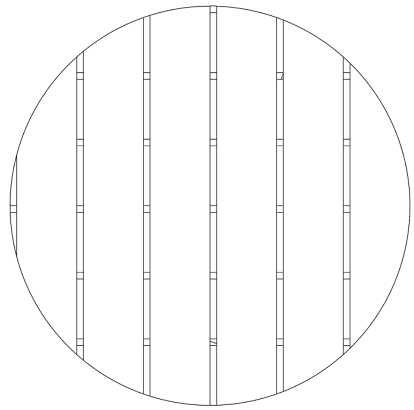

Figure 2 – Cap micro openings

Also in the chamber behind the cap I have added silicon fiber material, which further absorbs the sound waves and converts them into heat. The cell features 4 notches for easy cap removal, which is handy when mounting the panel on the wall or when changing the filler material.

The cells are organized into modules, each consisting of 16 cells arranged in a 4x4 grid. The total size of one module is 280x280 mm. This size was chosen in order to be easy 3D printable. Most of the modern printers can print objects of this size. To create panels of different sizes, multiple modules are combined. It is also possible to stack n x m cells together and to create custom sized module, according to your printer capabilities.

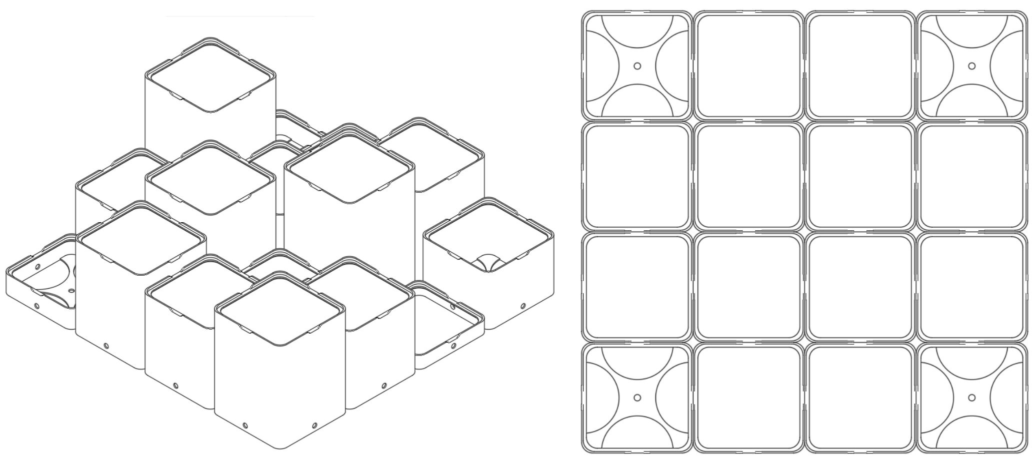

Figure 3 – Module design

Each module features four mounting points located at its corners, enhancing ease of installation. Additionally, each cell has four 4 mm openings on each side, providing additional versatility for mounting and/or cable management. A unique feature of these modules is their ability to interlock, allowing two modules to slide into each other. This significantly reduces their total volume, making storage and transportation more efficient.

For the primary design of the parametric cells and modules, Autodesk Fusion 360 was used. The most important dimensions of the cells were parameterized to allow for easy customization. This enabled the rapid creation of custom cells tailored to specific acoustic needs. Multiple variants of the cells were printed during the design process to ensure functionality, optimal fit of the cap, and efficient use of material. This iterative approach helped refine the design to meet performance and manufacturing criteria. The design of the cell caps was adapted from

Julien Dorra's research on 3D-printable sound absorbers[2]. These designs were created in OpenSCAD and integrated with the Fusion 360 cell models, ensuring a consistent fit.

The modules can printed one by one on a 3D printer with a build volume > 280 x 280 x 120 cm^3. I printed our test modules on a Voron 2.4 with a 0.4 mm nozzle. I used PLA as this was the material available to me at that time. Then I sliced the model on Orca slicer. No supports are required. Here are the main printing parameters used for the modules and caps:

Parameter	*Modules*	*Caps*	*Unit*
Nozzle diameter	0.4	0.4	[mm]
Layer height	0.3	0.2	[mm]
Initial layer height	0.2	0.2	[mm]
Line width	0.4	0.4	[mm]
Wall loops	2	3	-
Top surface pattern	Monotonic	Concentric	-
Top shell layers	2	4	-
Top shell thickness	0.8	0.8	[mm]
Bottom surface pattern	Monotonic	Concentric	-
Bottom shell layers	2	3	-
Bottom shell thickness	0.8	0.8	[mm]
Sparce infill density	15	15	%
Sparce infill pattern	Grid	Concentric	-
Outer wall speed	85	85	[mm/s]
Inner wall speed	200	200	[mm/s]
Small perimeters	50	50	%
Sparce infill	200	200	[mm/s]
Internal solid infill pattern	Monotonic	Concentric	-
Internal solid infill	200	200	[mm/s]
Top surface	85	85	[mm/s]

Table 1 – Printing parameters

Using these settings one module can be printed in **11 hours and 33 minutes**, while using approx. **330 grams of 1.75 mm filament**. For one module 16 caps are needed. They can be printed at once for **5 hours and 20 minutes**. They will consume around **82 grams of filament**. In total for one complete module with all caps we will need around **412 grams of filament and around 16 hours and 53 minutes**. It is possible to print 2 modules with caps with one 1 kg spool of filament with no spool change. Also after we print 2 full modules we still have around 100 grams of filament left, so if something goes wrong with the print we have some headroom.

For structural support and ease of handling, the modules are mounted onto an 18 mm thick wooden board. This board has a 20 mm border around the modules. The back of the board includes two 18 mm spacers that create a gap between the wall and the panel, reducing direct wall contact and introducing an air pocket that can enhance acoustic performance. Before closing the caps the cells are filled with silicone fibers for better sound absorption.

Figure 4 - Printed module

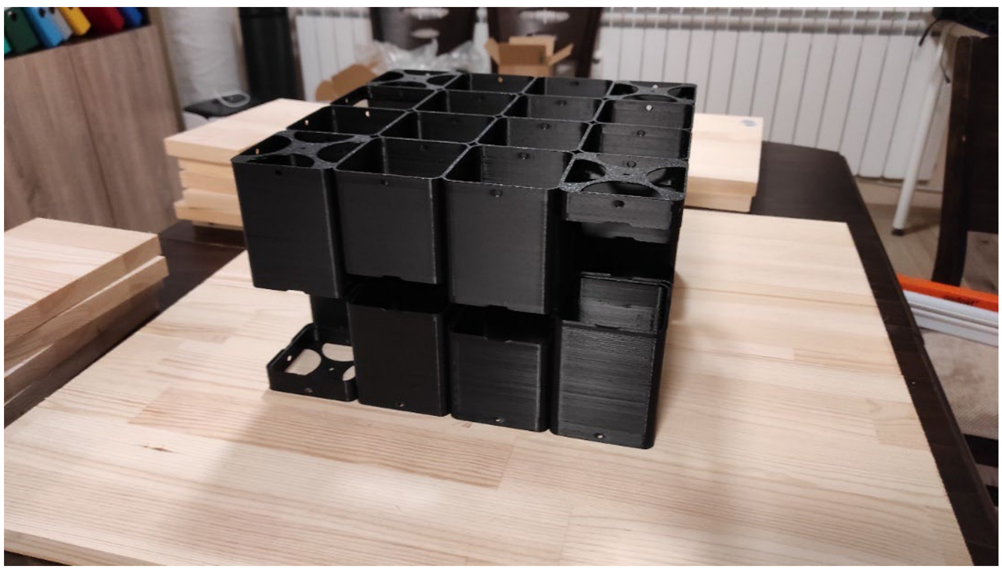

Figure 5 - Module interlocking

Figure 6 - Adding acoustic filler and caps

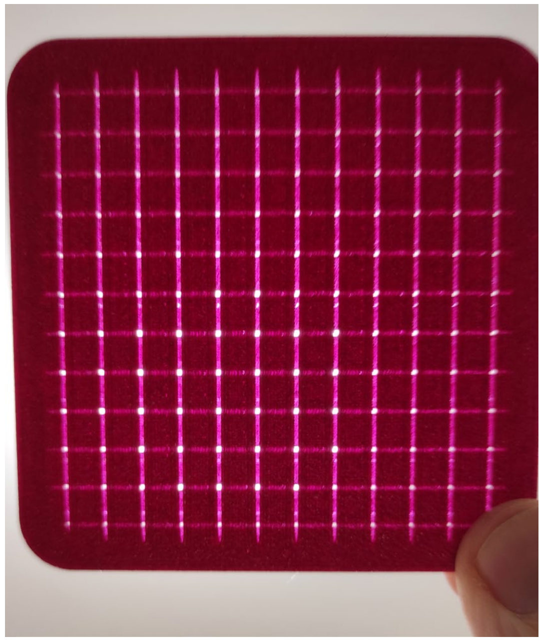

Figure 7 - Printed cap with micro openings

For the purpose of this paper four panels were created:

One **large panel**: Comprises 6 modules in a 2x3 configuration, resulting in a total effective size of 840x560 mm.

Figure 8 – Large panel

Three **small panels**: Comprises 4 modules in a 2x2 configuration, with a total effective size of 560x560 mm.

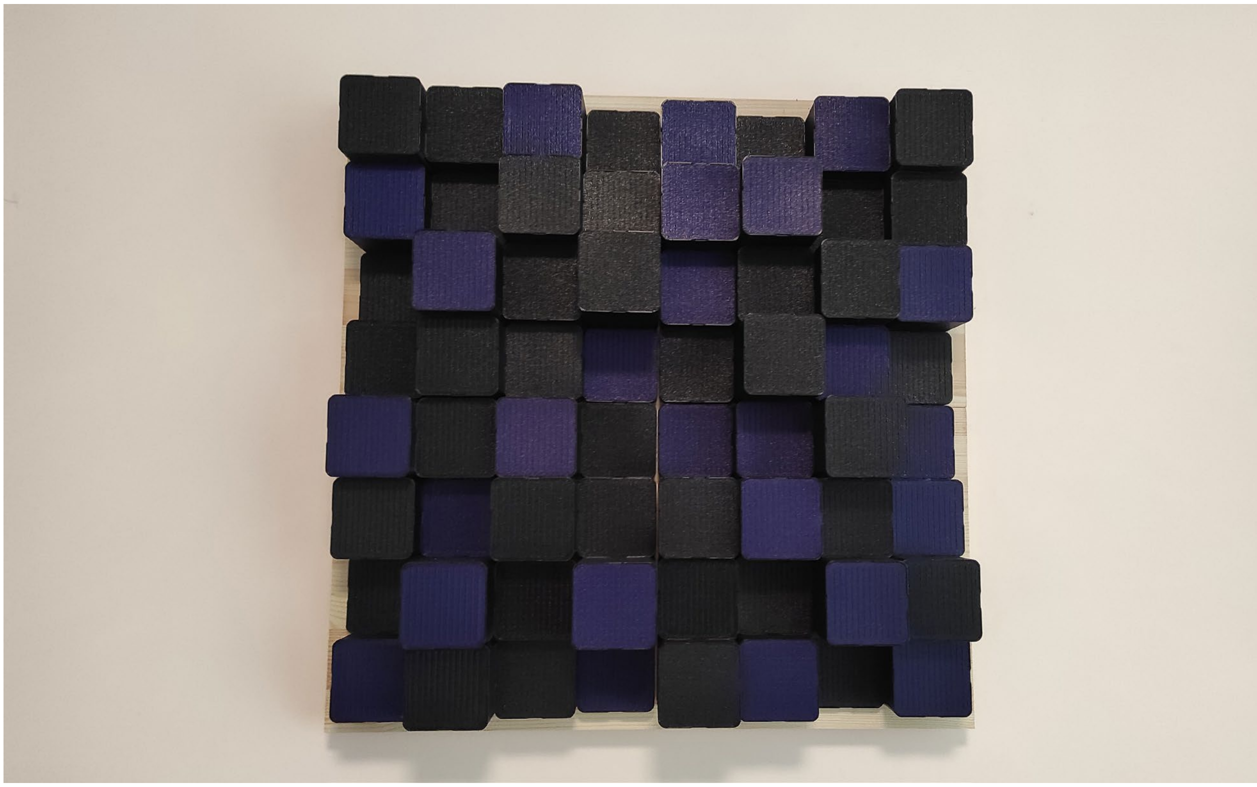

Figure 9 – Small panel

My goal from this point is to access the performance of the panels. For this purpose I wanted to mount the panels in a test room with size of approx. 12 m^2 and only 2 available walls for panel placement. On the left side of the room I have a big wardrobe and on the right there is a big window and a door. As a measurement device I used Sonarworks XREF20R5 measurement microphone. For the sound source in the room I used a pair of Focal Alpha 80 Evo studio monitors. Everting was connected to Universal Audio Volt2 USB interface. The measurements were done using Room Equalization Wizard software.

Before I started to measure I positioned the speakers and the microphone on the tips of an equilateral triangle with side length of 90 cm. The speakers are rotated exactly 45° towards the microphone, which was placed at the listening position in front of the speakers. Next I calibrated the audio interface and loaded the provided microphone calibration file. I choose to measure the room response in a 90° configuration. Then I used a SPL meter to calibrate our input level. Next I proceed to the measurements. First I measured the room response without panels, then the panels were mounted on the walls and the same measurements were performed again. On figure 10 you can see the entire room setup with the speakers, measuring point and the mounting position of the panels (in orange). After I captured the empty room response I first mounted the large panel on the wall behind the speakers. After that I mounted the rest 3 smaller panels on the opposite wall. All panels were mounted at the same height – 50 cm from the ceiling. Then the final measurements were taken.

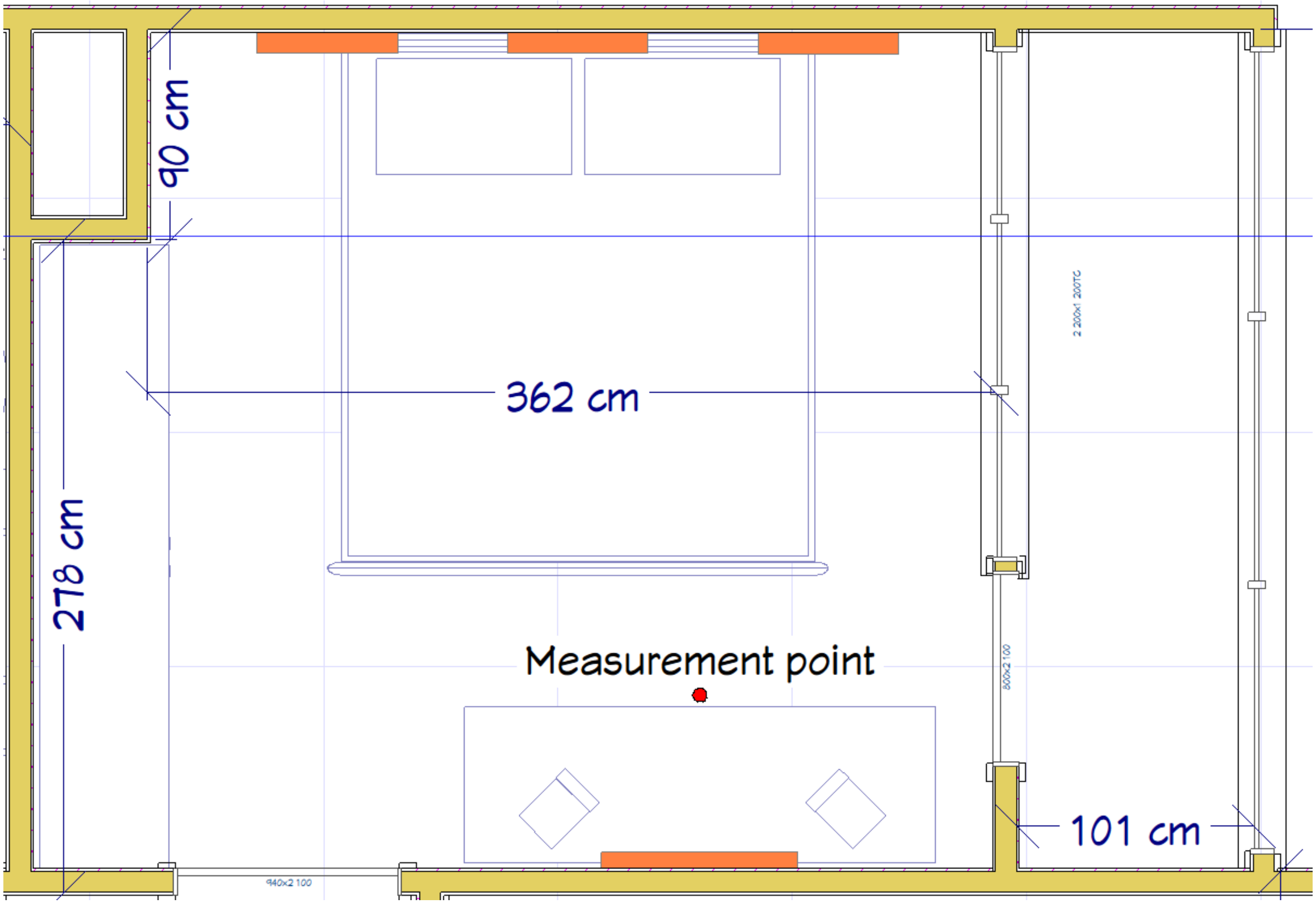

Figure 10 - Room setup

Results

In the diagrams below I have put all measurement results. Here is a list of all measurements:

- SPL graph before and after treatment for both channels (figure 11, 12)
- Distortion before and after treatment for both channels (figure 13, 14)
- Clarity before and after treatment for both channels (figure 15, 16)
- RT-60 reverb time before and after treatment for both channels (figure 17, 18)
- Impulse response before and after treatment (left channel) @ 125 Hz (figure 19)
- Impulse response before and after treatment (left channel) @ 250 Hz (figure 20)
- Impulse response before and after treatment (left channel) @ 500 Hz (figure 21)
- Impulse response before and after treatment (left channel) @ 1 kHz (figure 22)
- Impulse response before and after treatment (left channel) @ 2 kHz (figure 23)
- Impulse response before and after treatment (left channel) @ 4 kHz (figure 24)
- Impulse response before and after treatment (left channel) @ 8 kHz (figure 25)

Figure 11- SPL graph before and after treatment for left channel

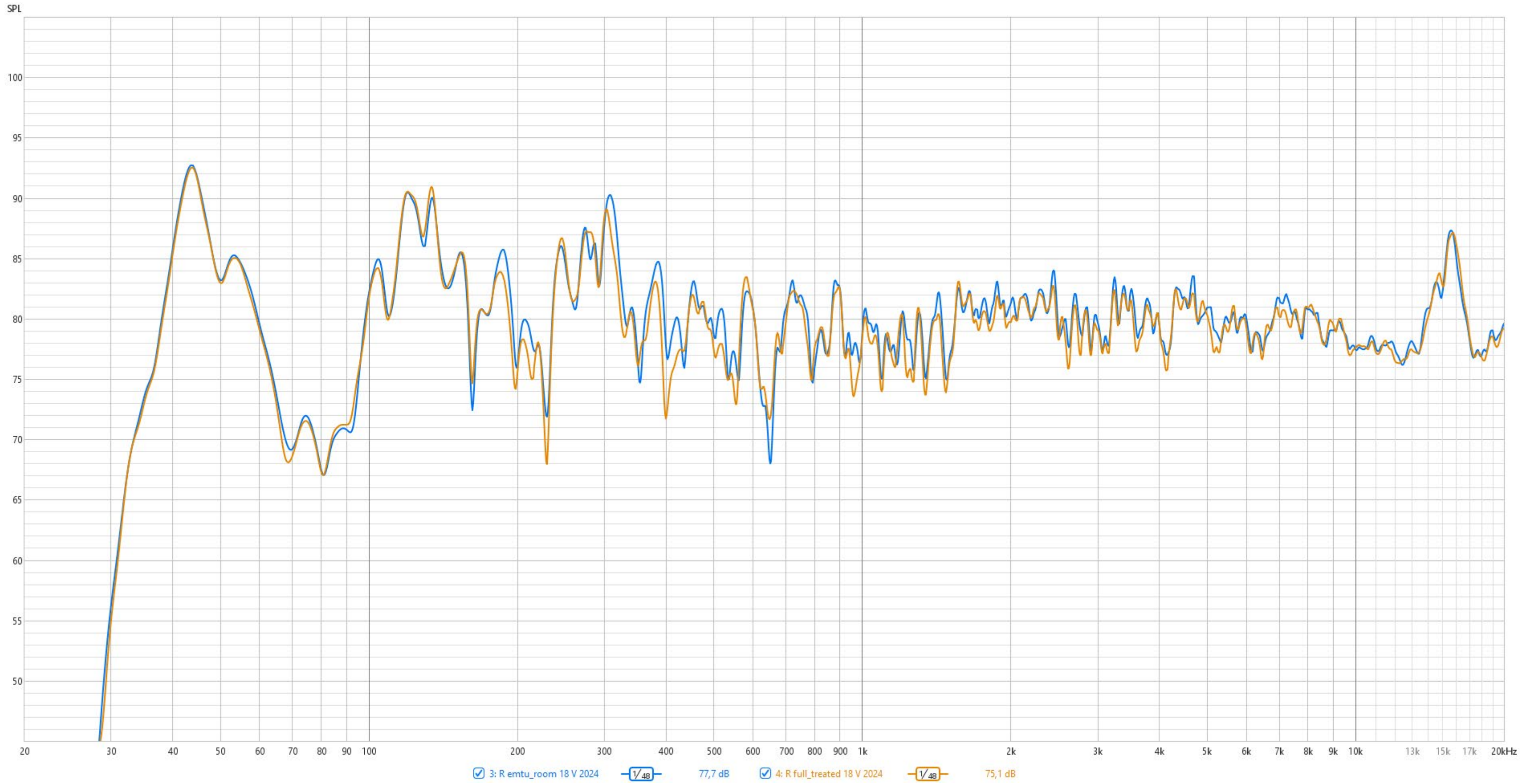

Figure 12 - SPL graph before and after treatment for right channel

Figure 13- Distortion before and after treatment for left channel

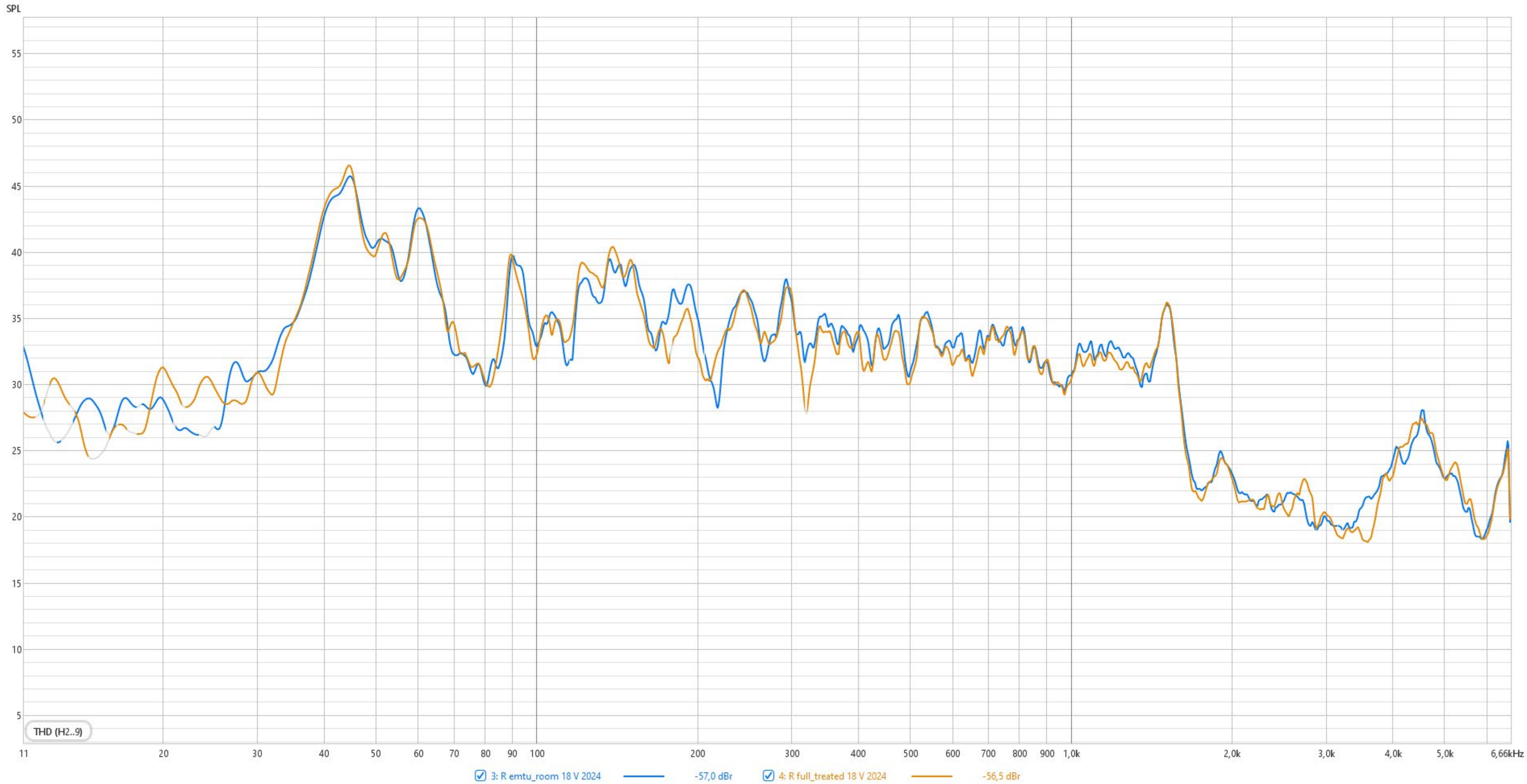

Figure 14- Distortion before and after treatment for right channel

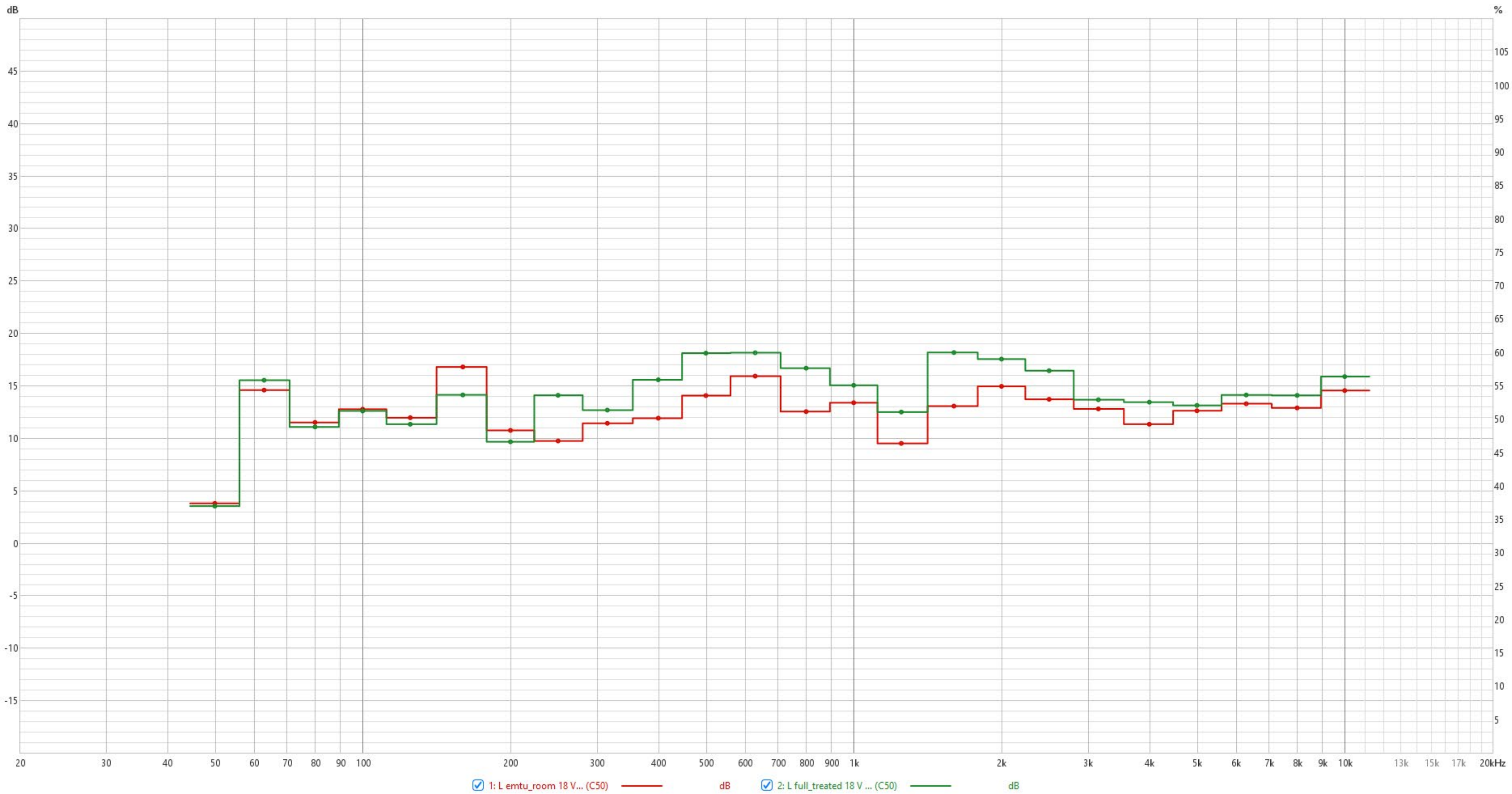

Figure 15 - Clarity before and after treatment for left channel

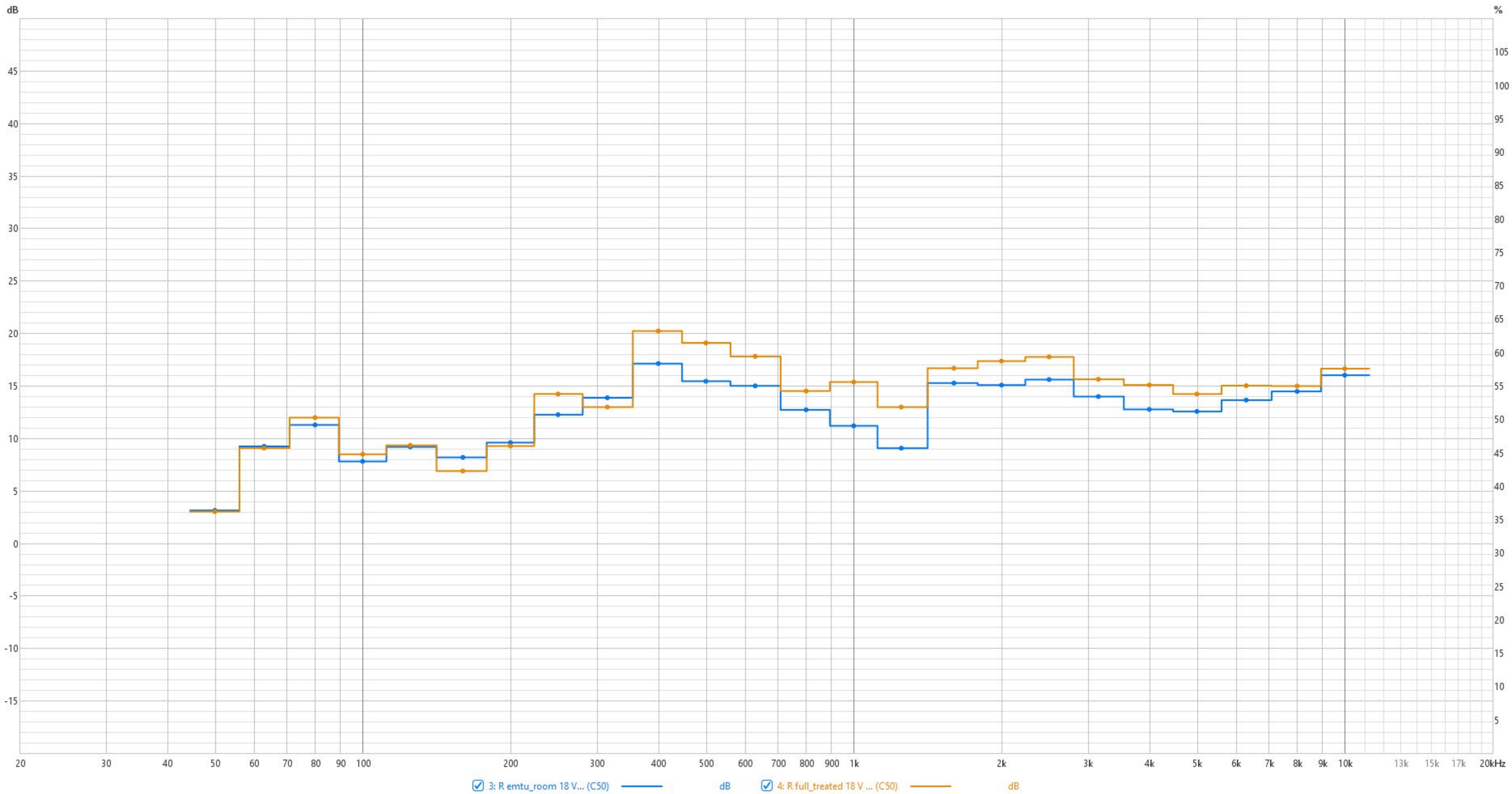

Figure 16 - Clarity before and after treatment for right channel

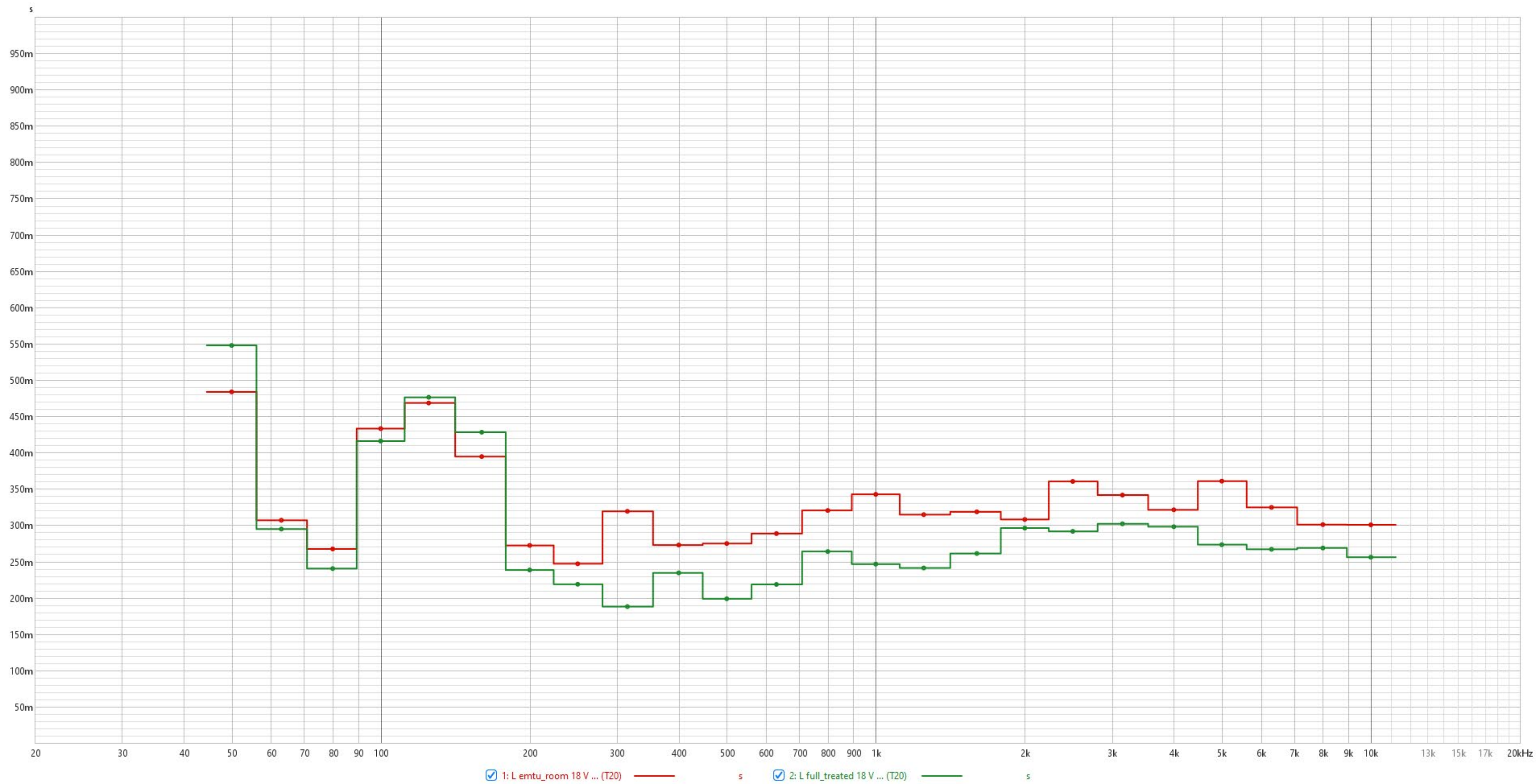

Figure 17- RT-60 reverb time before and after treatment for left channel

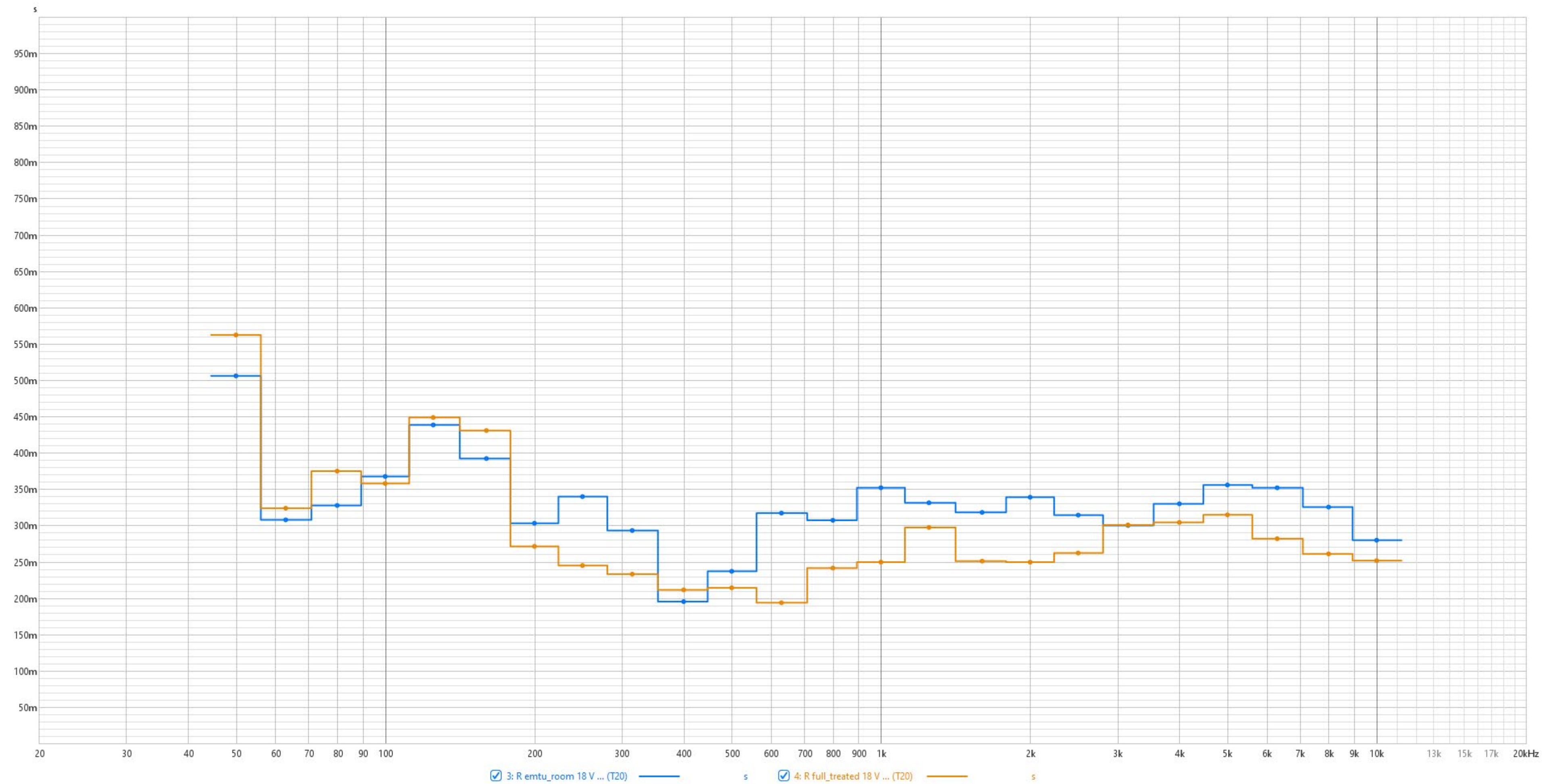

Figure 18- RT-60 reverb time before and after treatment for right channel

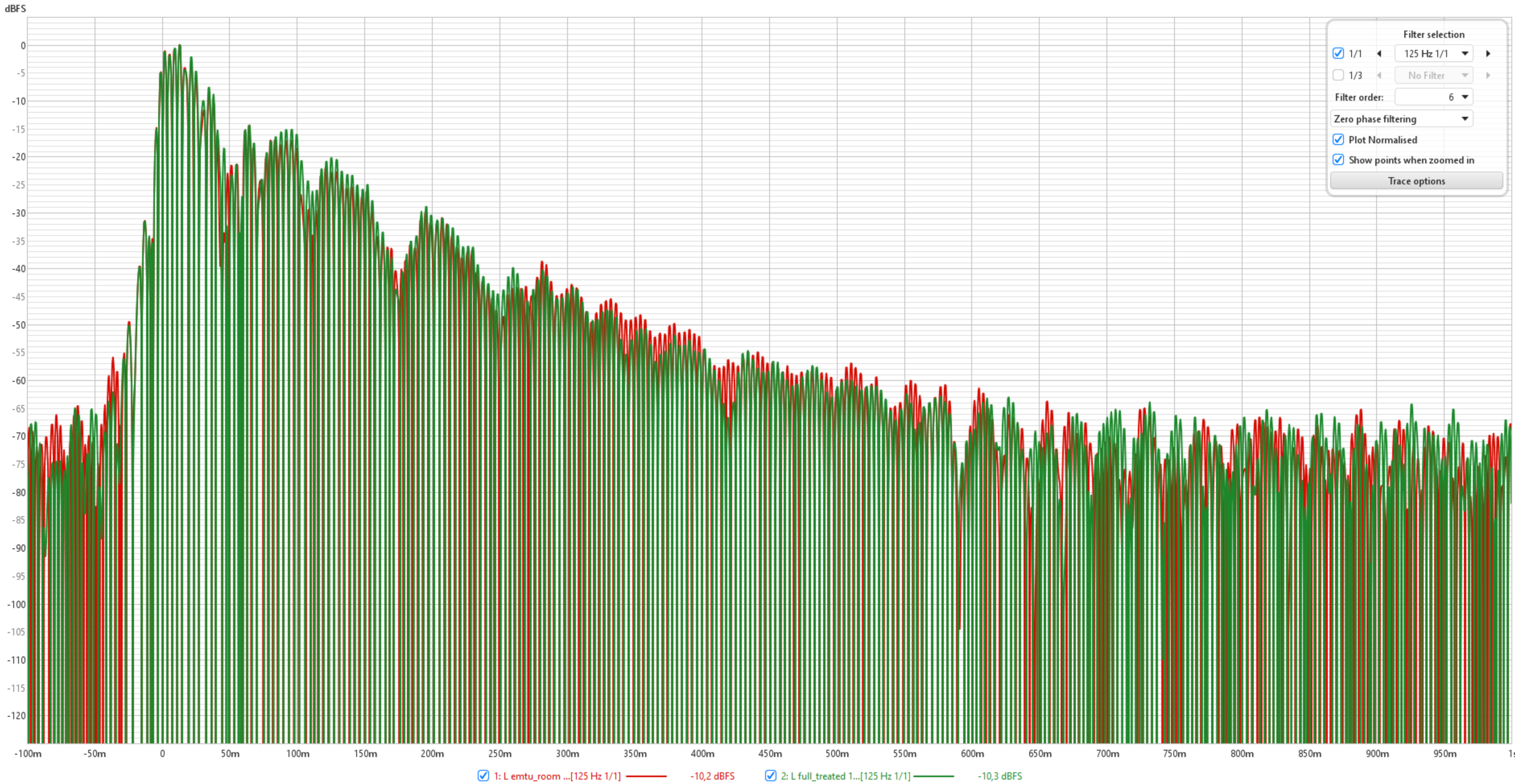

Figure 19 - Impulse response before and after treatment @ 125 Hz

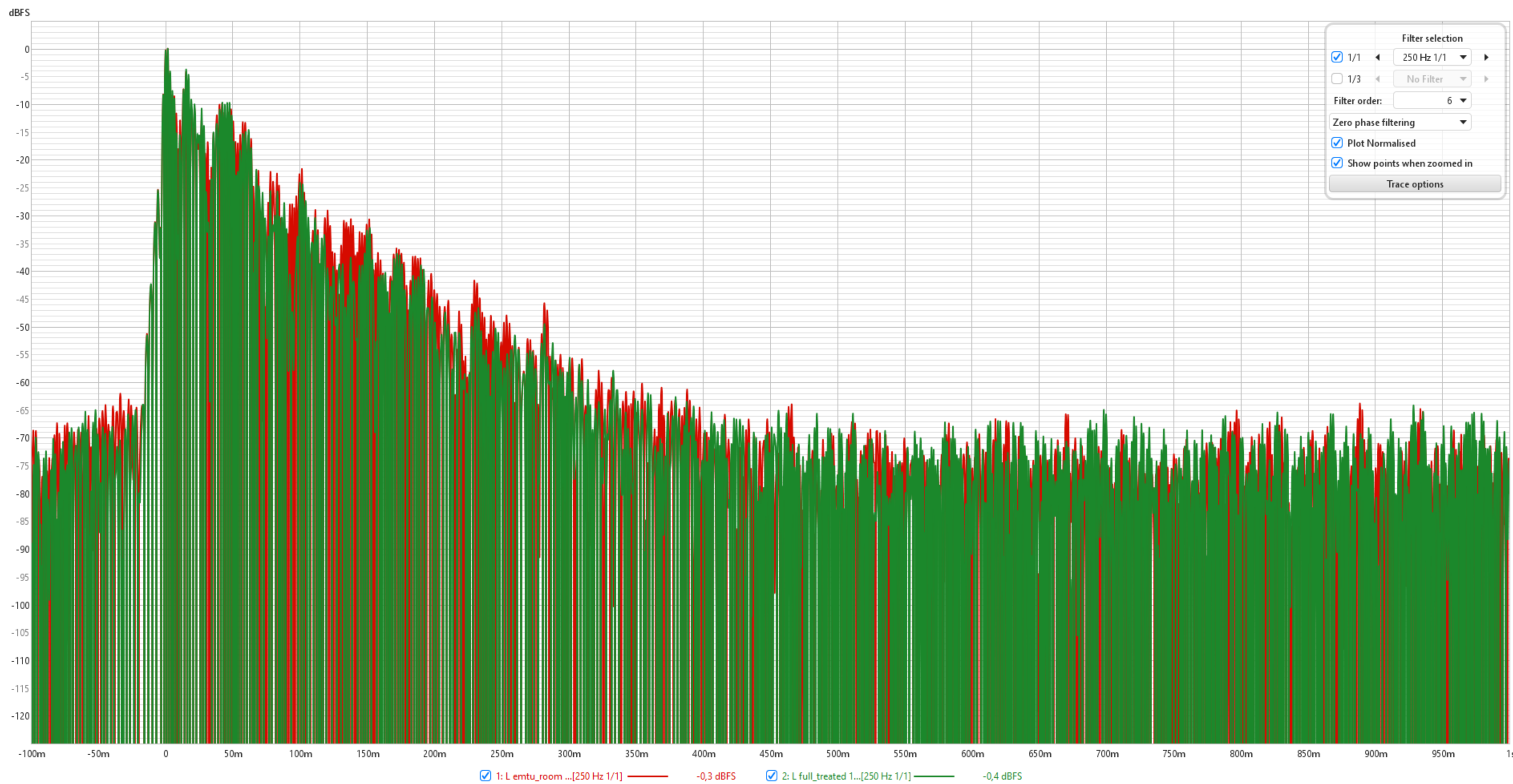

Figure 20 - Impulse response before and after treatment @ 250 Hz

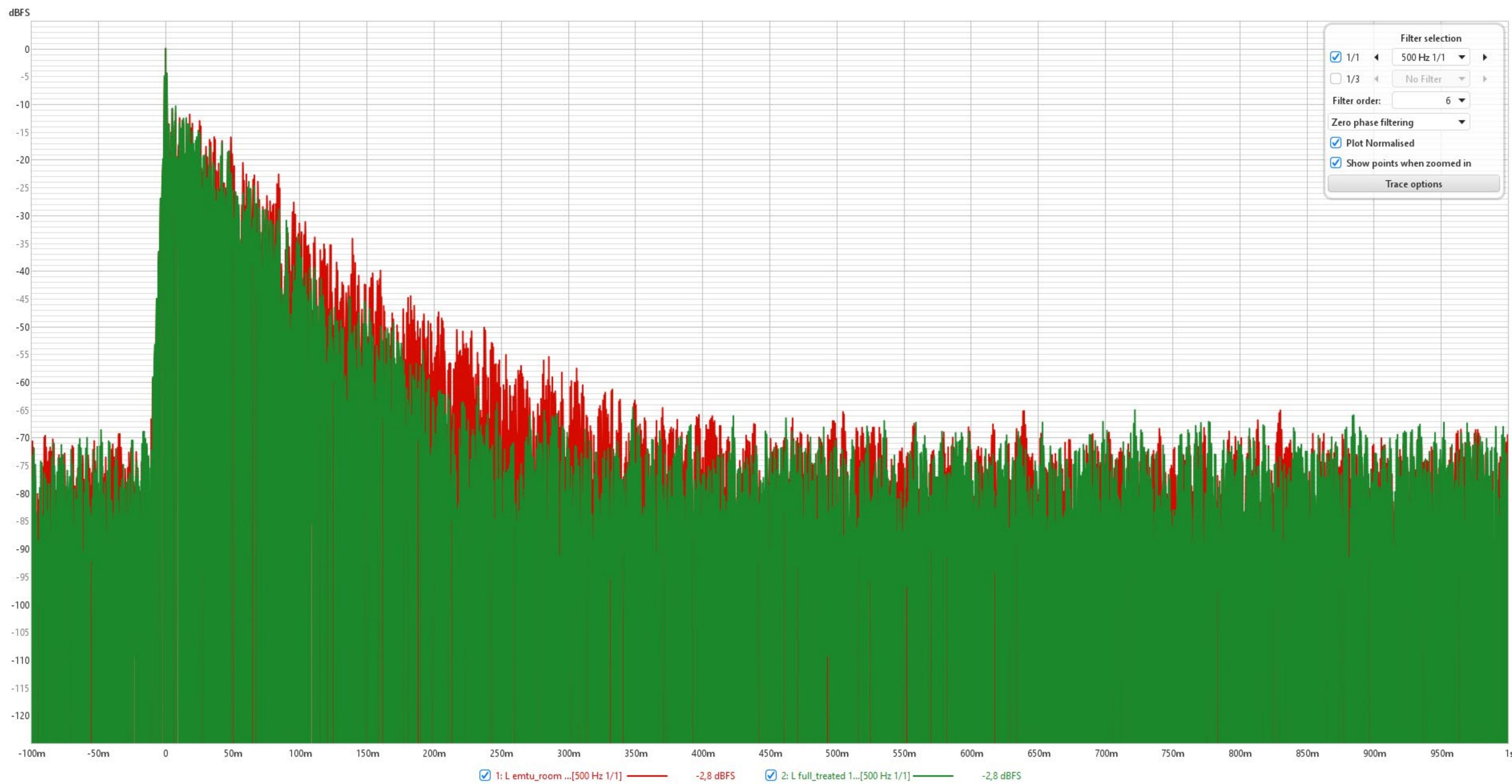

Figure 21 - Impulse response before and after treatment @ 500 Hz

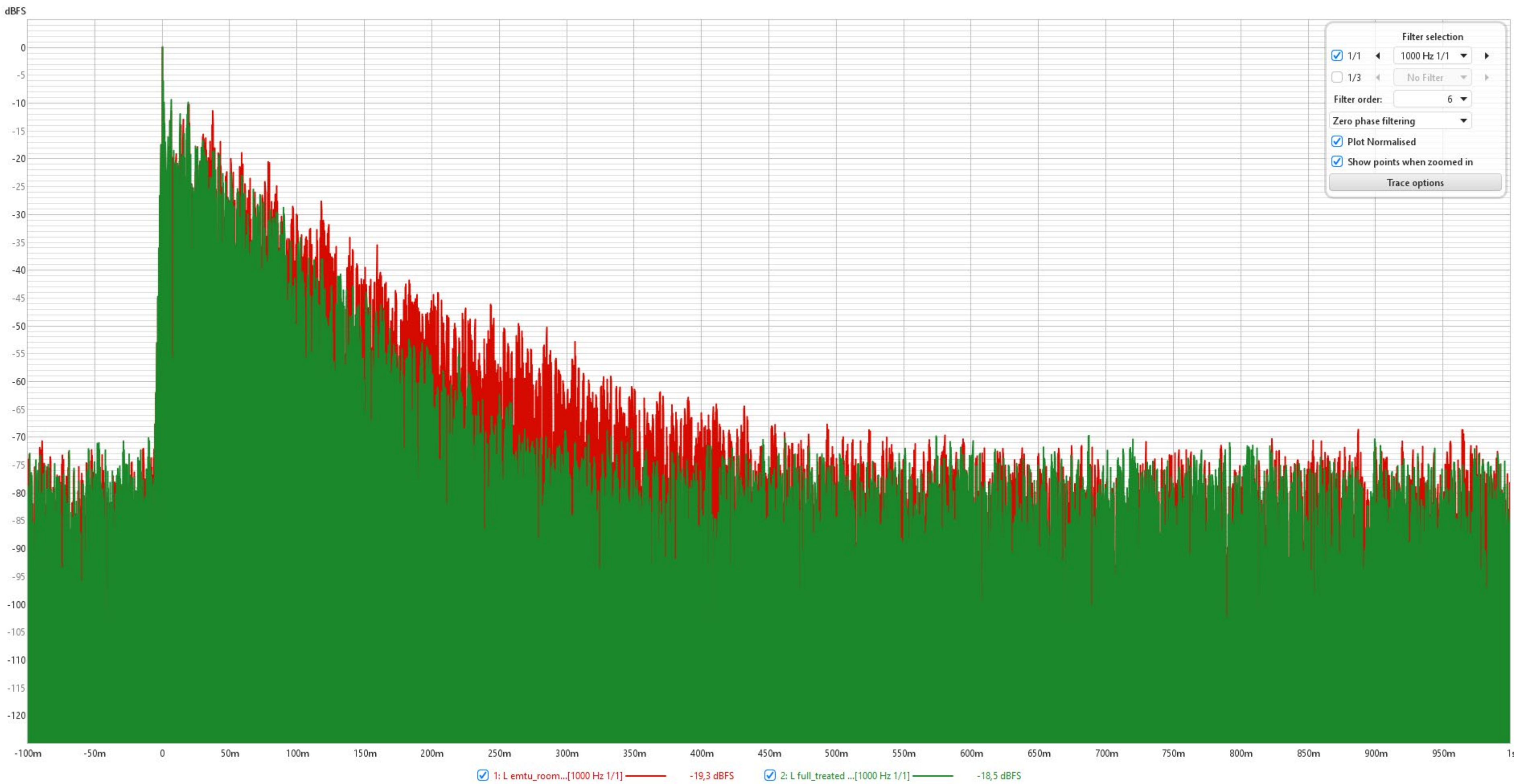

Figure 22 - Impulse response before and after treatment @ 1 kHz

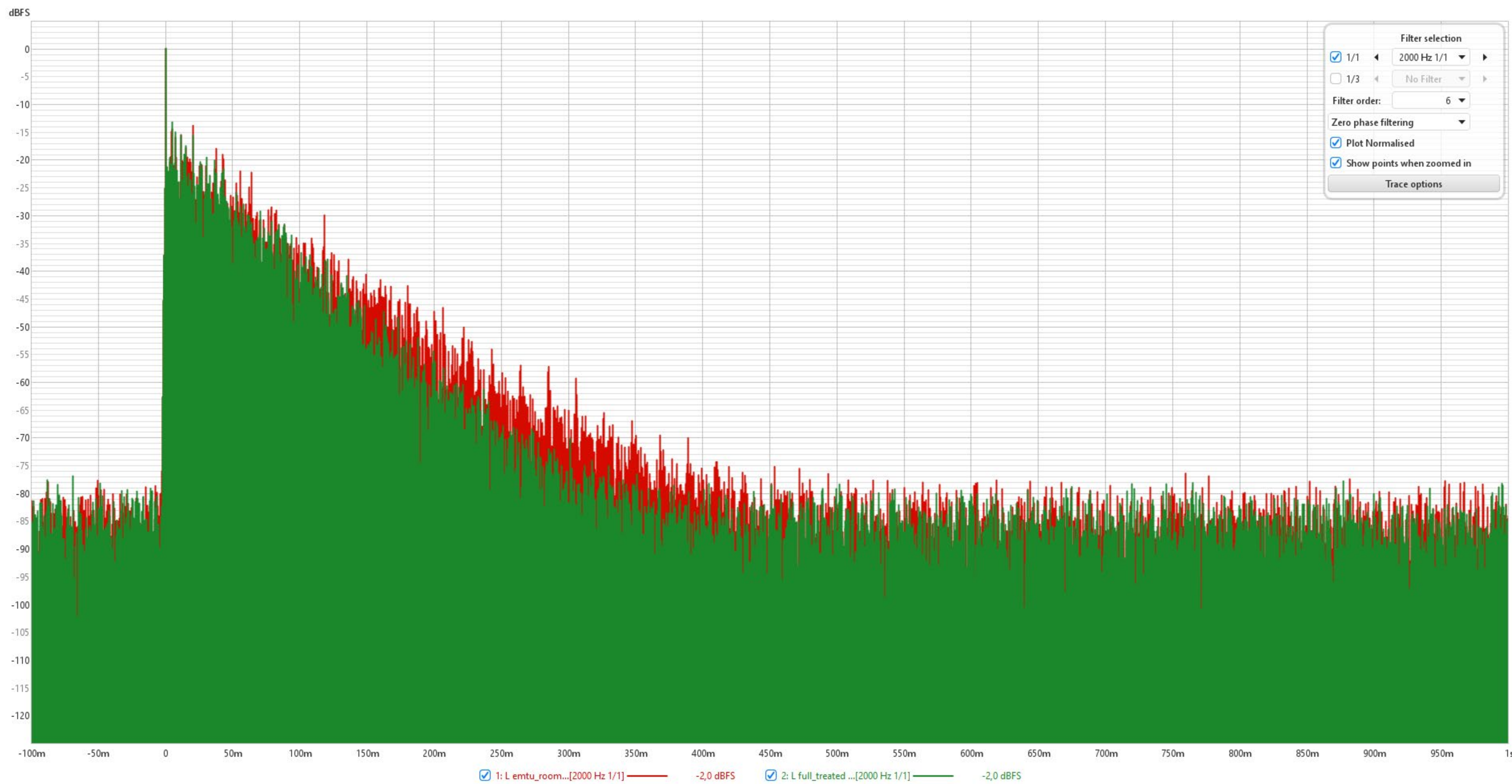

Figure 23 - Impulse response before and after treatment @ 2 kHz

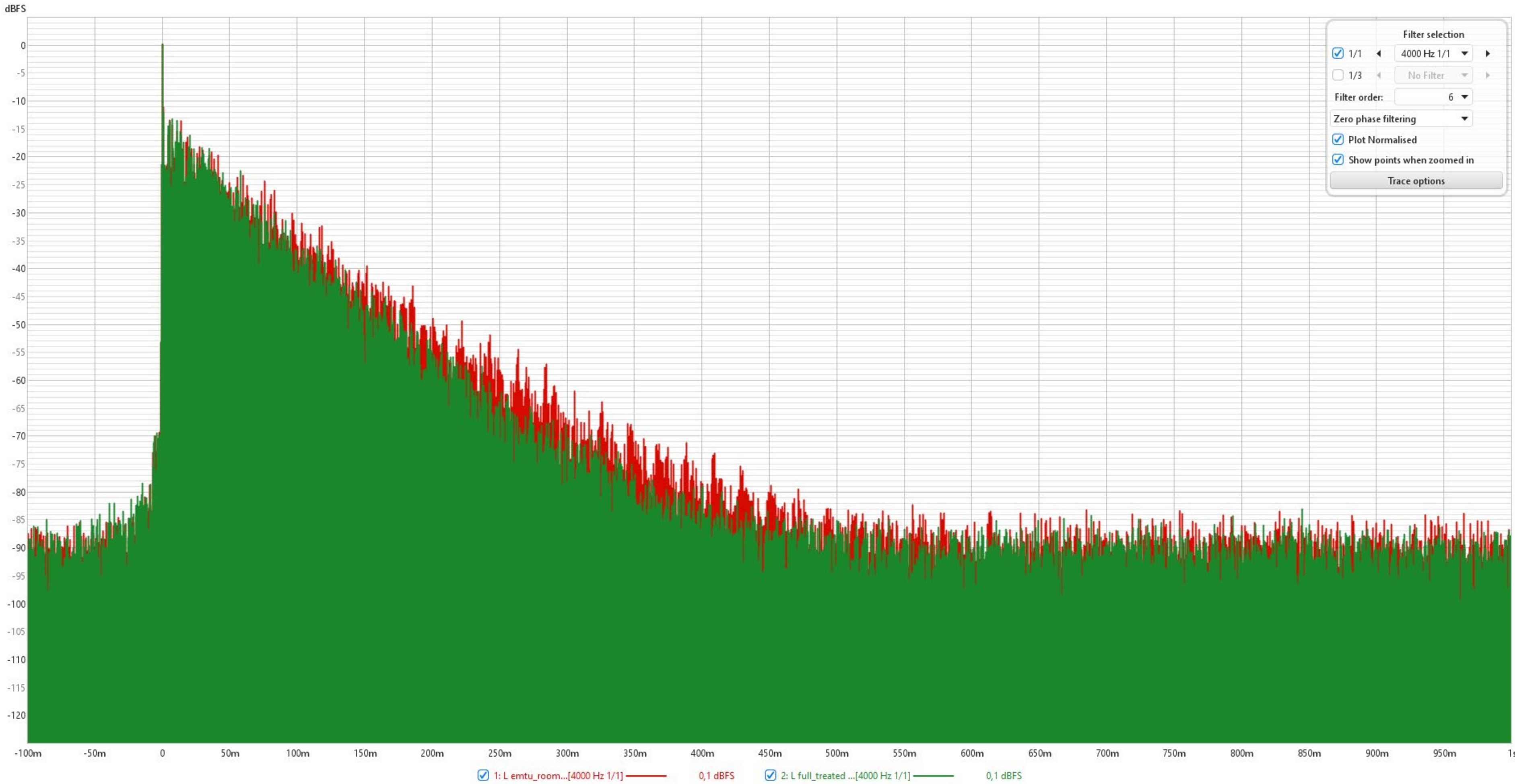

Figure 24 - Impulse response before and after treatment @ 4 kHz

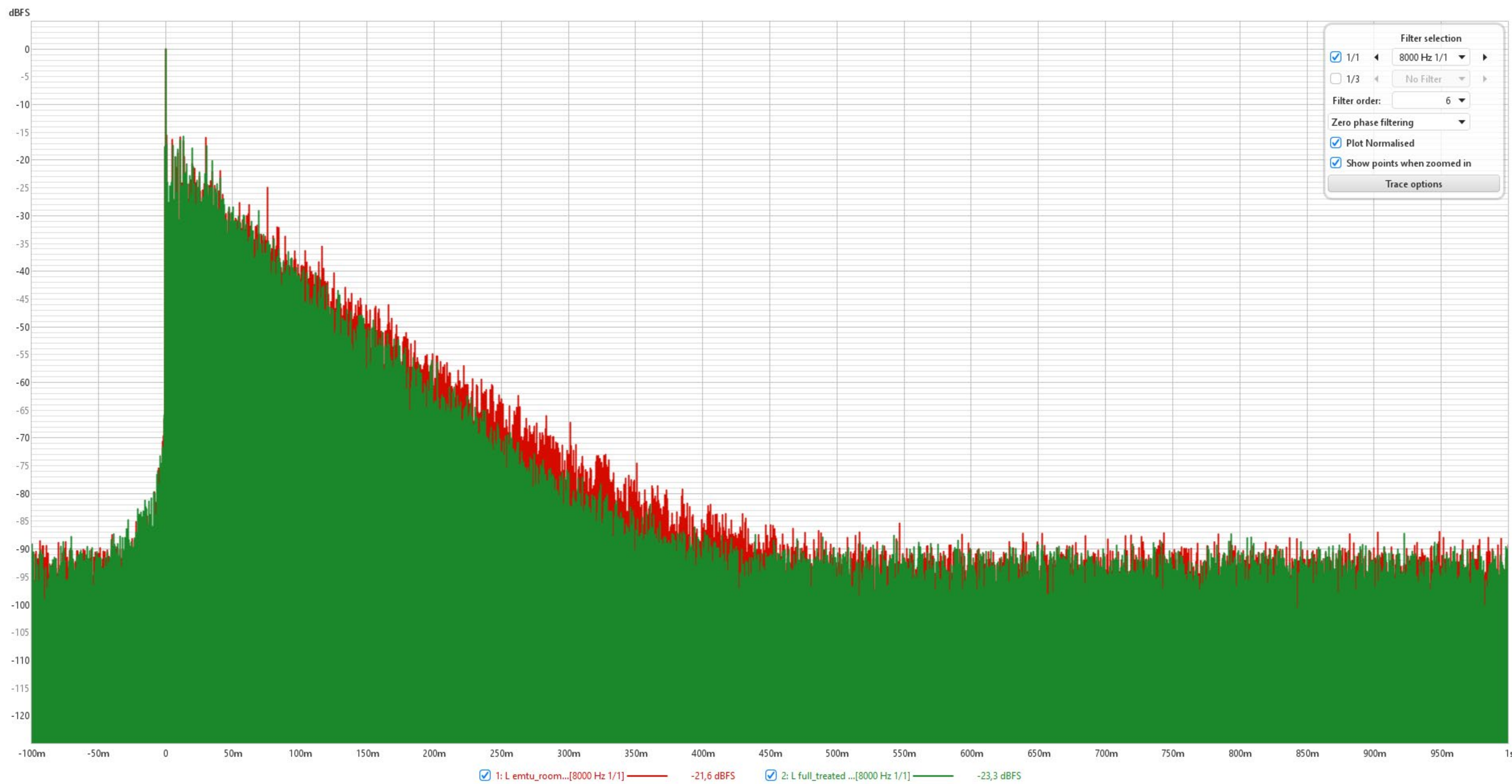

Figure 25 - Impulse response before and after treatment @ 8 kHz

Conclusions

The test results indicate that the 3D printed panels are effective as both sound absorbers and sound diffusers. In the SPL graphs, we observe that the treated room exhibits a smoother response with amplitude reductions of up to 3 dB at certain frequencies (410 Hz, 1252 Hz, and 4000 Hz). Additionally, the reduction in room distortion is evident, particularly at the lower end of the spectrum, as well as at frequencies around 20 Hz, 100 Hz, 130 Hz, 170 Hz, 319 Hz, 360 Hz, 400 Hz, 500 Hz, 660 Hz, 900 Hz, 1200 Hz, and 3560 Hz. The clarity graph shows an average increase in sound clarity by +3 dB across almost all frequency bands. The RT-60 graph demonstrates a decrease in reverberation times for nearly all frequency bands. The most significant reductions are observed in the 300 Hz, 500 Hz, 1245 Hz, 1000 Hz, 2460 Hz, and 5000 Hz frequency bands, with an average reduction of more than 30%. The Impulse graphs clearly show a significant reduction in reflected sounds across all bands, from 250 Hz to 8 kHz. **These results confirm the effectiveness of the 3D printed panels in improving the acoustic characteristics of the room**.

Future research

The promising results of the current study open up numerous avenues for future research to further optimize the acoustic properties of 3D printed panels. One potential area of exploration is varying cell sizes and configurations. By experimenting with different cell sizes, researchers can assess how these variations affect sound absorption and diffusion across various frequency ranges. Smaller cells might prove more effective at higher frequencies, while larger cells could better absorb lower frequencies. Additionally, testing various geometric patterns and configurations, such as irregular patterns, fractal designs, or gradient structures, could help identify the optimal designs for specific acoustic treatments.

Another important factor to investigate is panel thickness. Studying the impact of different panel thicknesses on acoustic performance might reveal that thicker panels provide better low-frequency absorption, whereas thinner panels could be more efficient at higher frequencies. Similarly, exploring different printing materials, such as PLA, ABS, nylon, or composites, will help understand how material properties influence sound absorption and diffusion. Combining different materials within a single panel to create hybrid structures could also prove beneficial in targeting multiple frequency ranges simultaneously.

Modifications to the caps present another promising area for future research. By varying cap thickness, researchers can examine how this impacts the panels' acoustic properties. Thicker caps may enhance low-frequency absorption, while thinner caps might improve high-frequency performance. Different micropening sizes in the caps can also be explored to determine the optimal balance between sound absorption and diffusion. Adding backing cones or other structures to the caps could further enhance sound diffusion and absorption, with potential structures including resonant elements or Helmholtz resonators designed to target specific frequencies.

The effectiveness of various filler materials, such as stone wool, styrofoam, or other porous substances, should also be tested. Each material's density and porosity could significantly influence the panel's acoustic performance.

Utilizing layers of different filler materials within the same panel could create a multi-band absorber that targets different frequencies more effectively.

To explore these research directions, future studies should employ rigorous experimental methods, including controlled acoustic environments and advanced measurement techniques like impedance tubes and reverberation chambers. Accurate assessments of different panel designs can also be aided by computer simulations, utilizing finite element analysis (FEA) and other tools to model sound behavior within and around the panels. This allows for rapid prototyping and optimization. An iterative approach to design and testing, where each new insight informs subsequent experiments, could lead to progressively more effective acoustic treatments.

The findings from these research directions could be applied to a wide range of environments. Customizable panels could be tailored to address specific acoustic issues within recording studios, enhancing sound quality. Improved panels could optimize sound absorption and diffusion in home theaters for a better auditory experience. Versatile acoustic treatments could also be developed for public spaces like concert halls and auditoriums, improving sound clarity and reducing reverberation. By exploring these future research directions, we can continue to advance the field of acoustic treatment, leveraging the flexibility and precision of 3D printing technology to create highly effective and customizable solutions.

References

1. Li, Y., & Assouar, B. M. (2016). Acoustic metasurface-based perfect absorber with deep subwavelength thickness. *Applied Physics Letters, 108*(6), 063502.

2. Dorra, J. (n.d.). 3D-printable sound absorbers. GitHub. Retrieved July 8, 2024, from https://github.com/juliendorra/3D-printable-sound-absorbers