A Study in Small Room Acoustics for the Purpose of Recording

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Abstract

Although many high-end studios are still generating business for themselves, the project and home-based studio has been on the rise since the advent of digital technology in the 1990's. Due to the availability and decreasing price point of digital recording technology, it is now easier than ever for someone to produce audio/visual content out of their own home.

However, there are several potential acoustical problems inherent in small spaces that could keep one's audio work from sounding truly professional. This thesis attempts to identify the problems of small spaces, while also offering potential solutions to these problems in order to produce the highest-quality content when working in an unideal space.

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I. Introduction

Since the inception of recording, audio engineers have strived to provide the highest fidelity recordings. Audio fidelity is important to everyone in the music industry; we make our decisions based on what we hear. If the musical content is not accurately reproduced, our entire decision-making process is flawed.

There are many variables that interact with audio/sound as it flows throughout space, and these variables all influence the final perceived sound. For example, the temperature of the atmosphere around a sound source influences how fast sound propagates through the air ("Speed of Sound"). Among others, one of the most important variables to consider is room size.

Room size is crucial, and for several reasons. Both categories (large vs. small) have different characteristics of which the audio engineer must be aware. For starters, a large room will sound different than a small room. Large rooms typically have more (longer lasting) reverberation, later early reflections, and a larger sense of space. Small rooms, while feeling more intimate than large rooms, come with a host of problems for the audio engineer to overcome. These problems include pronounced resonant frequencies, standing waves, odd reverberation times and tails, and often a lack of liveliness.

Despite these problems, there is a growing trend within the music industry of producers and artists alike building project studios in houses and apartments. These spaces are usually residential and not built with the end goal of recording in mind. As a result, the acoustic problems of small spaces are inescapable. Audio engineers must not only be aware of these problems, but also must have many solutions ready to combat these problems. They must also be aware that the problems require different approaches depending on whether the space will be used for recording audio, mixing audio, or both.

Usually whenever an audio engineer combats acoustic problems in a room, it is referred to as "treating the room." The main goal behind treating a room is to control and shape the way sound interacts with elements within the room, such as its size and boundaries. If the main application of the room is for mixing, the room will be treated such that the room gives as accurate a representation of the sound as possible. This is not necessarily the same goal as a room used for recording. When recording, an engineer may take advantage of a room's shortcomings and use those faults to color a sound in a specific way. This project will focus on the recording application of small rooms.

Depending on budgetary constraints, audio engineers will sometimes opt to use common household materials as acoustic treatment. I have often arranged blankets and furniture around a room to attempt to control and isolate different sound sources. However, there are companies that provide professionally manufactured acoustic treatment products. One such company, Auralex Acoustics, specializes in offering both amateur and professional grade products. Auralex received word of my pending study through my thesis advisor, Michael Hanson, and expressed interest in both the study and any conclusions I make. To that end, Auralex has donated several isolation and treatment products to MTSU. Though I plan on utilizing furniture in my studies, I used these Auralex products extensively, and communicated with them about the results at the end of the project.

This topic is important to me, since I will be graduating in May with a degree in audio production. If it is approved, this project will thrust me into a real-world scenario, ensuring that I leave with skills that will give me an advantage in an already competitive field. It has already landed me a contact within Auralex, and I have not even started taking measurements yet. Furthermore, I have been entertaining ideas of starting up a project studio of my own. If I decide to pursue this venture, the experience gained in this project will be crucial to succeeding in making myself and the studio legitimate.

Thesis Statement

Through the manipulation of materials, ranging from professionally manufactured acoustic treatments to cheap furniture, a producer/engineer can effectively "control" a room in such a way as to minimize its unwanted characteristics. I will attempt to prove this by first researching modern acoustics, and then applying that knowledge to rooms in my own house. The project will have graphs, charts, and empirical data to support my findings, and will also be supplemented with a couple recordings. These recordings will come in two variations: an initial recording and a final recording, to be recorded before and after the room(s) have been controlled. The current state of the music industry is showing a growing trend towards producing/recording music in unconventional spaces and project studios. These spaces often have less-than-desirable acoustic qualities, such as intense resonant frequencies, standing waves, and reverberation. This project will help provide me with skills necessary to identifying these qualities and implementing a solution.

Methodology

The first section of the project revolved around me researching and reading about small-room acoustics. The subject has been extensively written on, and from many different perspectives. Generally, one wants a room to handle sound differently depending on the intent behind using the room. For example, some people may want a room with a longer reverb tail during the recording process, while during the mixing process people may treat the room with acoustic panels to create a more accurate image of the reproduced sound. Given my findings, I had a general idea of what problems and characteristics to seek.

Before any measurements are taken, I recorded samples of typical rock instruments (guitar, bass, drums, vocals) as well as a fully realized, multitracked song. These recordings, as well as data about the untreated rooms' aural characteristics, will serve as a "reference" for the untreated rooms' qualities.

Once the recordings had been captured and mixed, I used Room EQ Wizard software in conjunction with a miniDSP UMIK-1 measurement microphone (with an omnidirectional polar pattern) to take measurements of several untreated rooms in my house, including my bedroom, a "studio" room, and the living room. The UMIK-1 microphone was positioned roughly 1.5ft from a speaker, to imitate a typical microphone setup. I used one Yamaha HS5 loudspeaker and a Focusrite Saffire Pro40 audio as an amplifier for the loudspeaker.

Room EQ Wizard (abbreviated as REW) is a software developed to measure and analyze frequency responses of rooms and loudspeakers. The end goal is to have a room response that is relatively flat, with no large peaks or valleys in the frequency response.

Any peaks or nulls in this line can indicate either a resonant mode or a null/cancellation. Resonant modes are frequencies that are naturally excited by the room, whereas nulls/cancellations are frequencies that are naturally attenuated by the room. It's important to remember that these peaks and valleys are attributes of the room. An engineer might be tempted to simply use an EQ as a solution, but the room will continue to act on these frequencies in the same way.

After the initial, untreated measurements were taken, I took more measurements of each room, each time changing something about the room's setup. I started by moving and placing my furniture around the room based on the type of material of which it is made. After the furniture had been rearranged, I took a measurement of that room's new qualities. After all the furniture setups had been measured, I used Auralex Acoustics products to try and control the rooms' sonic qualities, to see if this is any better or worse than the previous outcomes. This process of rearranging the room setup and taking measurements was repeated numerous times and with variations in each room to be tested.

After all the measuring had taken place, and I had found treatment setups that best showcased each room, I re-recorded the same instruments and song from the beginning of the project. The resulting recording was compared to the initial. I wrote a short reflection on my expectations of the project going in, my experiences in conducting the experiments, my thoughts/concerns about the outcome of the project, and an overview of what worked and what did not.

Despite my efforts, my findings might not be 100% accurate. There is a common accepted idea among audio engineers regarding the measuring of a microphone's and/or loudspeaker's performance. To measure a microphone's performance, you need a room to put it in, and loudspeakers to generate some sonic content. The room's qualities and the loudspeaker's limitations may result in inaccurate representations of the microphone's true performance. For example, if the room has a resonant mode at 2 kHz in the center of a room, and the microphone is placed within that mode, the mic will be judged as being particularly sensitive to mid-frequencies around 2 kHz. Similarly, to test a loudspeaker's performance, the chosen room and microphone play into how the loudspeaker's performance will be measured. The microphone may not be very responsive to low frequencies, in which case the loudspeakers themselves are judged as having poor bass response. There really is no ideal solution to this conundrum, other than to be aware of it and to attempt to use equipment with flat frequency responses.

II. Preliminary Thoughts

My thoughts going into the project were optimistic. I knew that small rooms have several problems that large rooms do not, but I was confident that I could overcome these problems and create a high-quality product. Many of my favorite records were recorded in domestic spaces, and sometimes by individuals who arguably knew less about audio production than I do. These records include *Cardinal* by Pinegrove, *Periphery III* by Periphery, *The Beautiful Game* by Vulfpeck, and *... Soundtrack to a Death* by Mura Masa. Granted, these records span various genres, and each album underwent a unique production process. But at some point during the making of these records (be it recording, mixing, or mastering), unideal spaces were used.

The acoustic problems inherent in small rooms can be dramatic, if not treated. I knew that after being treated, the room would react much differently when excited. However, I was unsure about exactly the degree of change that acoustic treatment would bring. My main concerns were that modal resonances would skew the room's frequency response, and that the room's dimensions would create awkward decay times. Modal resonances create acoustic dead spots called "nodes," where a particular frequency is cancelled out entirely due to the relationship between wavelength and room dimensions. These resonances can also create "anti-nodes," or areas that double the frequency's amplitude. These can create problems if a microphone is placed in either a node or anti-node; the acoustic information picked up by the microphone is inherently flawed. Long decay times can also be problematic. The longer the decay time, the more of the room's natural reverb is captured. This makes the reverb inseparable from the desired audio, and is one reason why many audio engineers place amplifiers in an acoustically dead space.

Another concern of mine was each room's dimensions. A room's shape has as much of an effect on sound as its size does. The bedroom and the studio room are both very square shaped, while the living room is slightly more rectangular. Eric Smith, founder and president of Auralex Acoustics, says, "One important thing to keep in mind is that the worst sounding rooms are always going to be ones whose three dimensions are all divisible by the same number, for example 24'x36'x12'." (39) This room could be described as having a dimension ratio of 2x3x1; an undesirable ratio for audio work. Furthermore, a room that is a perfect cube is also undesirable. In both examples, the room will resonate at a fundamental frequency, as well as harmonics of that frequency. Generally, a rectangular room is better than a square-shaped room. The rectangular shape helps minimize the possibility of a similar standing wave occurring across the three dimensions (length, width, and height).

As a side note, I decided not to record vocals for this project. Vocals are usually recorded as an overdub in a dead-sounding space, with little to no reverb present in the actual recorded audio. This gives the mix engineer a greater amount of control during the mixing process, and allows him/her to craft a desired reverb sound using either outboard gear or plugins to create a sound that best compliments the vocals for that song. Since this project focuses on small room acoustics, I felt that vocals did not necessarily apply here, so I simply left them out.

III. The Initial Recording

The initial recording took place across all three rooms. Electric guitars and bass were recorded in the studio room, drums were recorded in the living room, and a scratch acoustic guitar was recorded in my bedroom. The song to be recorded is an original song I wrote titled, "In Progress." I decided to record an original song to avoid any potential copyright issues (plus it's just more fun). The song is 4:34 in length, with a non-traditional structure.

I started by recording a scratch track using electric guitar. A scratch track is a temporary recording used alongside a metronome to give other musicians (usually drummers) some musical context to play from during the recording process. This scratch track helped to convey information such as transitions to different sections, dynamic builds, and rhythmic syncopation.

After recording the scratch track, I recorded drums. I cannot play the drum kit with any convincing amount of skill, so I called in my friend Wes Rodberg, a commercial percussion major from Belmont University. We set up his drum kit in the middle of my living room, moving the coffee table into another room to clear up enough space for all of the hardware. He brought a Tama Star Classic kit with an assortment of Meinl cymbals. We used six microphones to capture the drum kit's audio: two AKG C1000's, a Blue Spark, and three Shure SM57's. The AKG C1000's were arranged as a spaced pair above the kit, one above the ride cymbal and one above the snare drum. These were meant to capture cymbals, as well as some ambience from the kit as a whole. The three Shure SM57's were used to capture the kick drum, the top of the snare drum, and the bottom of the snare drum. It is common to place microphones on both the top and bottom of a snare drum due to the different timbres that each side produces. A mix engineer will then blend the two sounds together during post-production to create the typical snare drum sound. The Blue Spark was used as a room microphone, meaning it was placed a distance away from the kit to capture some of the room ambience as the drums are played. This microphone was placed behind one of the couches in the living room, to ensure that it did not pick up any direct sound from the drum kit.

After drums were recorded, I recorded bass guitar. I used an Acoustic B200 amplifier with 200 watts of power and a 12" speaker. The bass itself is an SX model, meant to be a copy of the popular Fender Jazz Bass. The song was written in an alternate tuning, so I tuned the bass to drop D (D A D G) instead of the normal E standard tuning

(E A D G). I used a single Shure SM57, placed an inch from the amplifier's grille, to capture the audio. It was recorded in the studio room, with the amplifier angled towards a corner and placed slightly off-center. All of the furniture in the studio room was left alone, as was the case in the living room during drum recording. One of my roommates keeps his desktop computer in the studio room, and I was concerned about mechanical noise such as fans bringing up the noise floor of the bass track. However, upon playback, it proved to not be too big an issue.

With a solid rhythm section foundation, guitars were next in line to be recorded. I used an Ibanez GAX70 with a Fender Super-Sonic amplifier, rated at 180 watts and equipped with a 12" speaker. As I mentioned earlier, "In Progress," was written in an alternate tuning, so the guitar was tuned to D A D G A D instead of the E standard tuning E A D G B E. There are two different guitar parts; one clean part, and one distorted part. These two parts follow the same chord progressions, but differ slightly from each other. These parts were recorded on the same day, using the same microphone setup. The microphones used were a Shure SM57, a Blue Spark, and PreSonus M7. The Shure SM57 was placed two inches away from the amplifier's grille, while the Blue Spark was placed five inches away. The PreSonus M7 was used as a room mic and placed several feet away from the amplifier. The amplifier was placed off-center in the room, roughly four feet from the studio room's corner, and oriented towards the opposite corner. For the clean guitar part, I just recorded the clean guitar signal coming out of the amp. The distorted guitar part required a distortion pedal, namely the Earthquaker Devices Crimson Drive. This pedal is the only real difference in the signal chain between the two guitar parts.

All the instruments and sound sources were recorded prior to any room testing. The idea behind this was that I would record a song as I normally would, test the rooms and research acoustics, and then apply my findings in a second recording and compare the differences between the two sound recordings. The idea to not give the songs a proper mix stemmed from the fact that this project is centered around working with unideal acoustic spaces. It seemed a little dishonest if I were to "sugar-coat" the raw audio to make it sound better, when this project is meant to be a close look at sound behavior in small spaces.

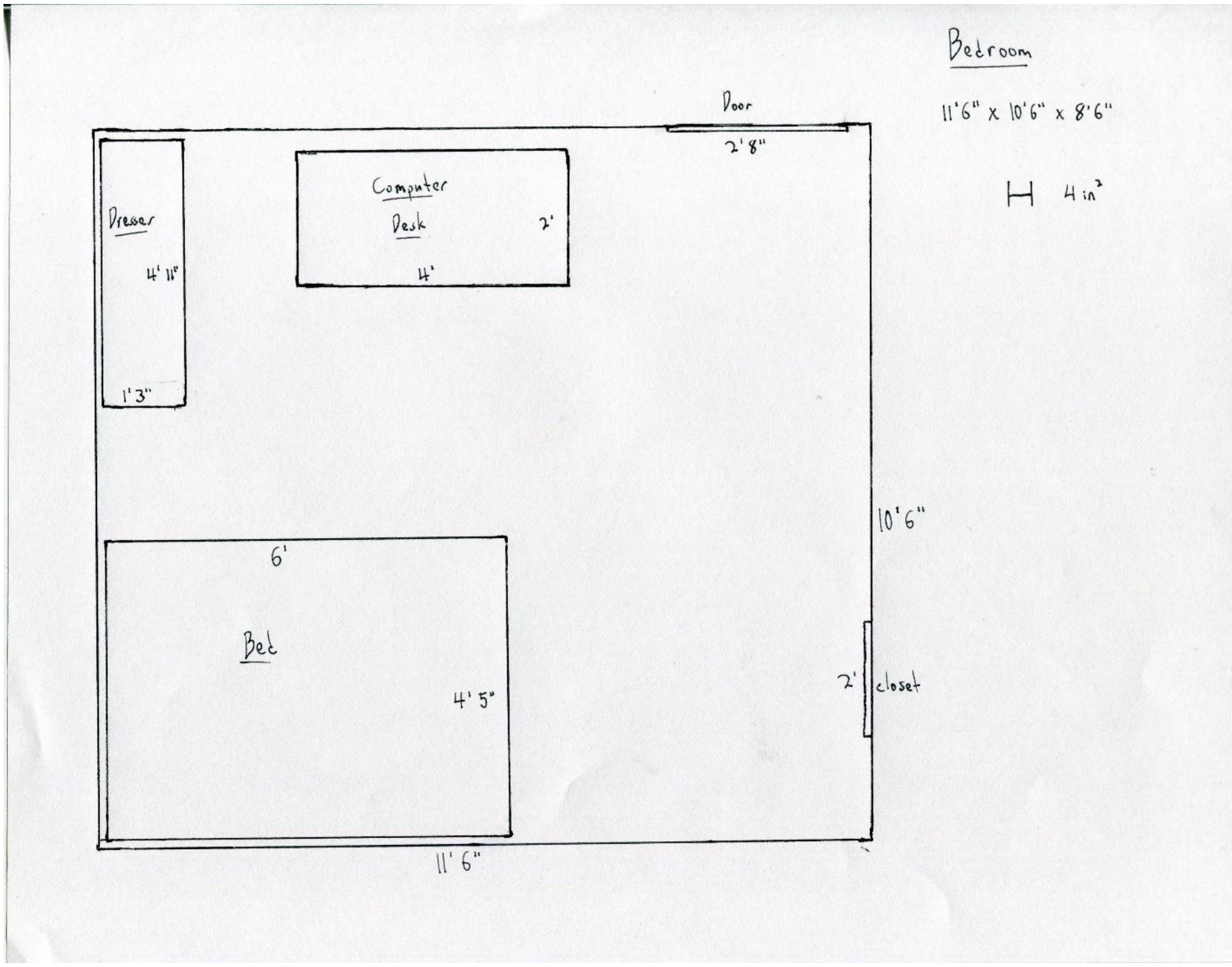
IV. Room Testing

Before any room testing was done, the first thing I did was measure each room's dimensions. With these measurements, I drew top-down maps of the room, to give the reader an idea of the room's layout. I also entered these dimensions into a program called ModeCalc. ModeCalc is a program developed by acoustician and audio engineer Ethan Winer, meant to calculate a room's axial modes given its dimensions. However, ModeCalc only shows modes from 20Hz – 500Hz. This is because low-frequency modes require more attention than higher-frequency modes, for several reasons. For one, low-frequency modes are more dispersed than high-frequency modes; in other words, modes from 20Hz – 500Hz are spaced further apart than modes located in higher frequencies. This is problematic because the sparser the low-frequency modes are, the more noticeable these resonances will be. These resonances create an inaccurate representation of any audio existing in the space and will effect an audio engineer's decision making process.

With ModeCalc graphs and maps made for each room, I had a slight idea of what to expect going into each room. Even still, the testing and treatment process required a lot of trial-and-error, as there was no easy way to calculate the changes that occur due to moving furniture and Auralex products.

All tests used one Yamaha HS5 speaker and one miniDSP UMIK-1 calibration microphone. The microphone was placed roughly 2 ft. away from the speaker. Each test used a sine sweep (a sine wave sweeping up through a prescribed set of frequencies) ranging from 10Hz – 20,000Hz at 85 dBSPL. I used Room EQ Wizard (REW) to capture and analyze the audio, and used a Focusrite Saffire Pro 40 audio interface as the computer's soundcard.

The Bedroom



The bedroom's dimensions are 11'6" x 10'6" x 8'6". This is not a particularly good space; generally speaking, a more pronounced rectangle shape will always beat out a square-shape. Furthermore, the bedroom only has 1,026 cubic feet of space. With a bed, dresser, and desk already occupying much of the floor space, the bedroom can quickly feel crowded with any more than two people in the room. For reference, Ethan Winer's suggested minimum volume for a room is 2,500 cubic feet. This being the smallest out of the three rooms, I knew it would be difficult to minimize the room's negative characteristics.

An initial measurement of the bedroom showed a very erratic frequency response (Figure 1.1), with several deep notches in the low-mids and high-mids. The difference between the loudest frequency (95 dBSPL at 902 Hz) and the softest frequency (40 dBSPL at 30 Hz) was 55 dBSPL. The second softest frequency was 1.46 kHz, at 53 dBSPL. Several of the modes present in the room had a very long decay rate (Figure 1.2), meaning that frequency continued resonating in the room long after other frequencies had decayed into inaudibility. I started to move around the available furniture in hopes of taming the low-frequencies and smoothing out the frequency spectrum's decay rate.

I started by propping up my bed mattress against the back wall and covering the bedframe with my comforter. I thought that the mattress would absorb some of the sound that was being reflected off the back wall, while the comforter would help to dampen the metal bedframe and keep it from resonating. The results did not bode well. These measurements showed even deeper notches than the Initial Test, and even boosted a mode at 55 Hz by 4 dBSPL (Figures 1.3 & 1.4). The low-frequency behavior was just as erratic and exhibited many of the same problems as the initial test. I draped the comforter over the mattress and took another measurement, thinking that the added padding might help. However, the difference between Test 1 and Test 2 was negligible. Both tests only changed the room's decay rates by miniscule amounts (Figures 1.5 & 1.6).

Test 3 eliminated some of the problematic notches present in the Initial Test. However, it also introduced some new notches at 325 Hz and 528 Hz (Figures 1.7 & 1.8). For this test, I simply moved the mattress over to the back left corner, in the hopes of taming low-frequency buildup in that area. Building off of this corner-treatment idea, for Test 4 I left the mattress in the back left corner and opened my closet door, draping the comforter over it. Now both back corners were somewhat treated. Test 4 was an improvement over Test 3, but again this improvement was miniscule (Figures 1.9 &1.10).

Given that the corner-treatment approach had yielded the best results thus far, for Test 5 I left the mattress propped up against the back left wall. Instead of using the closet door again, I moved my desk chair against the back right corner, stacking pillows, sweaters, and scarves on it to reach as high up the wall as possible. I also draped a blanket over the dresser on the left side of the room, to help tame any reflections caused by its surface and the books resting on it. This test was the most successful out of all five furniture-based tests, but even still the room was not as improved as I thought it would be. The notches present in this measurement were sparser than previous tests, and not as deep. The frequency response past 1 kHz was more smoothed out than previous tests as well (Figure 1.11). However, the decay rate across the frequency spectrum was erratic, with several nulls occurring across the spectrum. There is an especially noticeable resonance at 53 Hz that resonates much longer than 300 milliseconds (Figure 1.12); this is incredibly undesirable and can skew the accuracy of any audio played within the room. Having done as much as I could with the furniture available in the bedroom, I started introducing Auralex products into the testing process.

For Treatment Test 1, the Auralex products offered an immediate improvement over all of the preceding tests. Using just three Sunburst 360’s (I could not find a way to prop one up on top of my mattress in the back left corner), I was able to eliminate all but a few of the problematic notches in the room’s frequency response (Figure 1.13). The frequency response was still nowhere near flat, with boosts and dips all over the place, but getting rid of the notches was a large improvement over the furniture tests. The decay rate of this test largely reflected the frequency response, with frequencies that were boosted having a longer decay rate than those frequencies that were attenuated (Figure 1.14).

Treatment Test 2 felt like a step backwards. I moved the Sunburst 360's away from the corners and placed two of them behind the microphone. The Sunbursts were separated from each other by about 2.5 feet, with the UMIK-1 microphone placed in between them and forward by 1 foot. Without the corners being treated by something, comb filtering became a problem again, and there were several deep notches present that were not there in Treatment Test 1 (Figure 1.15). Treatment Test 2 also exhibited a worse overall decay rate across the frequency spectrum, with more resonant modes than Treatment Test 1 and longer decay times (Figure 1.16).

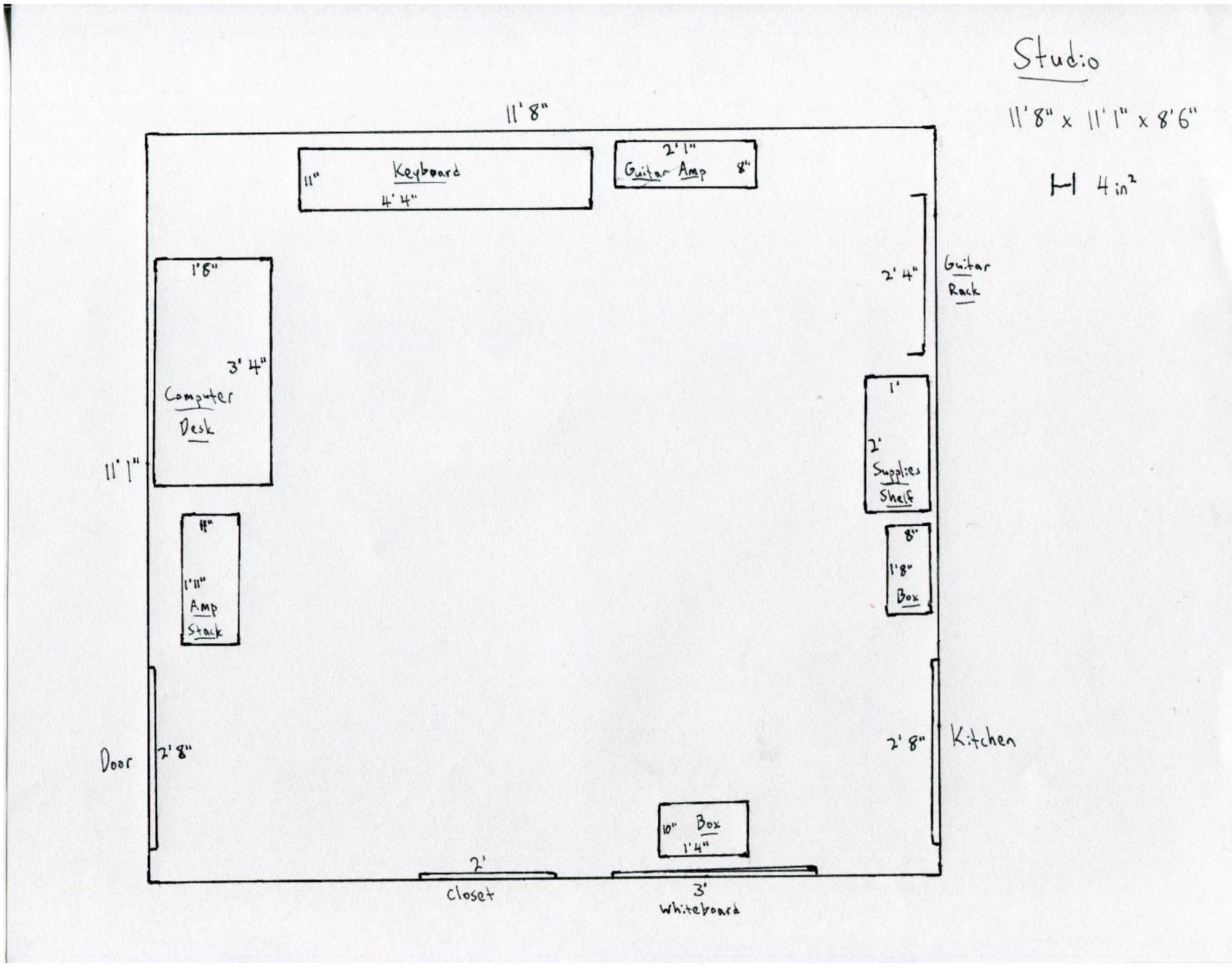
I returned the three Sunburst 360's to the back corners and the front right corner, and put two ProMax's up against both side walls, absorbing side facing out. I again propped up my mattress in the center of the back wall, to catch first reflections off of that wall. With this setup, Treatment Test 3 was not necessarily an improvement over Treatment Test 1. Some of Treatment Test 1's problems were remedied, but for each solution another problem arose. There were a couple notches in Treatment Test 3 that were not present before (Figure 1.17). Furthermore, the low frequency decay rates between 80Hz – 200Hz were slightly longer, but above 200Hz the decay rate was shorter and smoother than Treatment Test 1 (Figure 1.18). I believe treating the side walls was a big factor contributing to the shorter decay times; minimizing the reflections between the two side walls allowed for less sound to bounce around the room. The only difference between Treatment Test 3 and Treatment Test 4 was that the latter included an extra

Sunburst 360 placed 1.5 feet directly behind the UMIK-1 microphone. Test results were almost identical, with Treatment Test 4 having slightly improved low-frequency response (Figures 1.19 & 1.20).

Treatment Test 5 was very similar to the previous two tests. It utilized three Sunburst 360's placed in the front right corner and back corners, as well as another Sunburst placed 1.5 feet behind the microphone. The two ProMax's had been moved to either side of the microphone, angled inwards. They were roughly 2 feet away from the microphone, with the absorbing side facing towards the speaker and microphone. This test showed definite improvements over the previous tests, with very few notches present and a decrease in overall decay rate (Figures 1.21 & 1.22). The close proximity of the Auralex products is the result of these improvements; they absorb some of the direct sound before it ever gets a chance to reflect off of room boundaries.

Treatment Test 6 was identical to Treatment Test 5, except that the ProMax's had been turned around so that the diffusing side faced the speaker and microphone. This did not have a drastic effect on the frequency response; there were several notches present, but none of them were very deep and they were all present at and above 800 Hz (Figure 1.23). The main difference between Treatment Test 5 and Treatment Test 6 was the decay rate (Figure 1.24). Due to the diffusers used in the latter test, Treatment Test 6 exhibited a slightly longer overall decay rate. However, the low-frequency behavior was the most effected, with several resonances occurring below 200 Hz, specifically at 53 Hz, 60 Hz, 84 Hz, 106 Hz, and 120 Hz. These resonances extended well beyond 300 ms.

The Studio



The studio has slightly more space than the bedroom, measuring 11’8” x 11’1” x 8’6” with 1099 cubic feet. Even though it is only marginally bigger than the bedroom, the studio only houses smaller furniture items such as amplifiers, a guitar rack, a small computer desk, and an electric piano. All furniture items are pushed up against the walls, leaving the center of the room open. Despite being a larger space, the studio is actually squarer than the bedroom, making it more difficult to remedy all of the room’s problems. What’s more, the studio had more items in it that were likely to resonate when excited, such as instruments and metal signs decorating the walls.

The Initial Test showed a slightly more controlled low-end than the bedroom, but there were several deep notches spread across the frequency spectrum at 51 Hz, 192 Hz, 531 Hz, 1.176 kHz, 1.959 kHz, and 3.111 kHz (Figure 2.1). In this room, the difference between the loudest frequency (934 Hz at 91 dBSPL) and the softest frequency (22 Hz at 45 dBSPL) was 46 dBSPL. The decay rates were not particularly good, either. Above 2 kHz, the average decay time was 240 ms, with decay times above 8 kHz dwindling to under 120 ms. However, below 2 kHz the decay time rose to sit between 240 ms and 300 ms, with resonances at 30 Hz and 60 Hz ringing past 300 ms (Figure 2.2).

For the first test, I thought it would be best to cover some of the more oddly shaped things in the room that might diffuse sound. I draped a blanket over the computer and desk, and draped a comforter over the electric piano and guitar amp. This helped smooth out the low-frequency response a little bit, at the expense of creating a large notch at 27 Hz all the way down to 30 dBSPL (Figure 2.3). Some of the other notches present in the Initial Test were reduced during Test 1, but there were also some new notches present extending down to 55 dBSPL. Thinking that the next step would be to dampen instruments whose natural tendency was to resonate, I moved on to Test 2.

As it turns out, the idea to cover and dampen the string instruments in the guitar rack was a good idea. After moving the blanket from the computer and desk to cover the guitar rack, Test 2 showed improvements over both Test 1 and the Initial Test. There were some deficiencies in low-frequency behavior that were worse than the two previous tests, and also a large notch at 912 Hz reaching down to 47 dBSPL (Figure 2.5), but other than that Test 2 smoothed out some of the irregularities from the previous tests. Test 1 and Test 2’s waterfall graphs and decay rates were nearly identical, save for a notch at 24

Hz in Test 2 that significantly reduced the resonance at that frequency (Figure 2.6). There was still a long way to go before the room was considered acceptable.

After conducting Test 2, I wondered just how detrimental the metal signs adorning the wall were to the room's acoustics. So I removed the two blankets from the room, and took down all metal decorations on the walls to see if the room acted any differently without them. The result was different from the Initial Test, with less notches present and slightly improved decay rates (Figures 2.7 & 2.8). Despite having fewer notches, Test 3 did have one notch that was deeper than all of the Initial Test's, located at 1.620 kHz and reaching down to 41 dBSPL. Now that I knew the metal signs were somewhat of a detriment, I kept them out of the room for the remainder of the tests and continued covering and dampening furniture.

I returned the comforter to where it had been draped over the computer, and put the blanket back over the guitar rack. I also took a mattress pad from the studio's closet, and positioned it to cover the electric piano. This helped smooth out some of the notches found in the mids and highs, at 1.63 kHz and beyond (Figure 2.9). Test 4's frequency response below 1 kHz was nearly identical to the response from Test 3. After seeing the slight benefits from adding the mattress pad into the room, I wondered about my decision to place it on the electric piano. While the electric piano does have an odd shape, it was behind the speaker, so it would just be diffusing reflected sound.

I decided to put the mattress pad over the studio's closet door for the last furniture test. I kept the door only slightly open; my intention was to use the door to prop up the mattress pad so that it would hopefully absorb some of the direct sound from the speaker.

This helped to reduce two notches at 905 Hz and 1.283 kHz, but also introduced a new deep notch at 557 Hz (Figure 2.11).

Even though the frequency response across continually improved across each test, the waterfall graphs and decay rates are incredibly similar, even after removing the reflective metal signs from the walls. Removing the signs did decrease the upper-mids and highs decay right slightly, but there was still a good amount of low-frequency buildup present in the room. Having used all feasible pieces of furniture available in the studio, I started to implement the Auralex products.

First, I took two Sunburst 360's and placed them in the front corners of the room. I then took one ProMax panel, and placed it in front of the closet door, putting it directly in line with the speaker. I made sure the absorbing side of the panel faced outwards, as I thought this would be more beneficial than the diffusing side. This setup significantly reduced low-frequency buildup in the room, as evidenced by the accompanying waterfall graph (Figure 2.14). However, the addition of the Auralex products did not fix the notches at 217 Hz, 275 Hz, 351 Hz, and 415 Hz that were present in several of the previous tests. Despite that, these notches were all shallower than before, showing slow but sure signs of progress (Figure 2.13).

Curious about the effect that diffusion would have on the studio's acoustics, for Treatment Test 2 I simply turned the ProMax panel around so that the diffusing side faced outwards into the room. Besides that, this test was identical to Treatment Test 1. As it turned out, diffusing the sound did not improve anything. In fact, it only exacerbated the problematic notches from Treatment Test 1 (Figure 2.15).

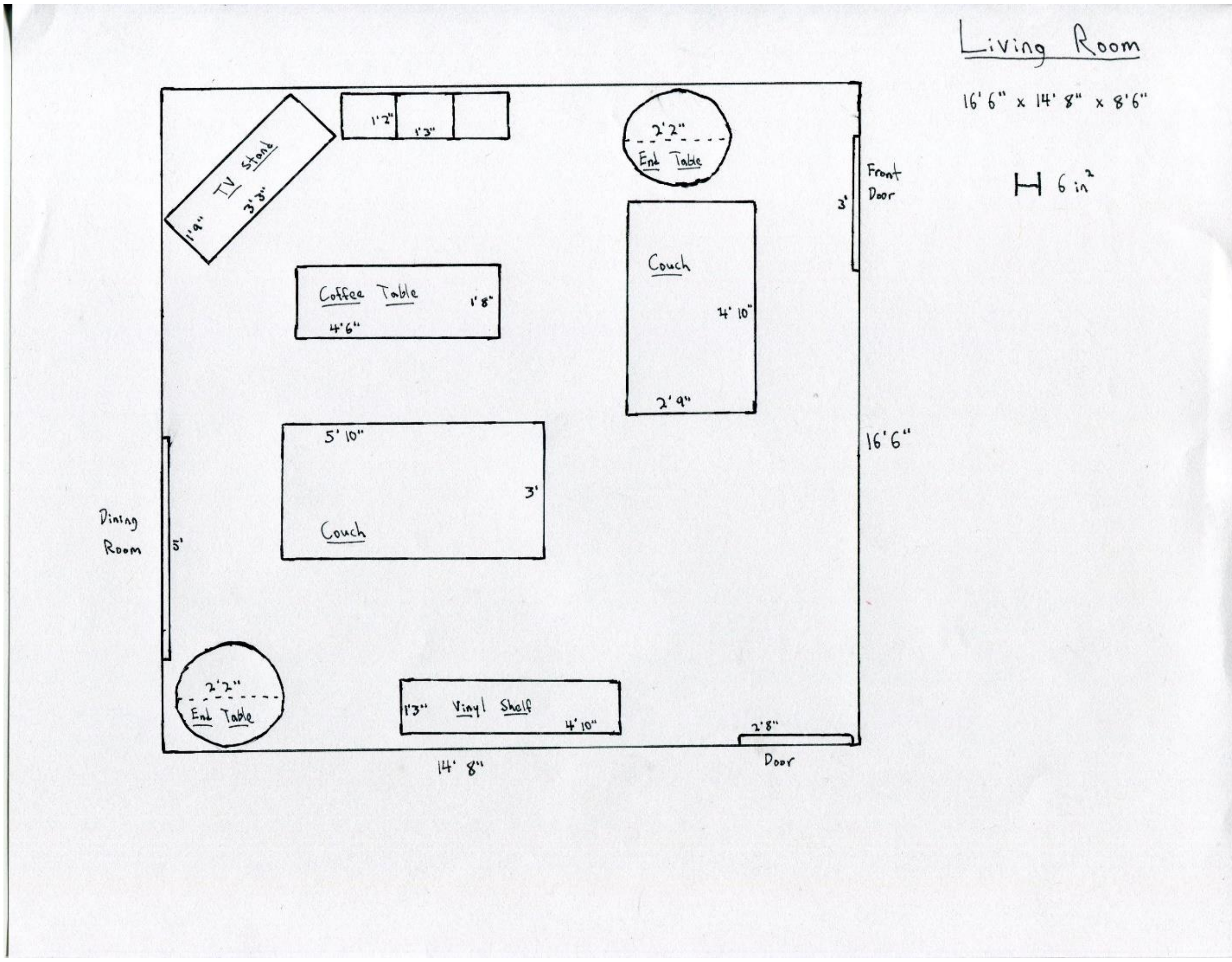
For Treatment Test 3, I removed both Sunburst 360's from the room. I took both of the ProMax panels, and positioned them diagonally in both of the front corners, absorbing side facing outwards. This helped clean up the notches at 350 Hz, 489 Hz, and 562 Hz. However, It did create some new notches at 909 Hz, 943 Hz, 1.255 kHz, and 3.355 kHz (Figure 2.17). I believe the reason for this is due the caddy-corner positioning of the ProMax's, as well as a lack of treatment on the wall in front of the speaker. The ProMax's created an absorbing barrier in front of the corners, but there was still space between them and the corner. This is good for bass traps, as a low-frequency sound wave with a long wavelength is best absorbed when there is some separation between treatment and surface. However, the bare wall in front of the speaker reflected a lot of the speaker's direct sound, allowing for mid and high frequencies to more readily reflect around the room, creating the cancellation present in the frequency response. Treatment Test 3's waterfall graph featured slightly increased decay rates from ~400 Hz - ~2 kHz (Figure 2.18). I also attribute this to the lack of treatment on the front wall.

I again turned the ProMax's around to face the diffusing side outwards for Treatment Test 4. Before actually taking a measurement, I had guessed that this test would yield deeper notches in the mid-frequencies, with extended decay times. However, Treatment Test 3 and 4 were startlingly similar. There were barely any differences at all, in fact. This was surprising, as I would have guessed that the additional diffusion added into the room would be problematic.

Treatment Test 5 featured just one Sunburst 360 and both ProMax panels. The Sunburst 360 was placed about one foot behind the speaker, while the two ProMax's were positioned in front of the speaker at the wall. Rather than keeping them flat against the wall, I angled them to create a “V” shape, with the speaker firing into the opening of the “V.” This test smoothed out some of the notches in the mid-frequencies, but created four notches at 273 Hz, 351 Hz, 560 Hz, and 675 Hz (Figure 2.21). Treatment Test 5’s overall decay rate was shortened in comparison to Treatment Test 4, but it also had some odd resonances. These resonances were located at 226 Hz, 436 Hz, 517 Hz, 675 Hz, and 1.074 kHz (Figure 2.22).

Throughout all of the tests conducted in the studio room, there had been an excess of low-frequency buildup and slow decay rates. The Initial Test showed buildup from 20 Hz all the way up to about 1.5 kHz, while the final Treatment Test 5 reduced the buildup from 20 Hz to 135 Hz. This is a significant improvement, but the decay rates in this bandwidth still extended well beyond 300 ms, and are very problematic for anyone trying to make precision-based audio decisions in that room. All decisions regarding low-frequencies would be skewed, since those frequencies would linger considerably longer than the rest of the frequency spectrum.

The Living Room



I saved the living room tests for last, because this room showed the most potential to be converted into a near-ideal space. The living room's dimensions measured 16'6" x 14'8" x 8'6", with 2057 cubic feet of space. There was one major problem with it, though. On one side of the room was an open entryway into the dining room measuring five feet long. There was no easy way to cover this opening. This simple architectural decision makes the living room function different from both other rooms, since any sound existing in the living room could reflect into the dining room area and (potentially) back into the living room. Furthermore, this room had the most furniture in it. Thinking that this room would be the most interesting, I was excited to begin testing.

Right out of the gate, the living room's Initial Test showed potential. The frequency response still exhibited its fair share of notches, with an especially deep one at 1.027 kHz, but overall the response was more flat than the previous rooms had been (Figure 3.1). The waterfall graph showed that there was some low-frequency buildup, especially from 33 Hz – 130 Hz, but there was also a lot of energy persisting in the room from 300 Hz – 5.65 kHz (Figure 3.2). The living room's walls are mostly bare, and has wood-paneled floors. The other two rooms had more wall decorations, and carpeted floors. Bearing this in mind, it makes sense that the living room is reflective, and the slow decay rates of the middle frequencies was not unexpected.

For the first test, I moved the large denim couch to block the entryway to the dining room, hoping that this would help absorb some of the rogue reflections moving in and out of the two connected rooms. I also pushed a small red chair into one of the room's corners, and draped a blanket over the TV and its stand. This test was actually a step backwards from the Initial Test. The most noticeable difference was the decay rates across the entire frequency spectrum. Moving the denim couch to the side of the room allowed for more sound to reflect off the floor and off of the vinyl shelf in the back of the room. There was a significant increase in decay time from 200 Hz – 10 kHz (Figure 3.4). Because of the increased reflectivity of the room, Test 1 introduced several deep notches that were not present in the Initial Test. Some of the deeper notches were at 290 Hz, 634 Hz, 710 Hz, and 3.439 kHz (Figure 3.3).

Curious about the diffusing effect of the vinyl shelf vs. the reflective effect of the floor, I left the furniture setup the same for Test 2, save for one thing. I moved the blanket from the TV stand and draped it over the vinyl shelf. This test also turned out worse than its predecessor. The waterfall graphs and decay rates between Test 1 and Test 2 were nearly identical (Figures 3.5 & 3.6). The difference was found in the frequency responses. Test 2 only deepened the notches that were present in Test 1. Clearly the current set up was not a good idea.

In preparation for Test 3, I moved the large denim couch out of the dining room entrance and propped it up in one of the corners next to the vinyl shelf. I left the small red chair where it was in the other corner along the same wall, and took a measurement. Again, the tests were strikingly similar. Test 3 still had the same notches present in Test 2, but they were not as deep, save for one notch at 97 Hz that was 13 dBSPL quieter than the notch in Test 2 (Figure 3.7). Again, the waterfall graphs and decay rates between these two tests were alike, showing the same problems that had been persistent since the start of testing (Figure 3.8).

I liked the idea of having some furniture in the corners to help with low-frequency trapping, but decided that the empty floor needed some attention. I left the denim couch and red chair where they were in the corners, but took the blanket off the vinyl shelf and laid it down on the floor in front of the speaker. I took all the pillows off the couches and chairs, and scattered them around on the floor, thinking that these might help reduce the floor's reflectivity. Interestingly enough, Test 4 showed worse bass response than Test 3 from 20 Hz – 30 Hz (Figure 3.9). Besides this, many of Test 3's notches were improved upon, although there were now a couple new notches present, mostly in the mid-frequencies. The decay rates were finally starting to improve, with the mid-frequencies from 200 Hz – 10 kHz being shorter than before (Figure 3.10). They were still persisting for much longer than both other rooms, though.

Since Test 4 was finally starting to show some (slight) improvements, I left the denim couch where it was, and propped the loveseat up against the corner where the red chair had previously been. I took a mattress pad and laid it down in the center of the room, and scattered the pillows around it. Then I took the blanket off of the vinyl shelf and draped it over the stack of HoverDeck's near the front door. Lastly, I took the comforter from my bedroom and draped it over the vinyl shelf in the back of the room, and took a measurement. Test 5 proved to be the best test since the initial test, with fewer notches than the rest of the previous tests and an overall improvement on decay rates across the frequency spectrum. However, there were still some problematic notches, specifically at 97 Hz, 270 Hz, 622 Hz, and 956 Hz (Figure 3.11).

For the next two tests I decided to get a little experimental with furniture placement. I moved the couches so that they faced each other, creating an aisle that led from the speaker to the vinyl shelf. I left the mattress pad on the floor in between the two couches, and left the pillows as they were. The comforter remained draped over the vinyl shelf. After running Test 6's measurement, it became clear that this setup was unideal. Test 6's frequency response deepened all of the notches that were present in Test 5, as well as adding some new notches at 961 Hz, 1.469 kHz, and 1.687 kHz (Figure 3.13). It also exhibited increased decay times from 370 Hz – 500 Hz (Figure 3.14).

For the last furniture test, I again decided to try an odd furniture layout. I pushed the denim couch close to its normal position, but closer to the mic. Then I moved the loveseat so that it was positioned directly behind the denim couch. The mattress pad was positioned on the bare floor next to the couches, and the pillows again were scattered around the floor. Again, this test showed mixed results. Although Test 7 improved notches at 267 Hz and 623 Hz, it deepened notches at 398 Hz, 765 Hz, and 969 Hz (Figure 3.15). The waterfall graph and decay rates were very similar to Test 6, as well (Figure 3.16). So far, none of the furniture tests had yielded a very accurate, useable room. I hoped that the Auralex products would have a better effect on absorbing sound and diminishing reflections bouncing around the room.

In preparation for the first Treatment Test, I returned all the furniture to its normal position. I then placed two Sunburst 360's in each of the back corners, totaling in four Sunburst's being used. Finally, I placed one ProMax panel against the side wall near the TV stand, and one ProMax on the opposite wall near the front door. The pillows remained scattered on the floor to minimize how much of the floor was uncovered. Although the Auralex treatment did not help with the low-frequency notches at 46 Hz ad 87 Hz, the frequency response and decay time were drastically improved upon. The absorption provided by the Auralex products significantly reduced the decay times of the low-mid and middle frequencies, reducing them down to between 300 ms – 240 ms (Figure 3.18). The frequency response was much flatter overall, with no deep notches to speak of, save for the two at the bottom end. There was a slight high-end roll-off beginning at 17.8 kHz, dropping down ~7 dBSPL before reaching 20 kHz (Figure 3.17).

On the whole, this was the best test out of any room so far, and boded well for the remainder of the living room treatment tests.

For the second Treatment Test I left the Sunburst 360's where they were in the two corners, and moved the ProMaxes so that they blocked the entryway to the dining room. I made sure that the absorbing side was facing out into the room, and ran another test. Blocking off the dining room entryway did not have a noticeable change on the room's frequency response, but the decay rates were slightly reduced across 85 Hz – 1 kHz (Figures 3.19 & 3.20). Curious about what benefits there might be to treating every corner in the room, I took one Sunburst 360 from each of the front corners and placed them in the room's opposite corners and ran another measurement for Treatment Test 3.

Treatment Test 3's frequency response was almost identical to Treatment Test 2's, save for some low-frequency activity differences (Figure 3.21). There were a couple differences between the two waterfall graphs; specifically, Treatment Test 3 exhibits a very resonant mode at 124 Hz and reduces a mode at 38 Hz (Figure 3.22). All three of the Treatment Tests have shown very similar decay rates across all frequencies above 200 Hz. The Auralex products appeared to be remedying many of the living room's problems in a way that they had not been able to do in the other two smaller, more square rooms. I decided to see what would happen if I "livened up" the room a little bit, so I flipped both ProMax panels in the dining room doorway around so that the diffusing side faced into the room.

I had expected that the added diffusion would introduce some problematic modes, as it had in the past. However, Treatment Test 4's results proved me wrong. The only new notch introduced was at 24 Hz (Figure 3.23). It seemed that the Sunburst 360's were and furniture were absorbing most of the problematic frequencies, such that added diffusion did not create any additional nodes and anti-nodes.

Since blocking the dining room entrance did not seem to have very much effect on the living room's qualities, I moved the two ProMax panels out of the entryway and placed them opposite each other on the living room's side walls. I left the diffusing sides facing into the room, allowing for a slightly more reverberant room sound, and ran another sine sweep measurement for Treatment Test 5. Unsurprisingly, the differences between Treatment Test 4 and Treatment Test 5 were very limited. Treatment Test 5 showed one worse notch at 645 Hz, but the notch was only deepened by ~3 dBSPL (Figure 3.25). The decay rate across the frequency spectrum was slightly elongated, probably because two of the four walls now had some diffusion treatment (Figure 3.26).

Since the living room was the largest out of all three rooms, and since I had enough Auralex products to do so, I decided that for the last two tests I would construct a small space within the living room, and test this space. I set up both ProMax panels in between the denim couch and the speaker, absorbing side out, and placed one Sunburst 360 behind the speaker. Very surprisingly, constructing this small space for Treatment Test 6 had little effect on the decay rates and frequency response (Figures 3.27 & 3.28). The decay rates were shortened a little bit in comparison to Treatment Test 5, but that makes sense given that the sound waves had to travel less distance before being absorbed. It was more surprising that the frequency response was basically unchanged, despite treatment being brought so close to the microphone and speaker.

Again curious about diffusion, I flipped around the two ProMax panels before conducting Treatment Test 7. As was to be expected at this point, any changes between this test and Treatment Test 6 were minute at best. Due to the diffusion panels, the decay rates were slightly longer than before, but still under 300 ms (Figure 3.30). This marked the end of the room testing process. After documenting all of the findings, I moved on to re-recording "In Progress" using the Auralex products during the recording process.

V. The Final Recording

This time around, I started by recording bass and scratch guitar first. These were meant to be reference tracks for the drummer to play along to in the future, but I still treated the room before recording just to get an idea of what the amplifiers sounded like. Instead of using the studio room, I used the living room to record both the scratch bass and scratch guitars, since the living room had a much flatter and smoother frequency response than both the studio room and bedroom. I used a single Shure SM57 for the bass, and placed the amplifier in front of the denim couch (in almost the same spot that the testing speaker was). I used another Shure SM57 and a Blue Spark to record the guitar, and placed that amplifier in the same spot as the bass amplifier. I replicated the Living Room Treatment Test 5 setup with the Auralex products; one Sunburst 360 in each corner, two ProMax panels set up on opposing walls, a blanket draped over the TV stand, a comforter draped over the vinyl shelf, and furniture in its normal positions. However, this time I positioned their absorbing side to face out rather than the diffusing side.

With the scratch tracks recorded, I moved on to recording drums. I again brought in Wes Rodberg to perform, and he brought the same Tama Star Classic kit and selection of Meinl cymbals that he had brought the first time around. Again, I used the same room treatment setup as before. In addition to that, I also used eight pieces of Auralex's HoverDeck series. These are panels that are meant to acoustically isolate the drums' vibrations from the floor, so that the drums don't vibrate the entire floor. As far as microphones go, I used a pair of Shure SM57's and a pair of AKG C1000's positioned around the kit; the two SM57's were capturing the kick drum and snare drum, while the two C1000's were used as overhead microphones and positioned above the cymbals. I recorded five passes of the song, and two passes of just the second verse and chorus.

With the drums re-recorded, I decided to re-record the bass. I could have simply used the previously recorded bass track, but Wes had changed the drum part slightly, and I felt it was artistically appropriate to change the bass part to match the song's new intensity. I used a different bass this time than the Initial Recording; the one I was going to use had broken a few days prior to these recordings. In its place, I used a 5-string Brice A10000 model. I used the same setup of one Shure SM57 placed in front of an Acoustic B200 bass amplifier. The amplifier was placed in the living room in almost the same position the testing speaker was. I left the Auralex products where they were, save for the HoverDeck's. I removed all of those from the room, and instead used Auralex's GreatGramma isolation pad. This product's design is philosophically identical to the HoverDeck; to isolate a sound source from its surrounding environment. However, the GreatGramma was designed with guitar/bass amplifiers in mind rather than drums. The B200 amplifier was placed directly on top of the GreatGramma.

After bass and drums had been recorded, I recorded both clean and distorted guitars, also using the living room. I used the same microphone setup as the Initial Recording; one Shure SM57 and a Blue Spark placed close to the amplifier's grille, and one PreSonus M7 placed behind the denim couch to capture the room's ambience. However, this time around I oriented the M7 to point up, thinking that this might more effectively capture the reflected sound from the guitar amp. I again used the Ibanez GAX70 with a Fender Super-Sonic amplifier, and used an Earthquaker Devices Crimson Drive pedal for the distorted guitar parts.

VI. Reflection on Initial and Final Recordings

After listening back to the Initial Recording, my first thoughts were that it sounded very mediocre. There was a lack of definition across all instruments. The guitars were all dull and muddy, and it was hard to pick out the bass line from the rest of the musical elements. After soloing up the guitar's room mic, it was apparent that the room mic was picking up a lot of the amplifier's direct sound as well as the reflected noise bouncing around the room, creating some weird phase issues. The bass was warm, but lacked any punch or clarity.

I attribute a lot of the Initial Recording's problems to the space in which it was recorded. Both the guitars and the bass were recorded in the studio room, which was the most square out of all three rooms. Furthermore, this was recorded prior to any treatment being done, so all of the metal signs and instruments in the room were resonating during the recording process. The square shape of the room also accentuates certain frequencies (room modes) and can distort the aural characteristics of anything recorded in that space. The drums were recorded in the living room, but without any treatment the living room has a very deep notch near 1 kHz, which is where a lot of the drums harmonic content would sit.

Technical problems aside, I think this mix is fairly boring. There is not a whole lot of movement between each section, and the balance between the instruments remains stagnant throughout the song. The only noticeable differences between sections are the different guitar parts change volume sometimes.

The Final Recording is a big improvement over the Initial Recording. Right off the bat, there is an improvement in clarity across the drums and guitars. The drums are more up-front and in-your-face, and don’t sound quite as ambient. The guitars are brighter, and cut through the mix better. Some of the parts were slightly re-written across all instruments to make the music a little more interesting and compelling, and although this does not necessarily affect the sonic quality of the recording, it does help make a more memorable song.

For the Final Recording, every instrument was recorded in the living room. The living room was also treated with Auralex products, to even out the room’s frequency response, lessen the decay rate across the frequency spectrum, and isolate the sound sources from the house’s foundation. The improved acoustics of the room surely helped with the added definition of the recorded material. It is easy to distinguish both guitar parts from each other, and even though the bass is still somewhat muddy, it sits in the mix better than the bass from the Initial Recording. Although the drums are more lively and up-front, they still sound a little ambient. This is probably the result of only being able to use four microphones to record the whole drum kit with. Ideally, I would have liked to use six or seven microphones.

The Final Recording's mix is more interesting than the Initial Recording. I experimented more with level changes across all instruments, and also automated more panning changes than I had for the Initial Mix. The result was a mix that was more fluid and dynamic than before. By featuring different recorded tracks across different sections of the song, I attempted to create a sense of movement and momentum to drive the song to its end. I am pretty proud of this mix despite its flaws, and am proud of how far it has come in comparison to the Initial Recording.

VII. Conclusion

One of the biggest lessons learned from this project is that, given the materials available to me, I could not completely fix a room with bad dimensions. Even with extensive treatment, the bedroom and studio room still showed many problems in their frequency responses and decay rates. I was never able to completely get rid of nulls and cancellations, which skews the decision making process during mixing and recording. In conjunction with having bad dimensions, the bedroom and studio room also were limited in the amount of cubic feet that they held. Generally, the more a room abides by good dimension ratios, the better the room will sound. This, in conjunction with more appropriate dimensions, is a contributing factor to why the living room was so much better than the other two rooms after being treated.

Secondly, I learned firsthand that treating a room's corners should be the priority. There is a lot of bass buildup that happens in corners, and treating those first will help a lot in making a room more sonically accurate. Once corners are treated, the next most important thing to treat are the first-reflection points. By treating these, you can minimize the amount of sound that gets reflected back into the room, reducing reverb times and allowing your ears to hear more of the direct sound. This is not a new concept by any means, but it was interesting to see its effects firsthand.

Although using furniture as acoustic treatment is definitely better than not treating the room at all, its effects are minimal. If you can afford it, it is well worth the price to invest in some serious acoustic treatment. Large pieces of furniture (like couches) are more effective at treatment simply because of their size; they can absorb a large band of frequencies due to the material used and dimensions. But smaller things like pillows and blankets are somewhat ineffective.

Lastly, it is important to make smart decisions during the recording and mixing process. Part of the reason the Final Recording sounded more unified than the Initial Recording was because everything was recorded in the same room; the space effectively tied everything together, as if they were all actually playing together in the room. This obviously is not the only reason for improvement, but nevertheless is worth noting. Moreover, the decision to make the Final Recording's mix more dynamic and fluid makes for a more interesting listening experience. It is important to remember that, at the end of the day, people listen to music for entertainment and fun, not to experience the highest-quality audio ever.

Through my experiments and research, and thanks to Auralex's kind donation, I believe I have gained the skills to effectively produce and record high-quality audio in domestic spaces. This will allow me to be more in my comfort zone in the future when working with unideal spaces, and has shown me several tactics to use to combat potential acoustic problems. I am excited to apply this new knowledge to whatever project I decide to take on next.

References

Albano, Joe. "Max Out Your Monitoring." *Recording*, March 2018, pp. 24-31.

Besser, Barry and Linda-Ruth Salter. *Spaces Speak, Are You Listening? Experiencing Aural Architecture.* MIT Press, 2009.

Burgess, Richard James. *The Art of Music Production*. Omnibuss Press, 2005.

Corey, Jason. *Audio Production and Critical Listening Technical Ear Training.* Focal Press, 2013.

Katz, Bob, et al. *From Demo to Delivery: The Process of Production.* Focal Press, 2013.

Kleiner, Mendel, and Jiri Tichy. *Acoustics of Small Rooms.* CRC Press, 2017.

Lindenschmidt, James. "Beyond the Clap Test: Evaluate Your Room." *Recording*, March 2018, pp. 44-53.

Smith, Eric. *Real-World Acoustics.* Auralex Acoustics, Inc., 2013.

"Speed of Sound." *National Aeronautics and Space Administration.* NASA and the Glenn Research Center, www.grc.nasa.gov/www/k-12/airplane/sound.html.

Winer, Ethan. *The Audio Expert: Everything You Need to Know About Audio.* Focal Press, 2013.

Appendix A: Room EQ Wizard Graphs and Charts

The Bedroom

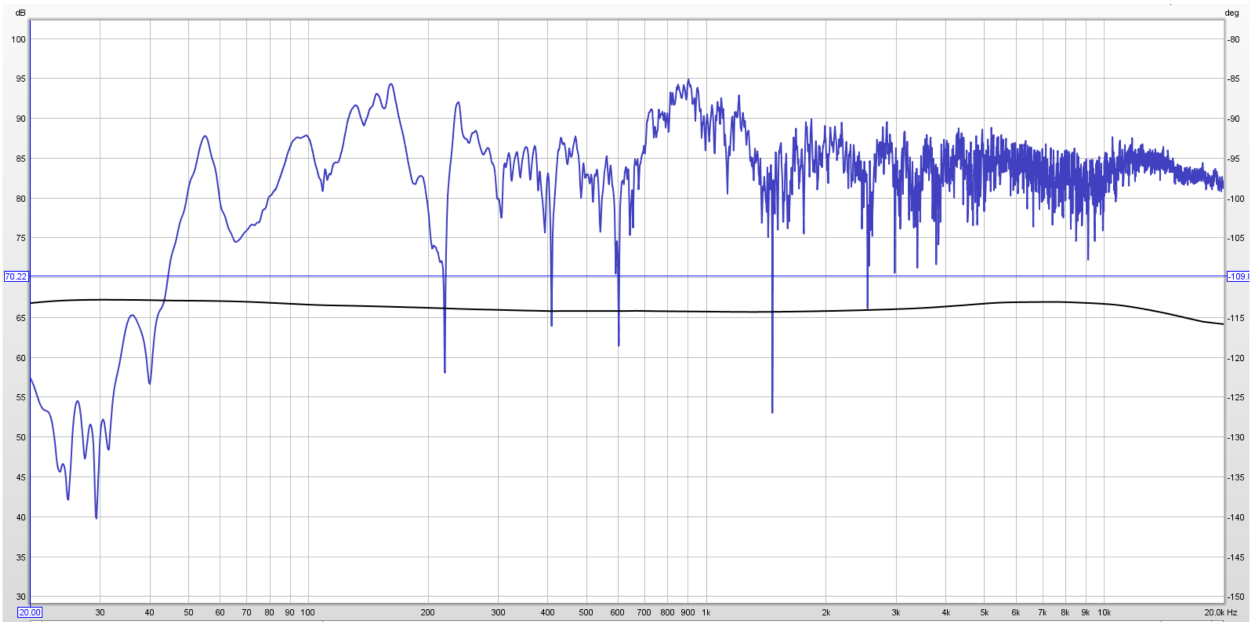


Figure1.1 Bedroom Initial Frequency Response

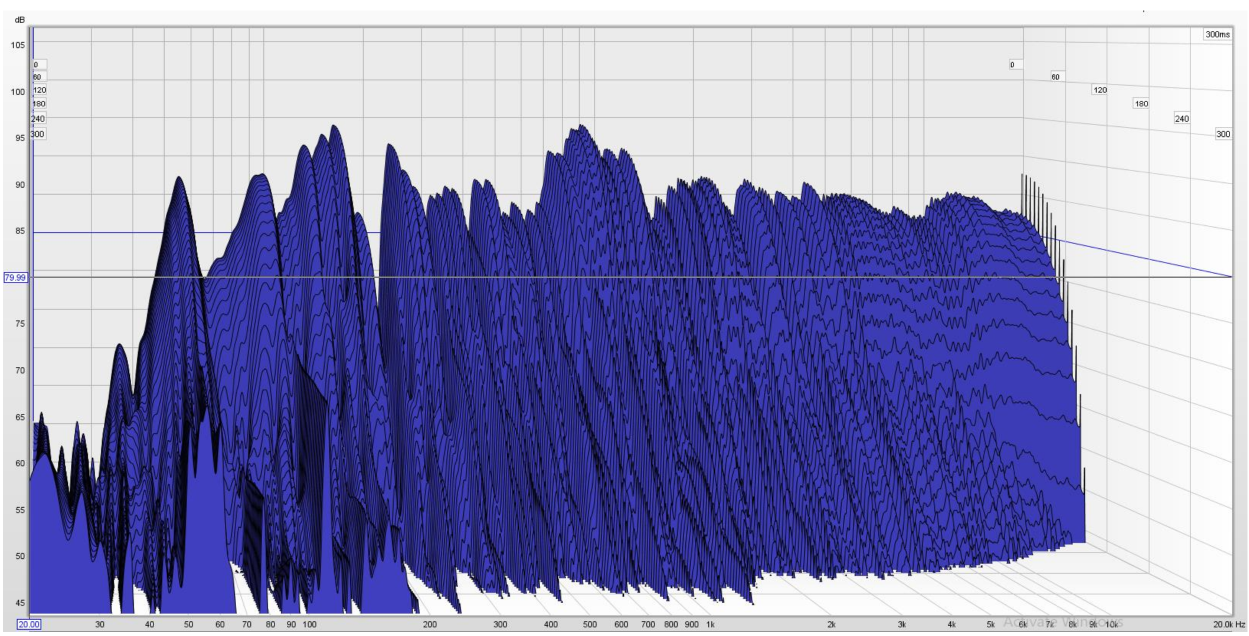


Figure 1.2 Bedroom Initial Waterfall Graph

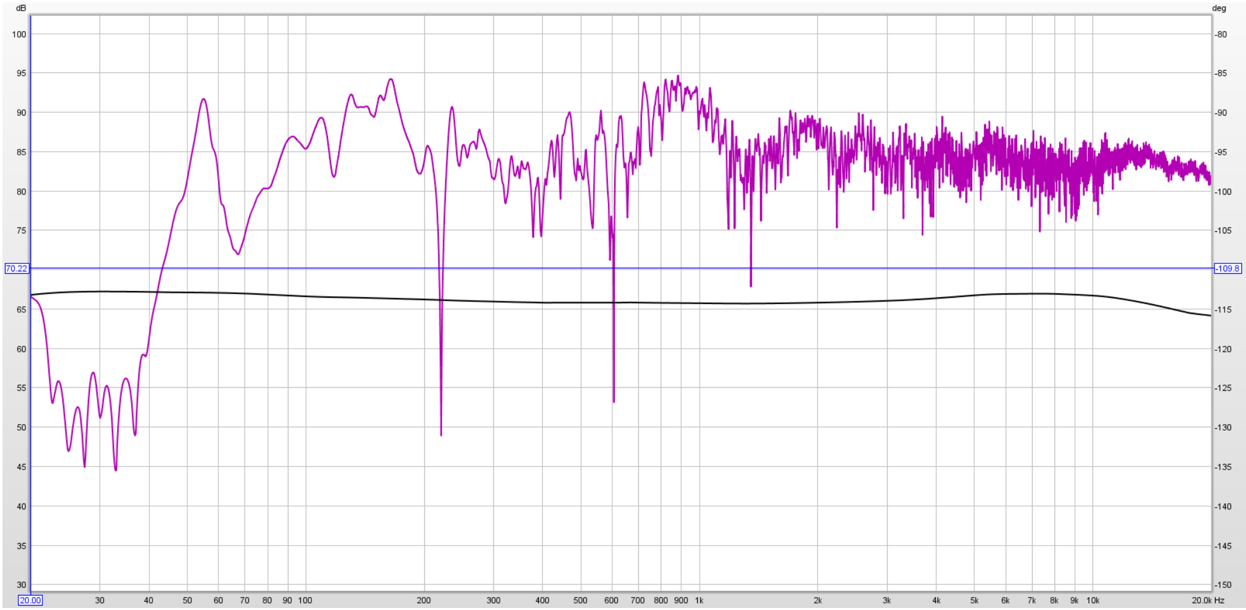


Figure 1.3 Bedroom Test 1 Frequency Response

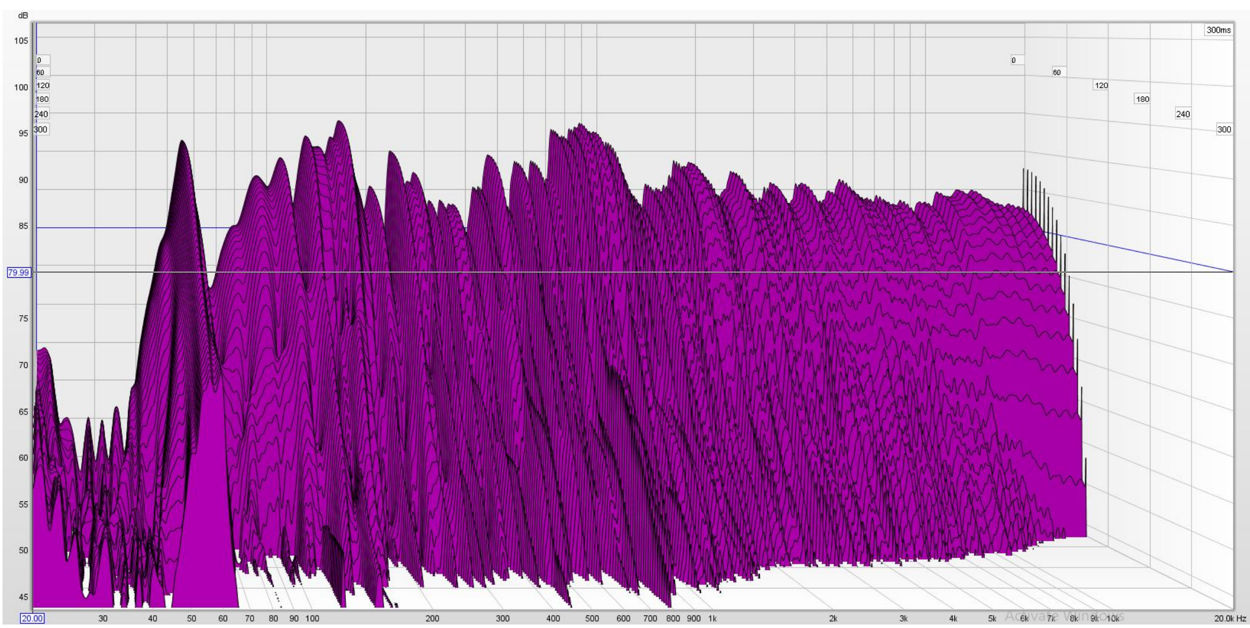


Figure 1.4 Bedroom Test 1 Waterfall Graph

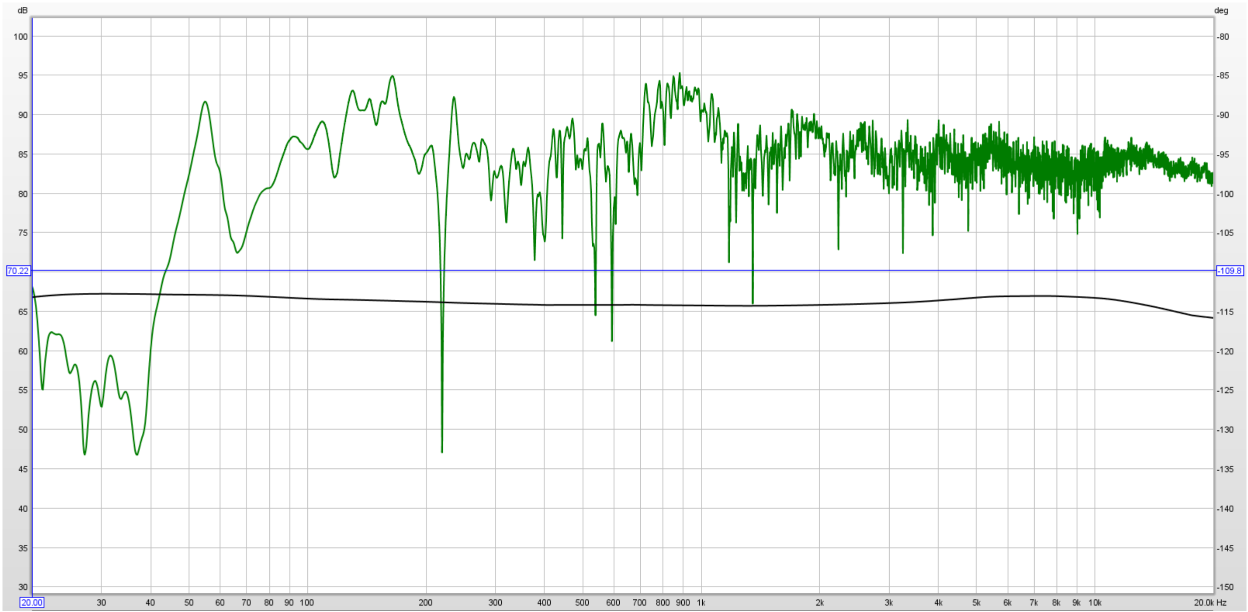


Figure 1.5 Bedroom Test 2 Frequency Response

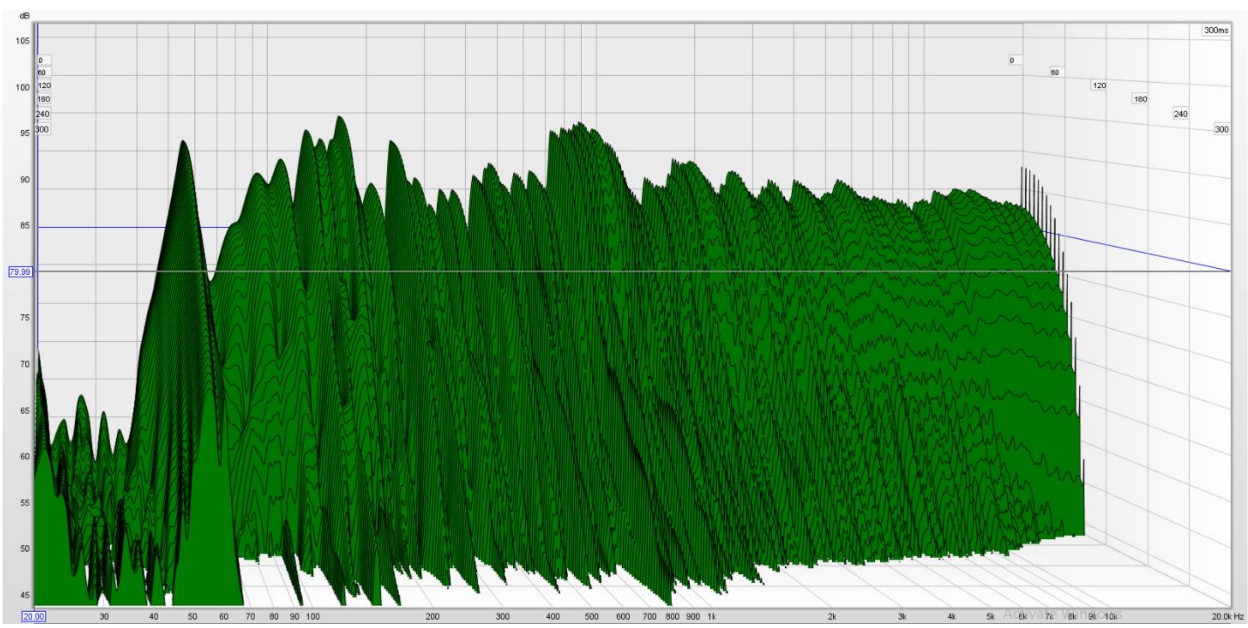


Figure 1.6 Bedroom Test 2 Waterfall Graph

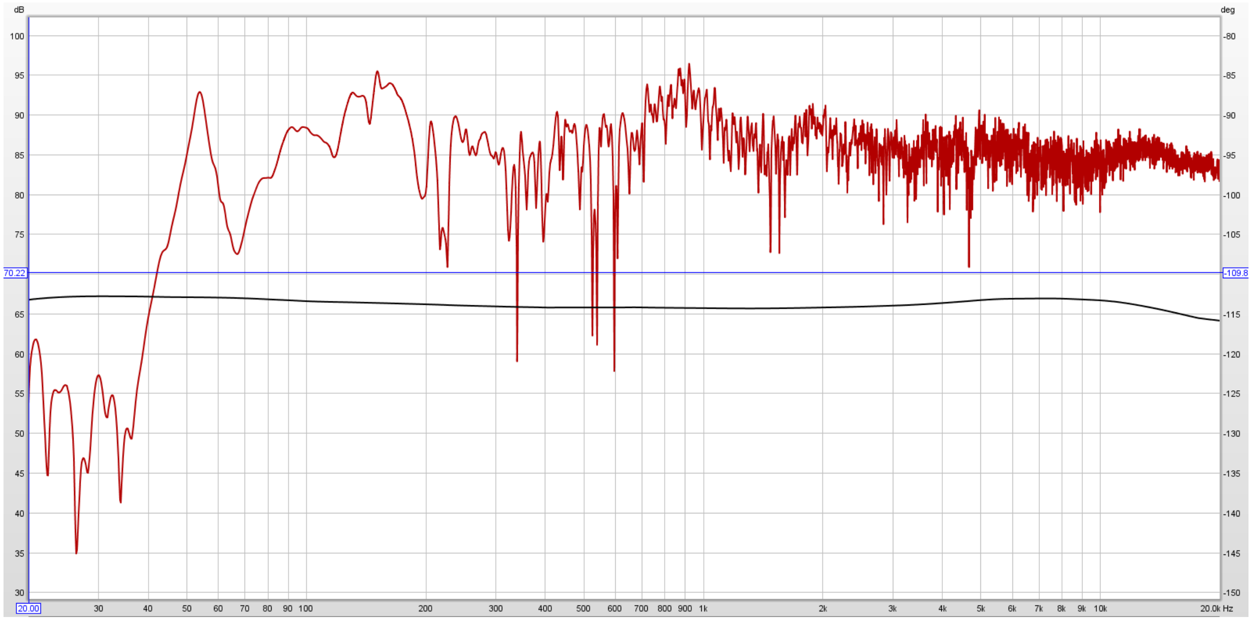


Figure 1.7 Bedroom Test 3 Frequency Response

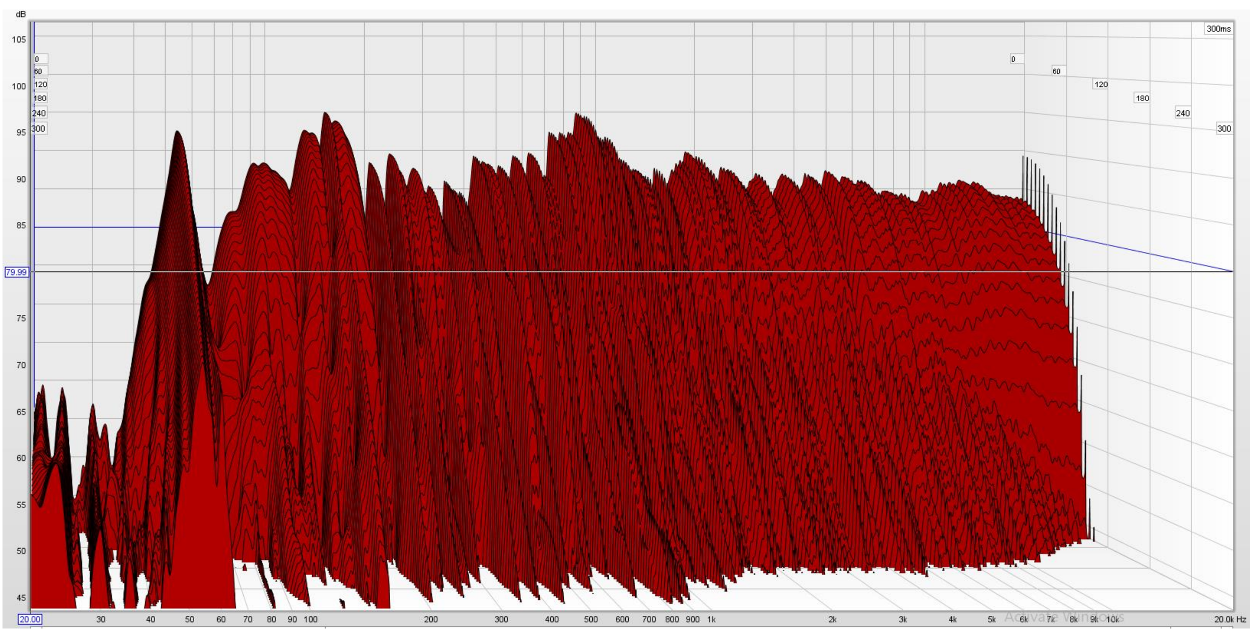


Figure 1.8 Bedroom Test 3 Waterfall Graph

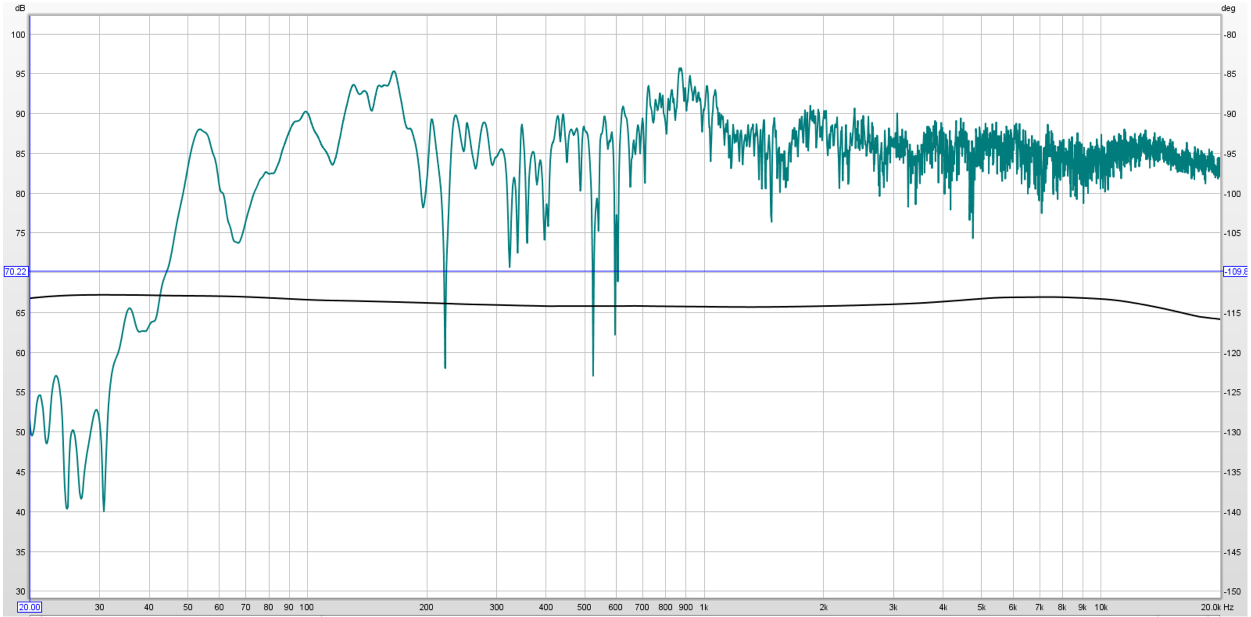


Figure 1.9 Bedroom Test 4 Frequency Response

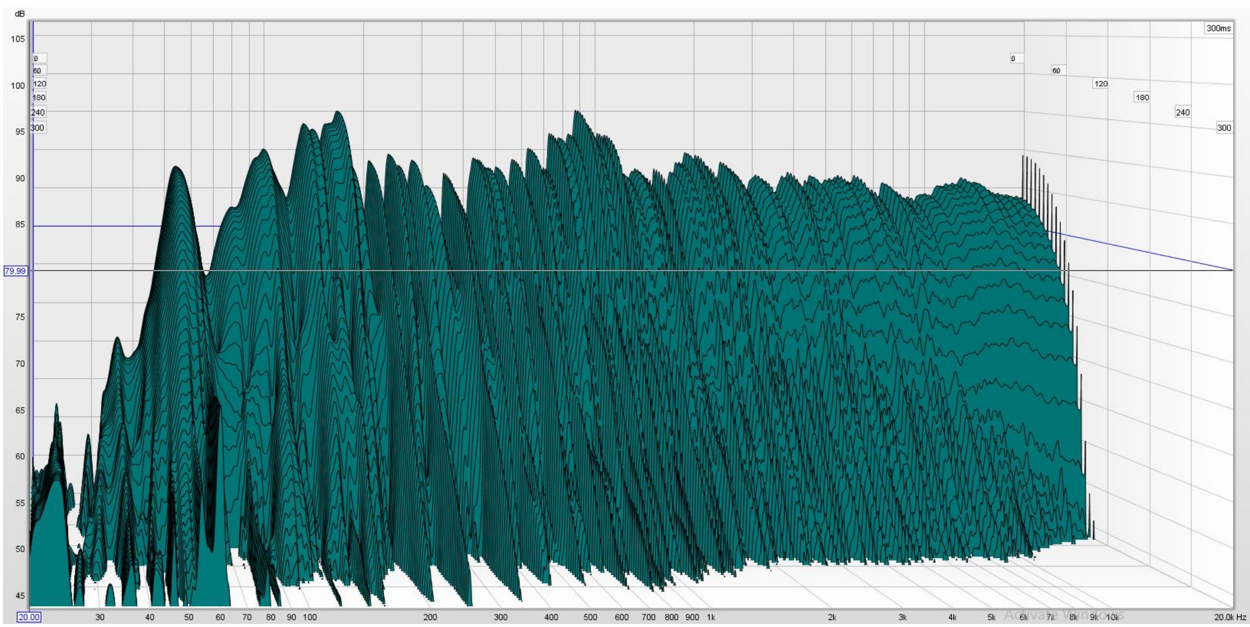


Figure 1.10 Bedroom Test 4 Waterfall Graph

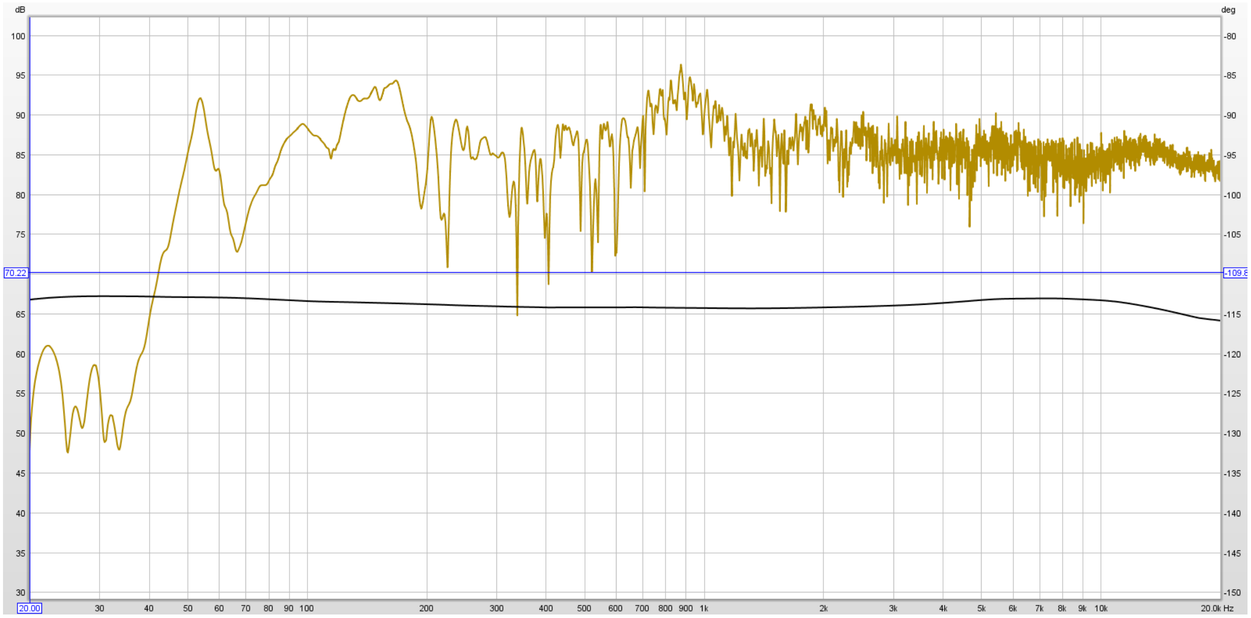


Figure 1.11 Bedroom Test 5 Frequency Response

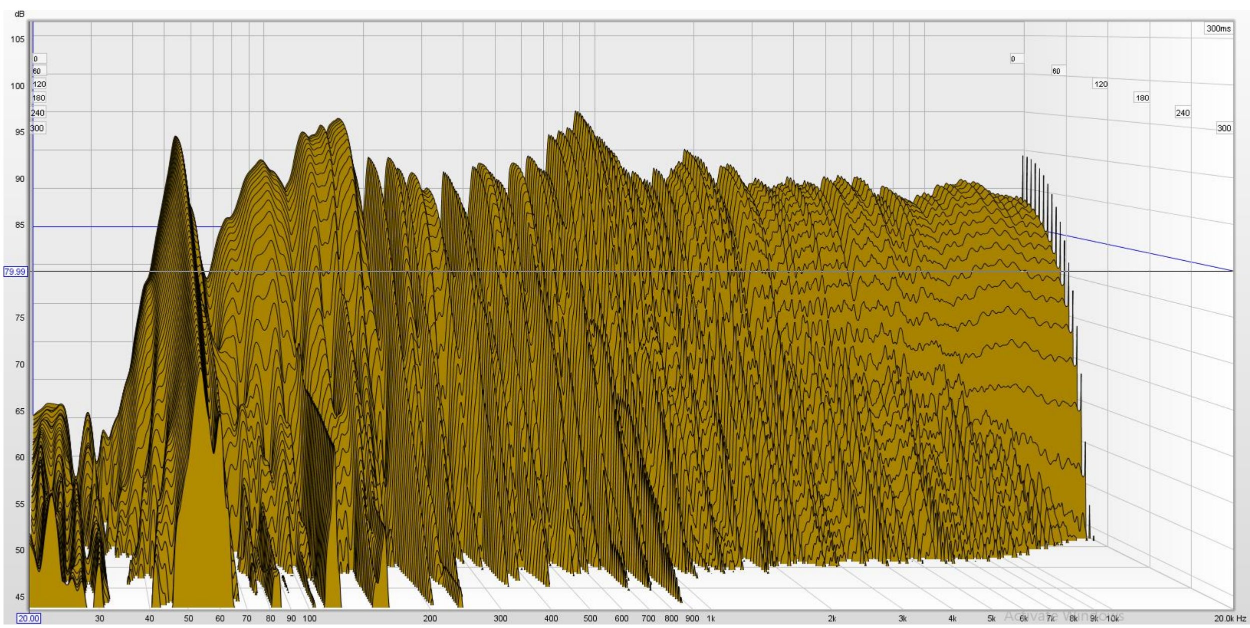


Figure 1.12 Bedroom Test 5 Waterfall Graph

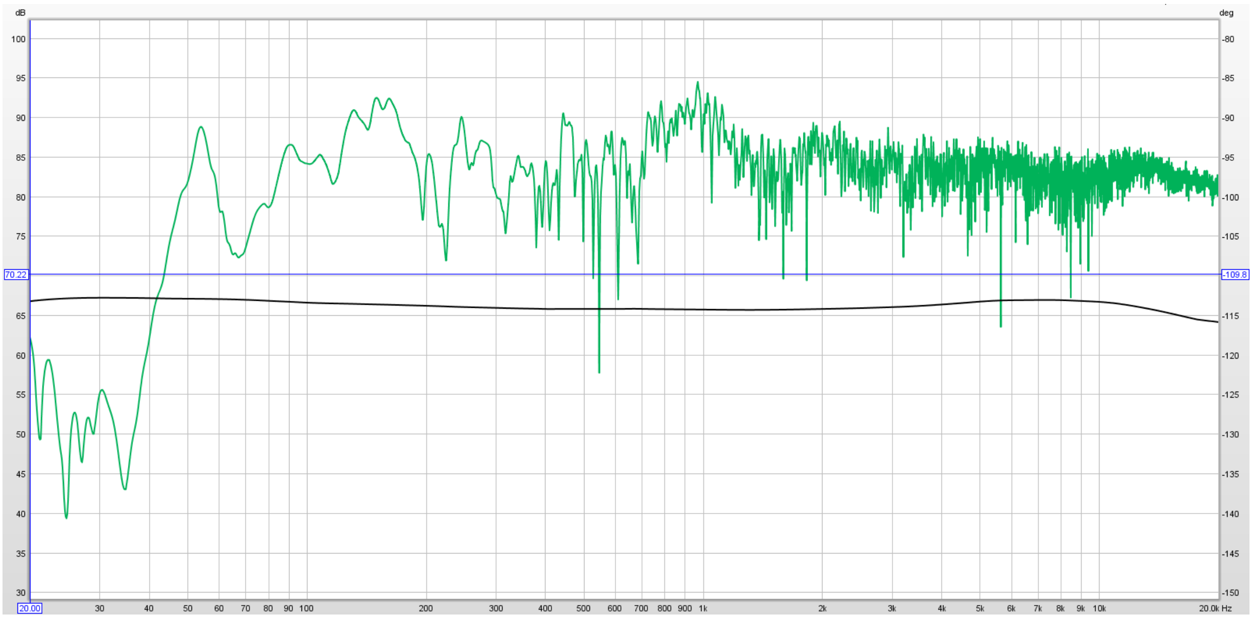


Figure 1.13 Bedroom Treatment Test 1 Frequency Response

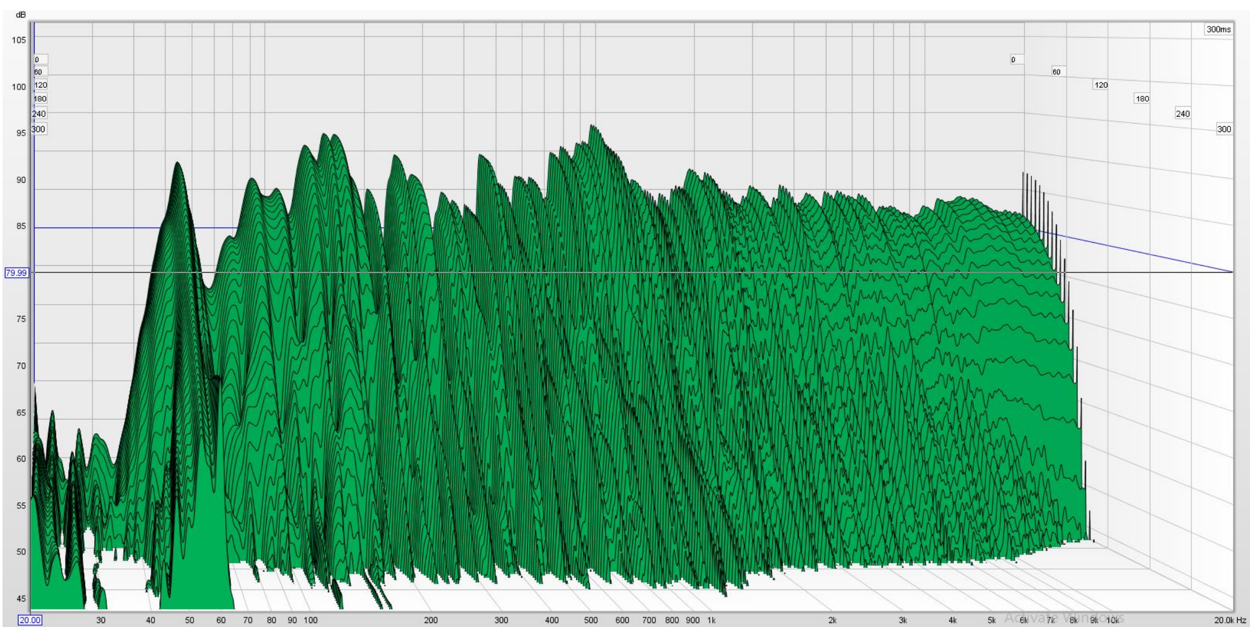


Figure 1.14 Bedroom Treatment Test 1 Waterfall Graph

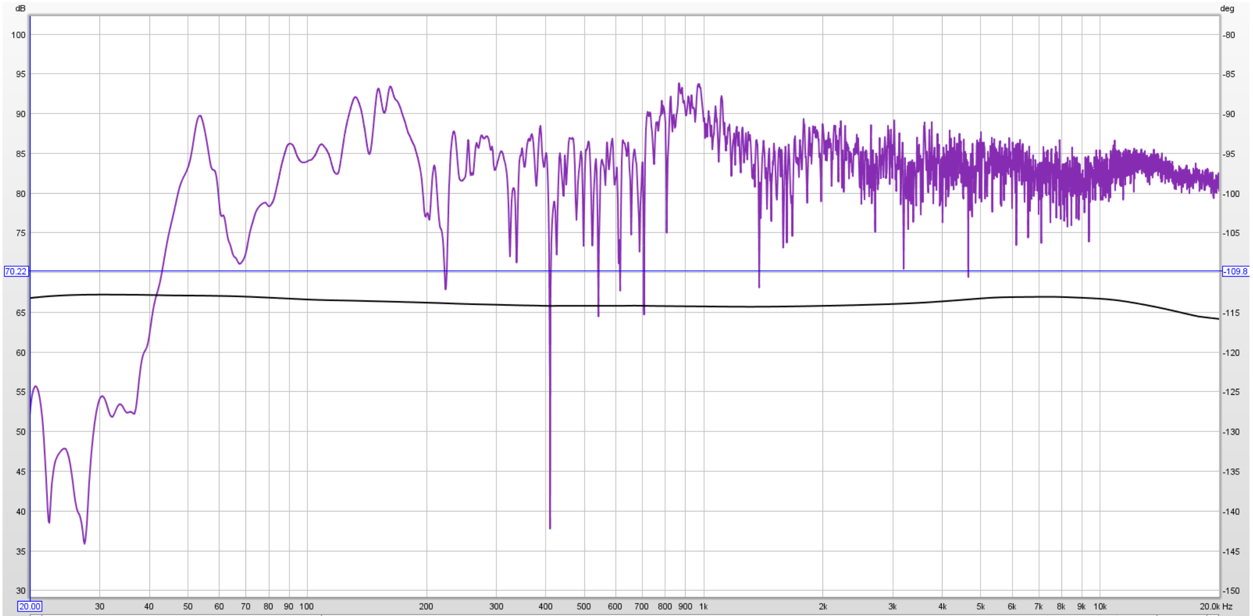


Figure 1.15 Bedroom Treatment Test 2 Frequency Response

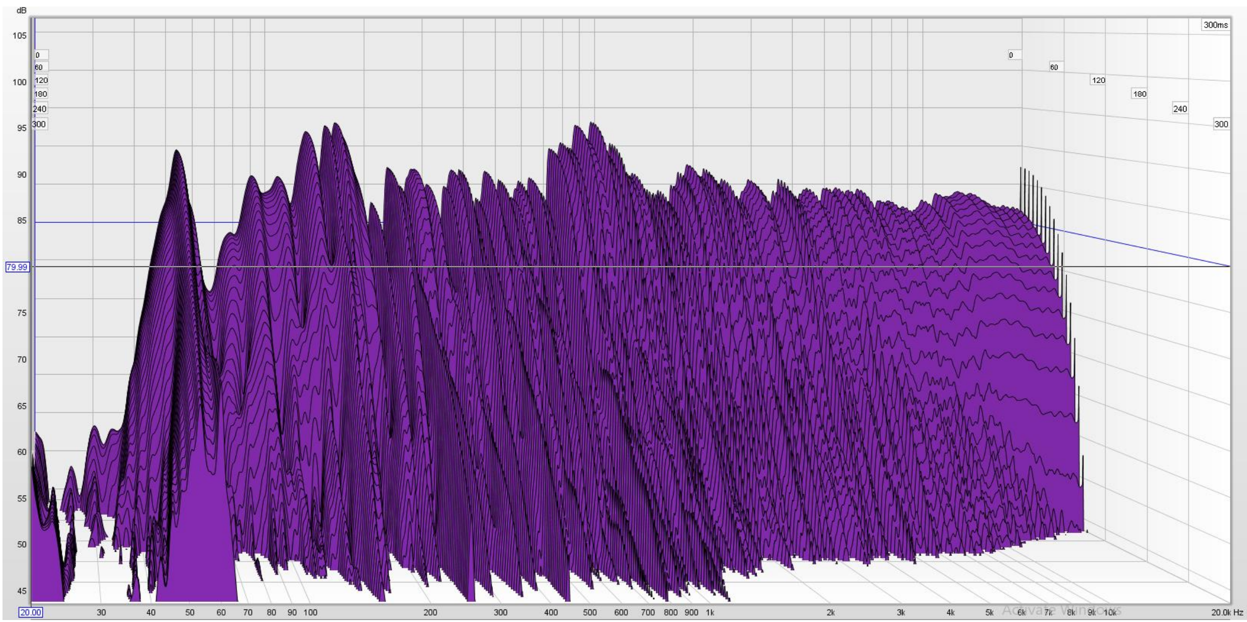


Figure 1.16 Bedroom Treatment Test 2 Waterfall Graph

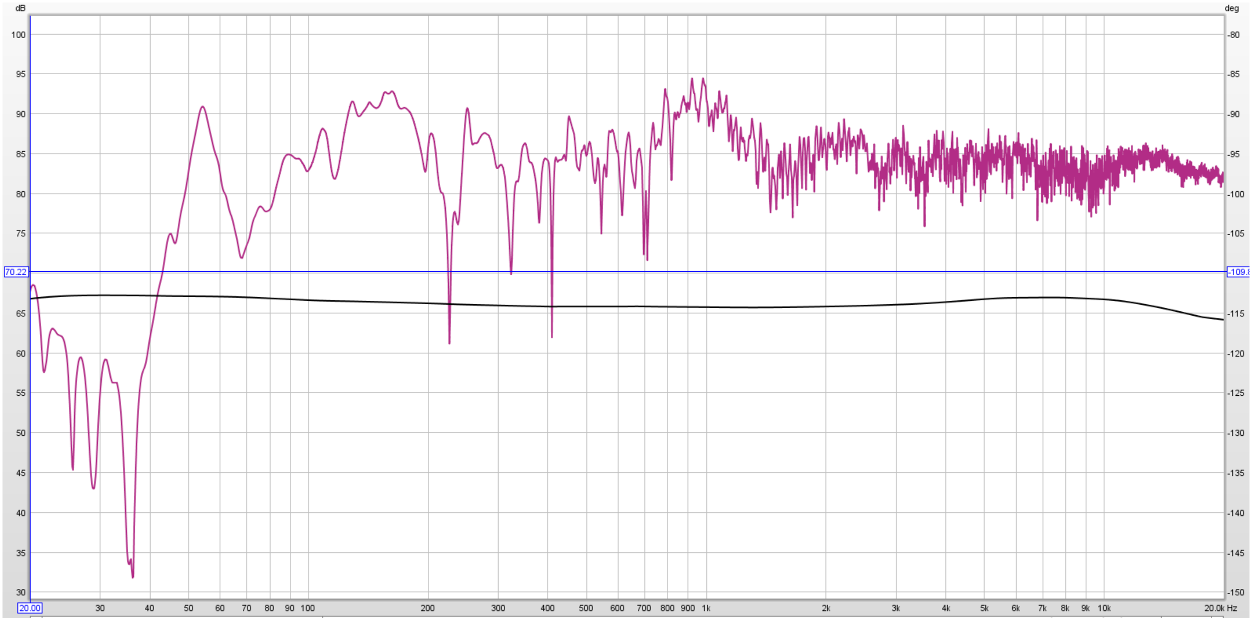


Figure 1.17 Bedroom Treatment Test 3 Frequency Response

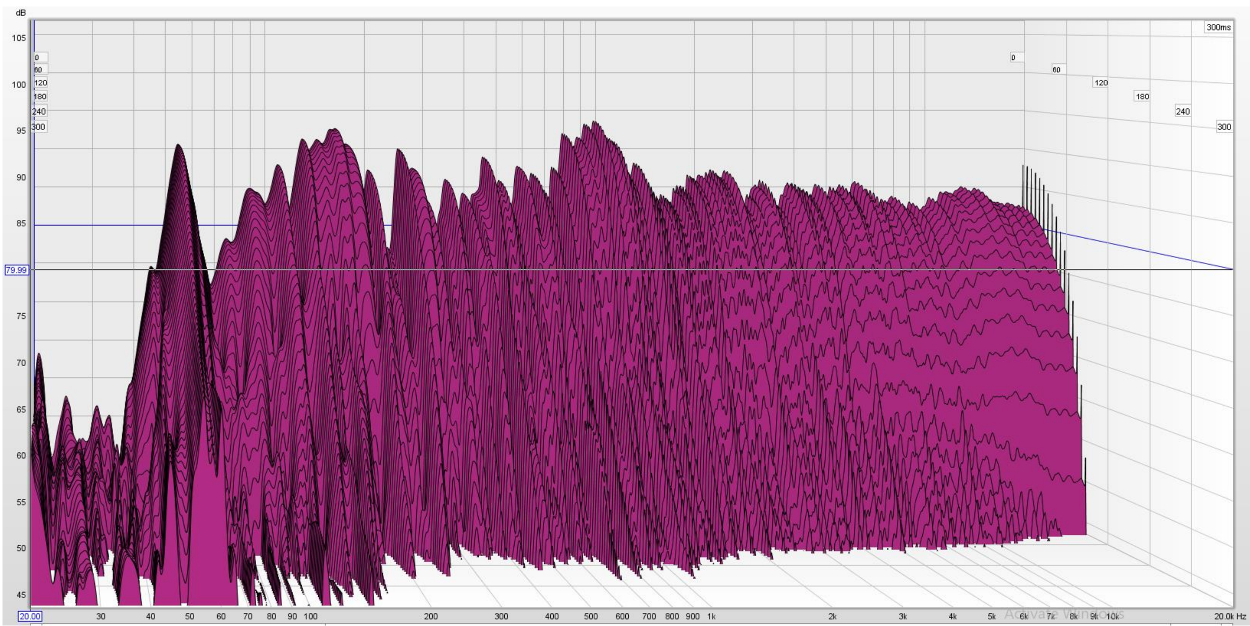


Figure 1.18 Bedroom Treatment Test 3 Waterfall Graph

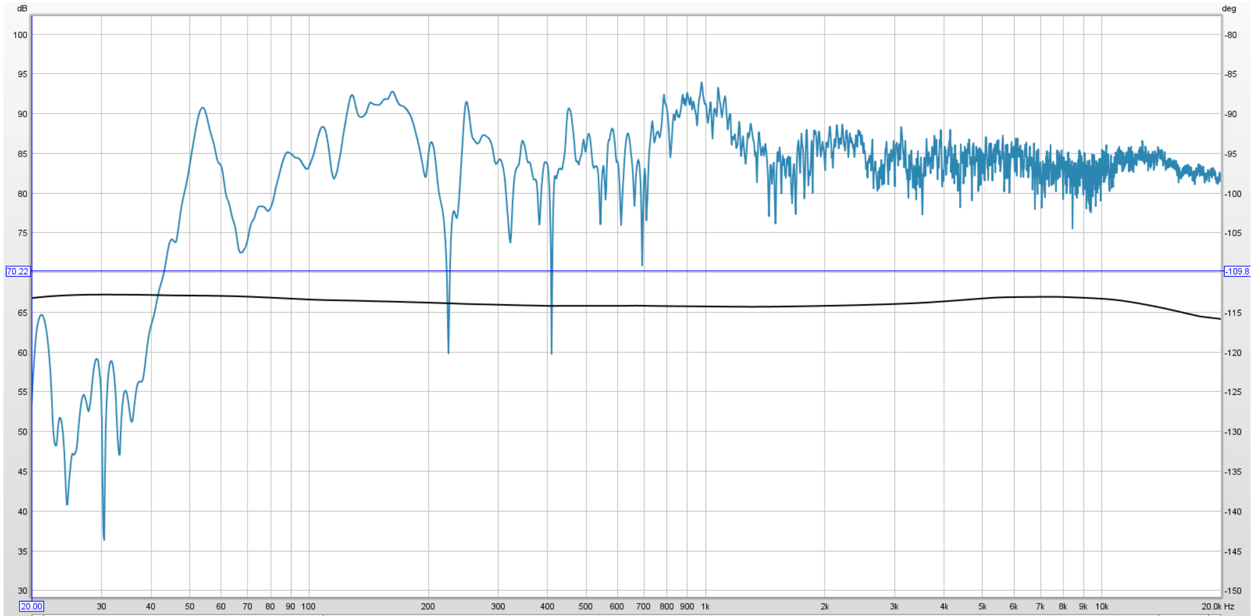


Figure 1.19 Bedroom Treatment Test 4 Frequency Response

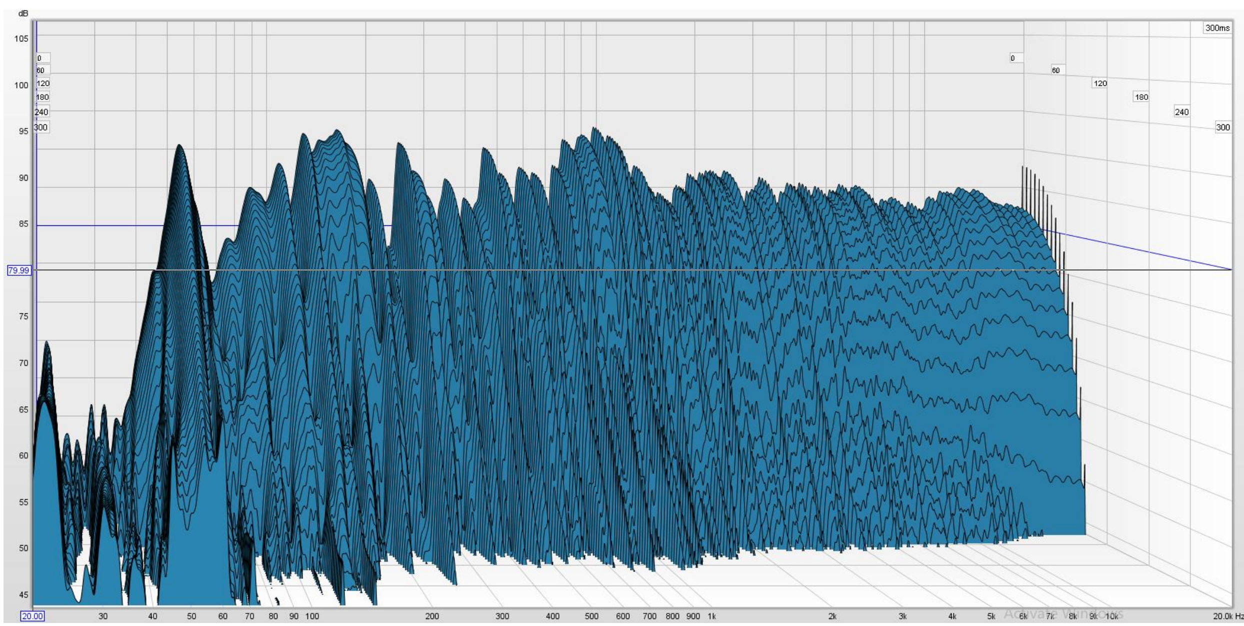


Figure 1.20 Bedroom Treatment Test 4 Waterfall Graph

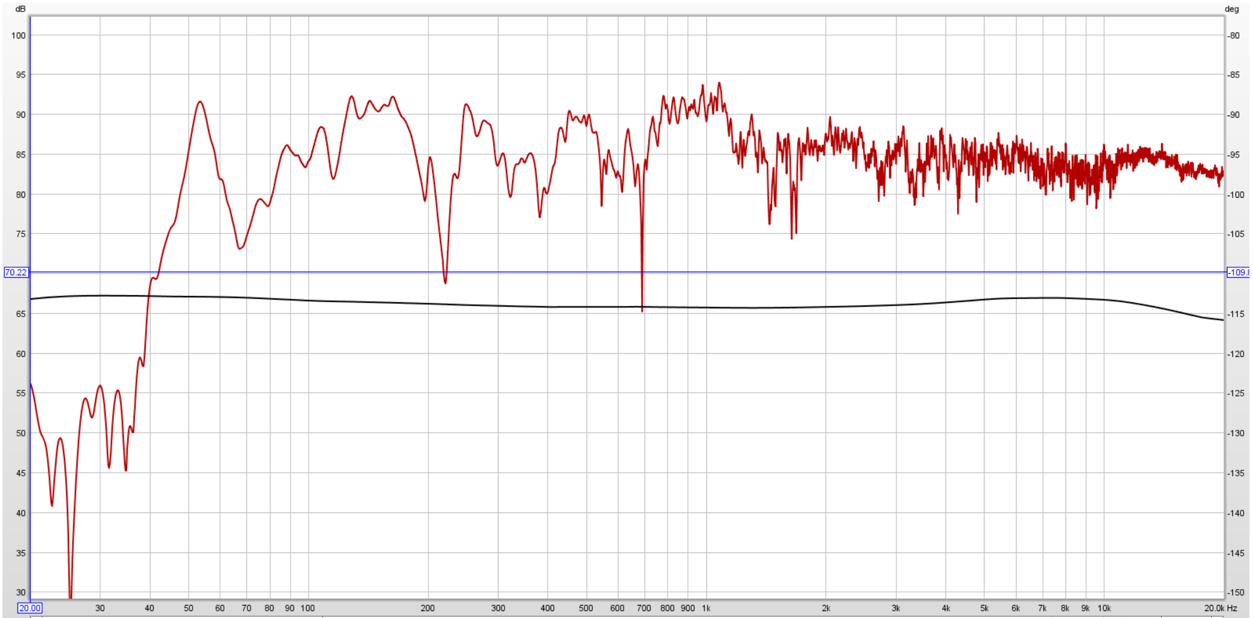


Figure 1.21 Bedroom Treatment Test 5 Frequency Response

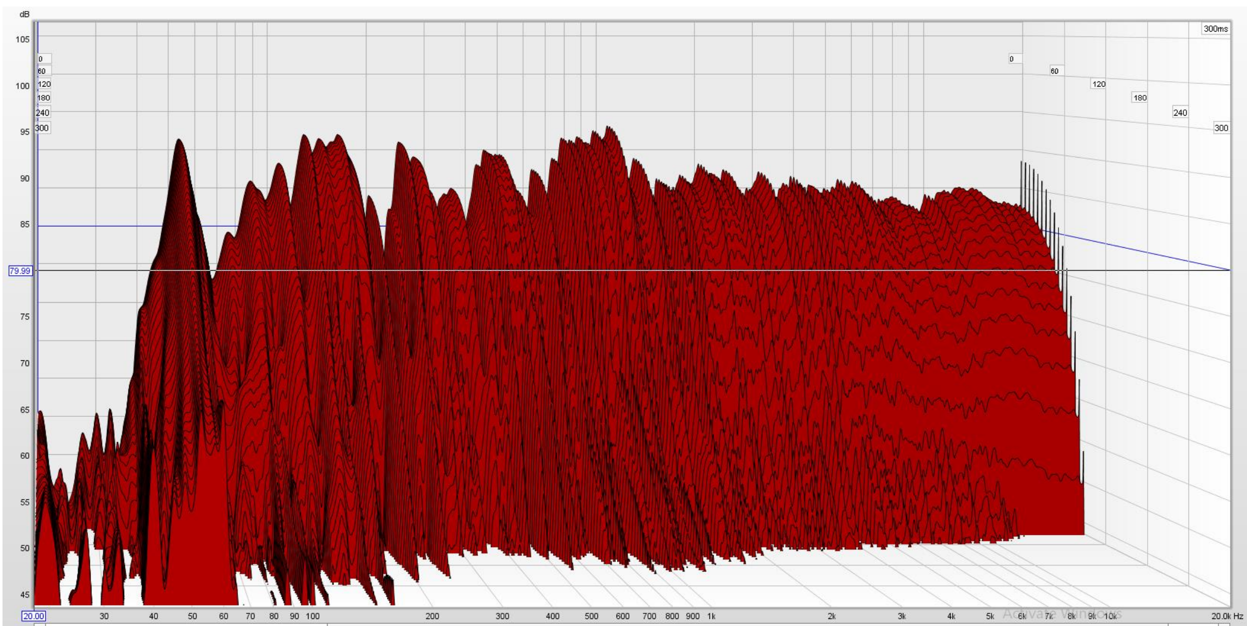


Figure 1.22 Bedroom Treatment Test 5 Waterfall Graph

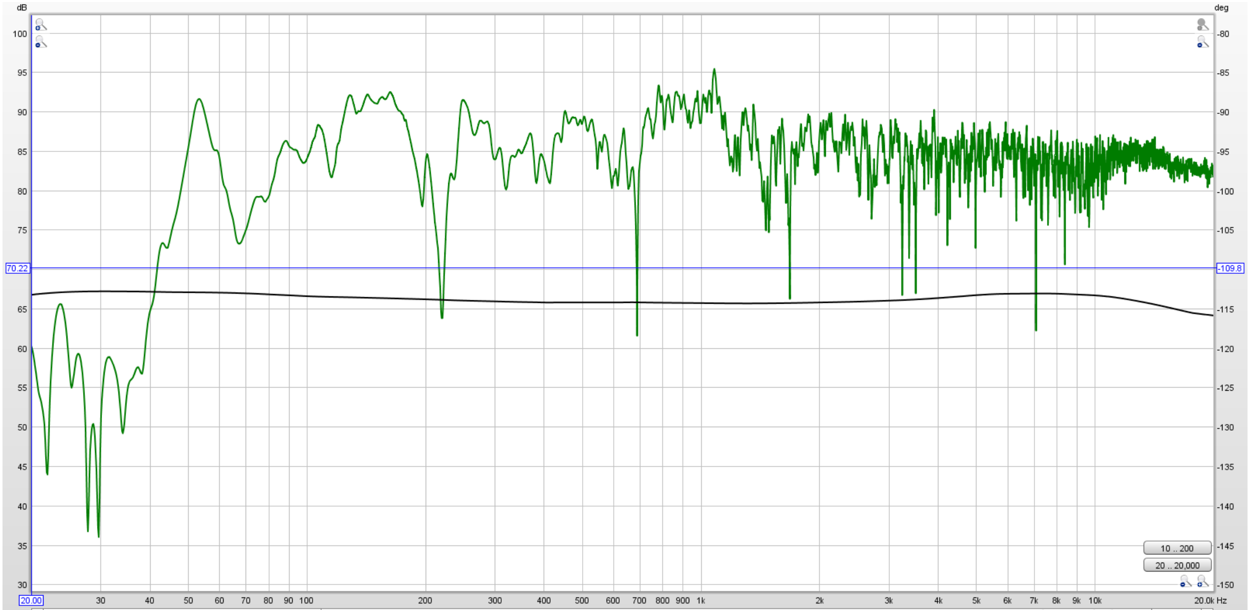


Figure 1.23 Bedroom Treatment Test 6 Frequency Response

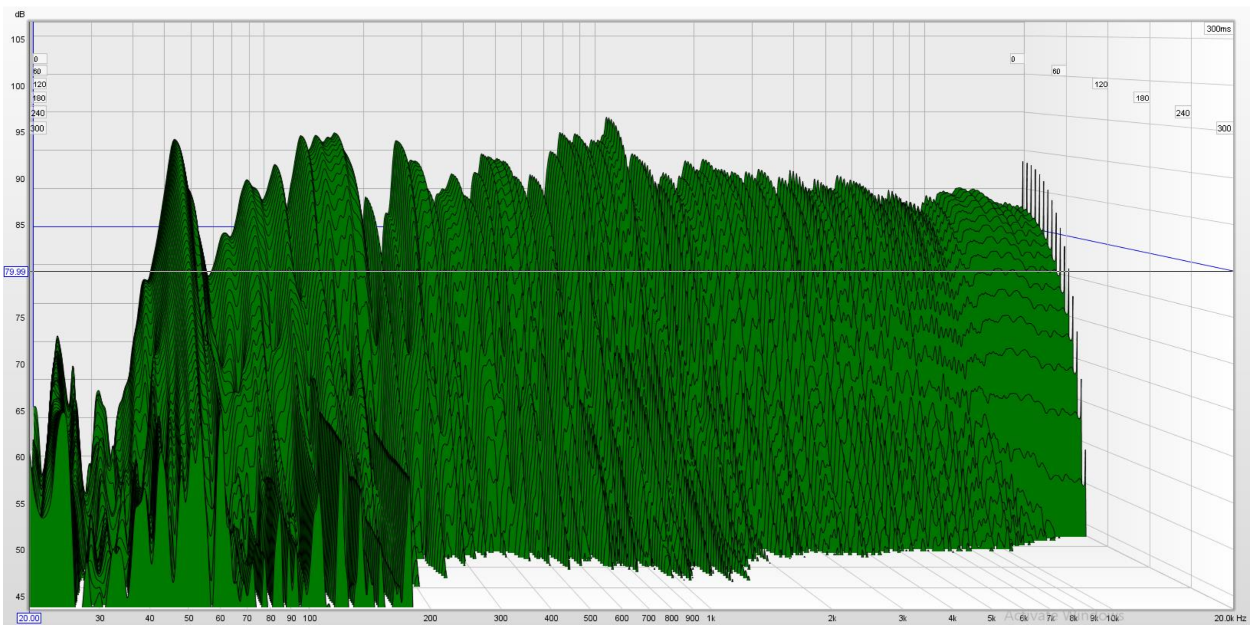


Figure 1.24 Bedroom Treatment Test 6 Waterfall Graph

<u>**The Studio Room**</u>

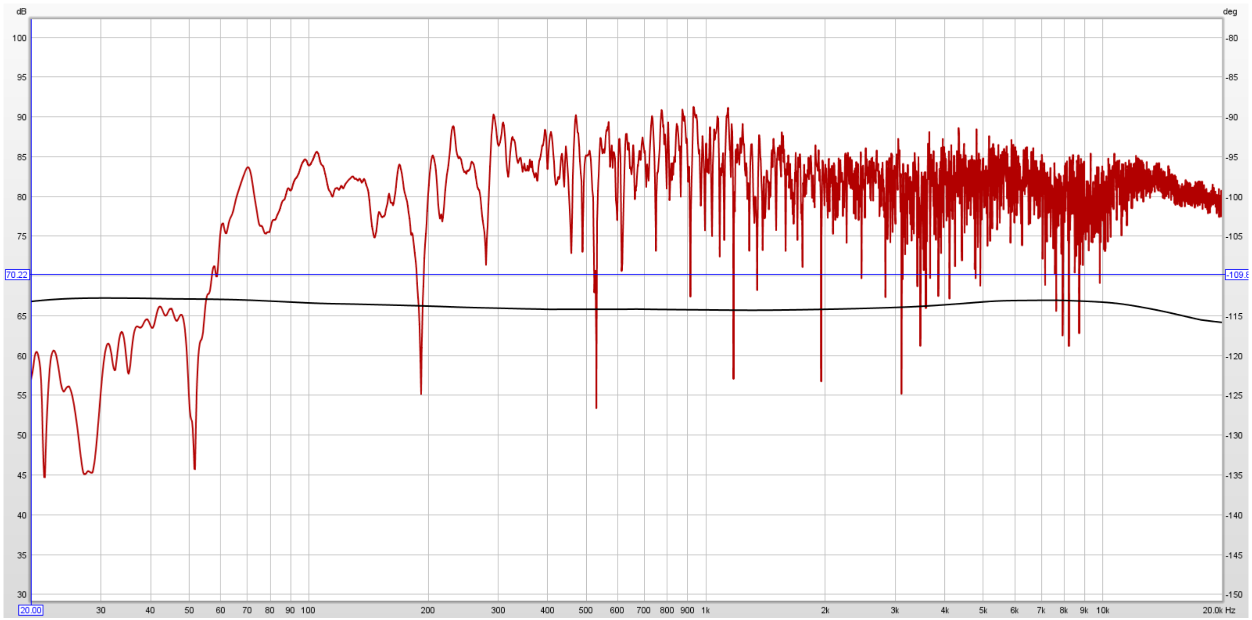


Figure 2.1 Studio Initial Frequency Response

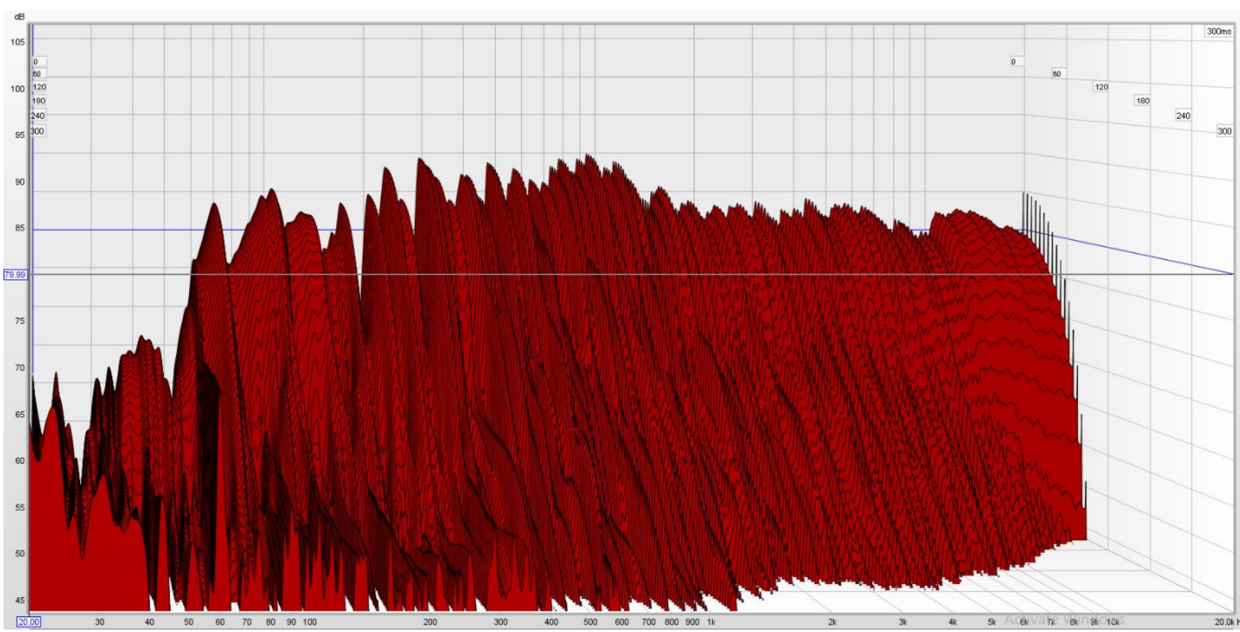


Figure 2.2 Studio Initial Waterfall Graph

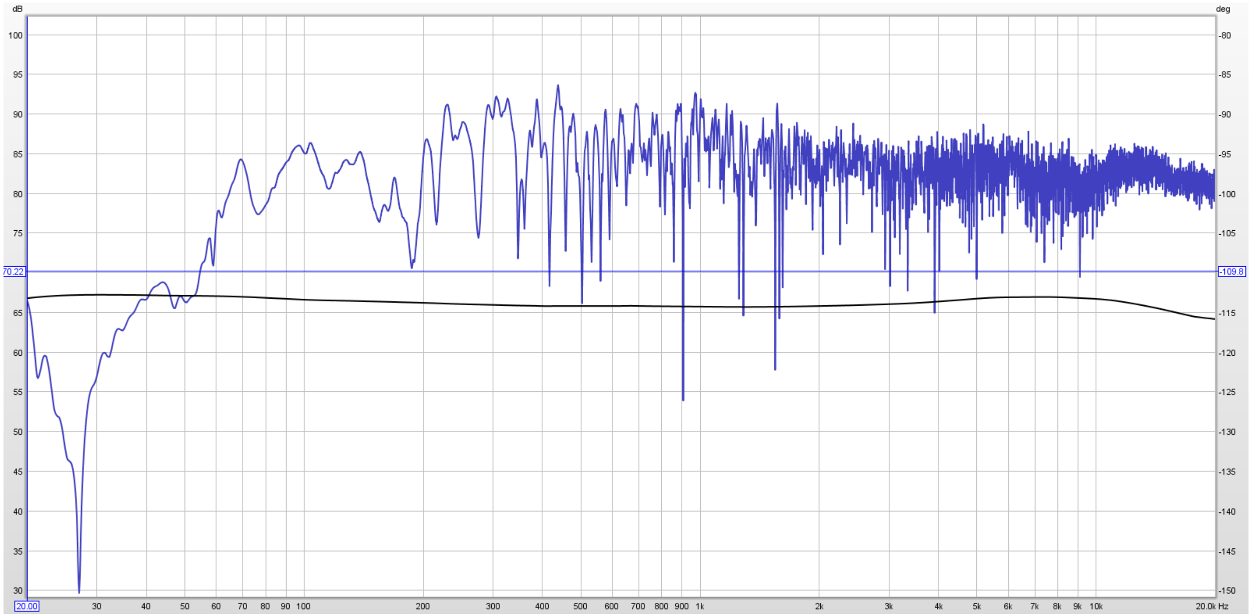


Figure 2.3 Studio Test 1 Frequency Response

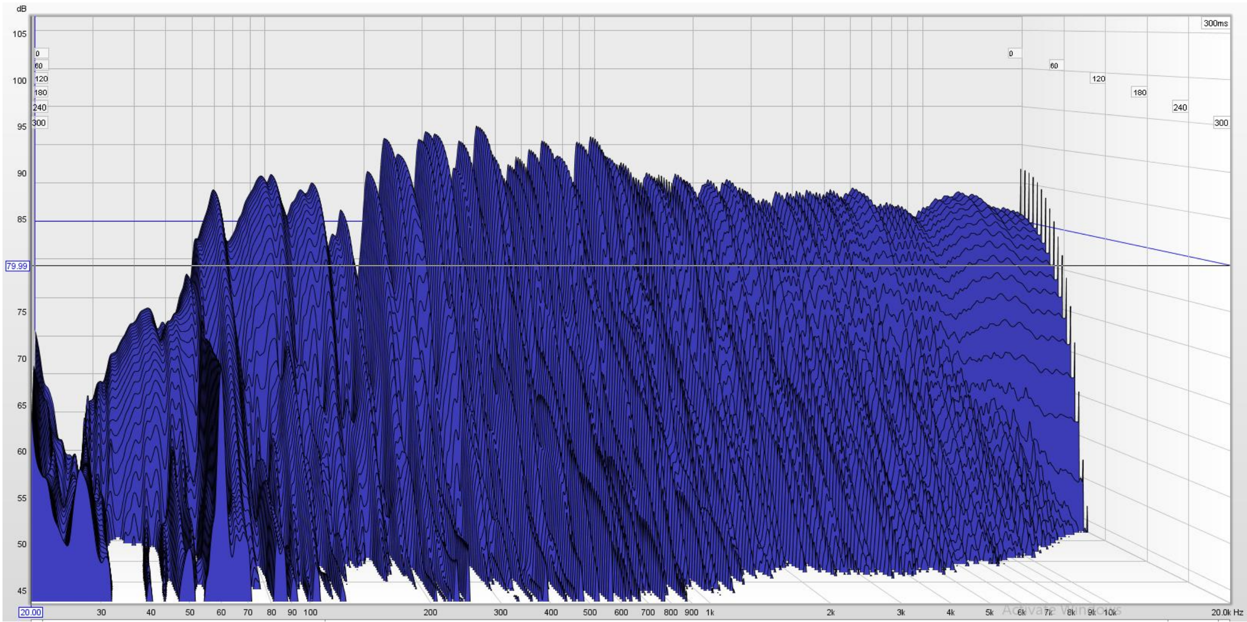


Figure 2.4 Studio Test 1 Waterfall Graph

Figure 2.5 Studio Test 2 Frequency Response

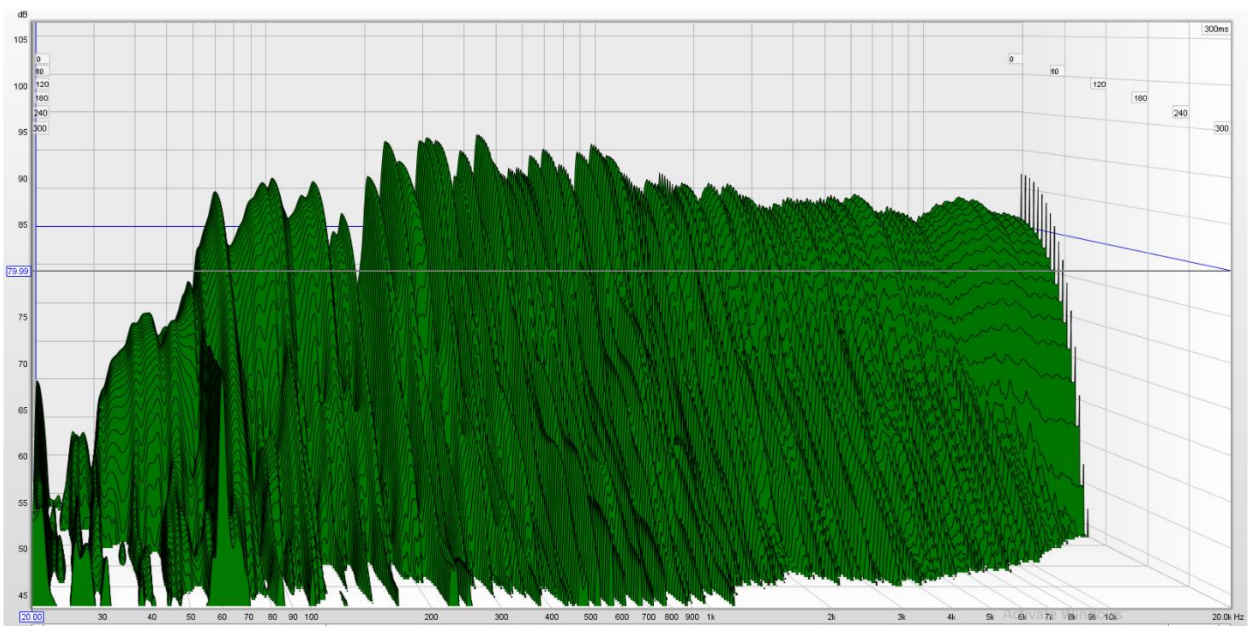


Figure 2.6 Studio Test 2 Waterfall Graph

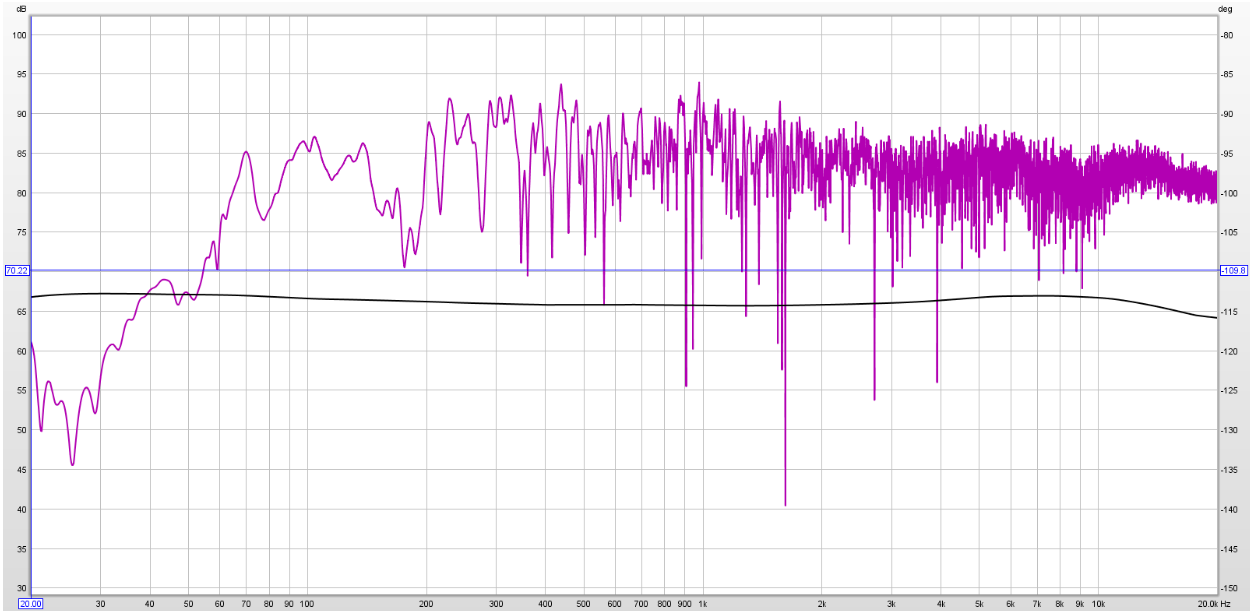


Figure 2.7 Studio Test 3 Frequency Response

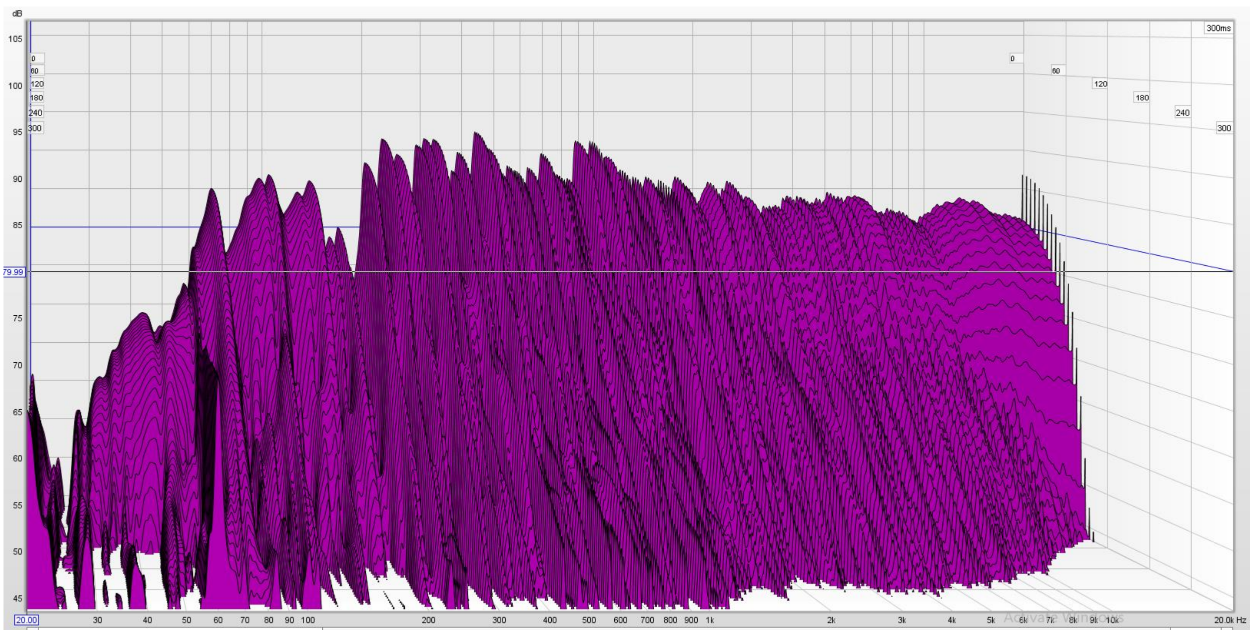


Figure 2.8 Studio Test 3 Waterfall Graph

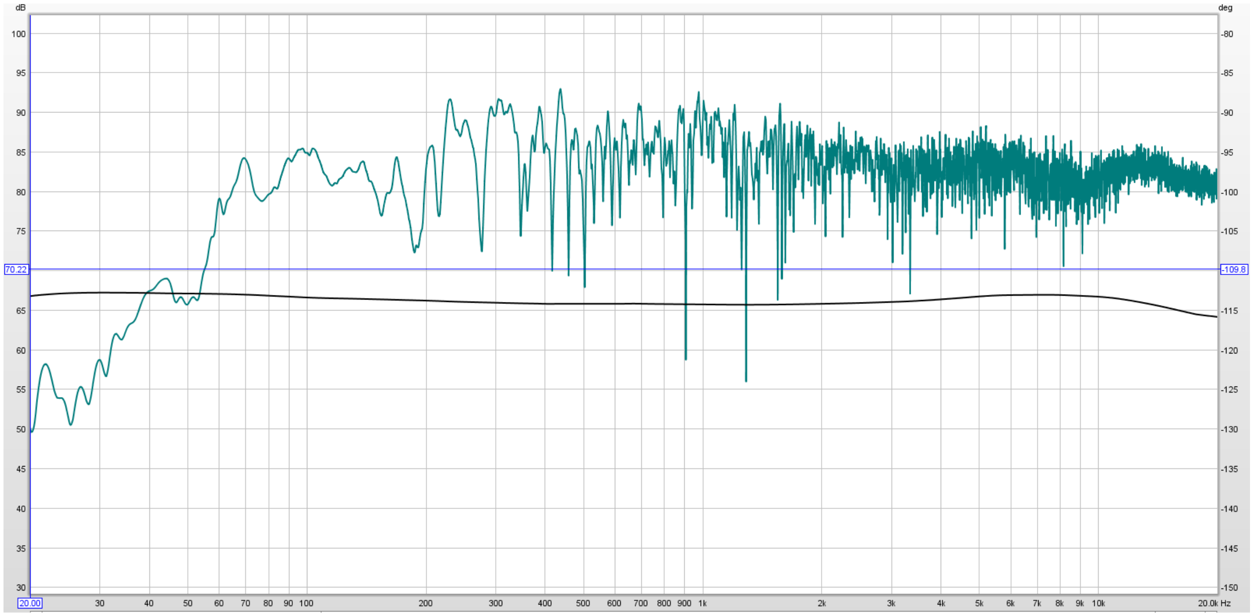


Figure 2.9 Studio Test 4 Frequency Response

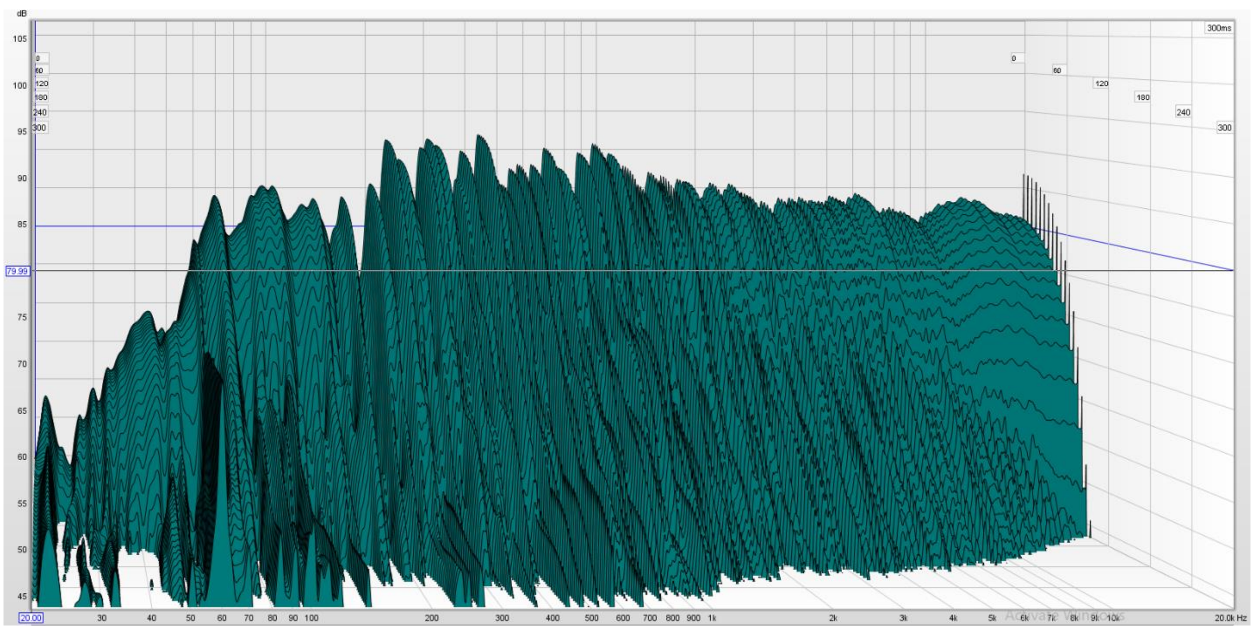


Figure 2.10 Studio Test 4 Waterfall Graph

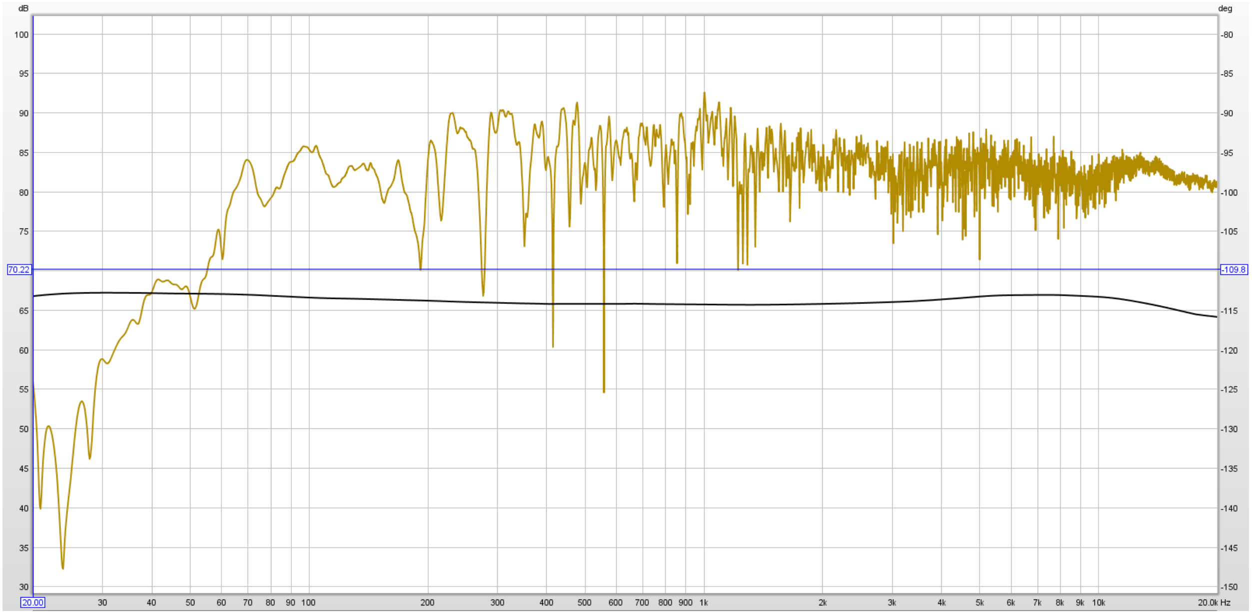


Figure 2.11 Studio Test 5 Frequency Response

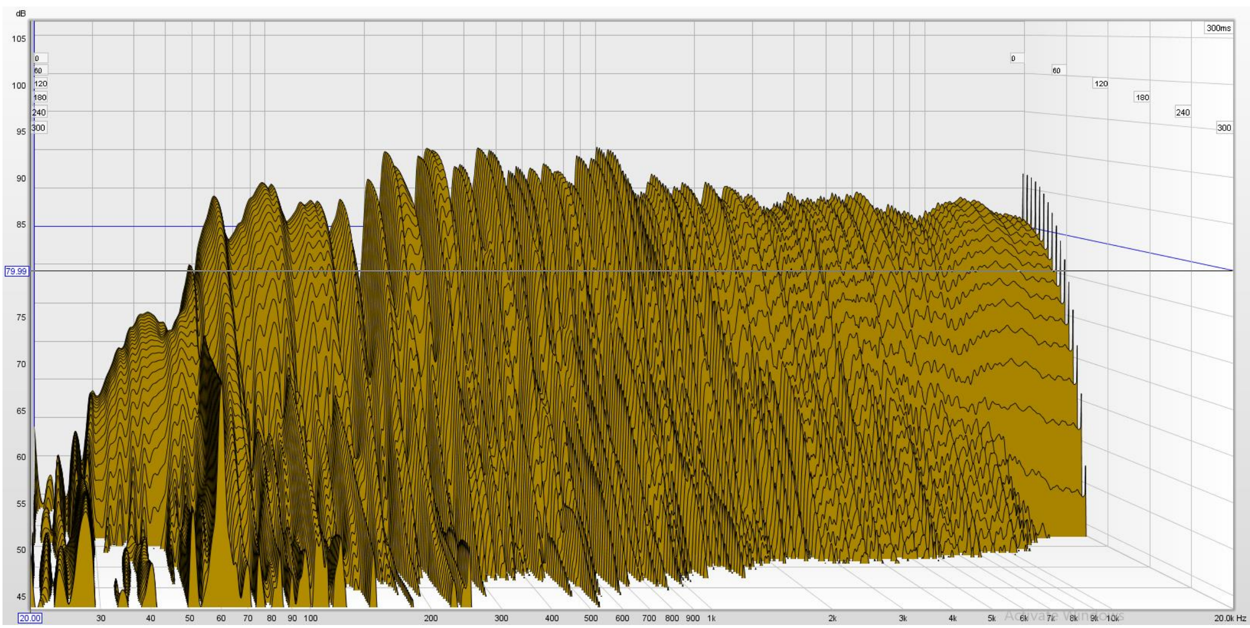


Figure 2.12 Studio Test 5 Waterfall Graph

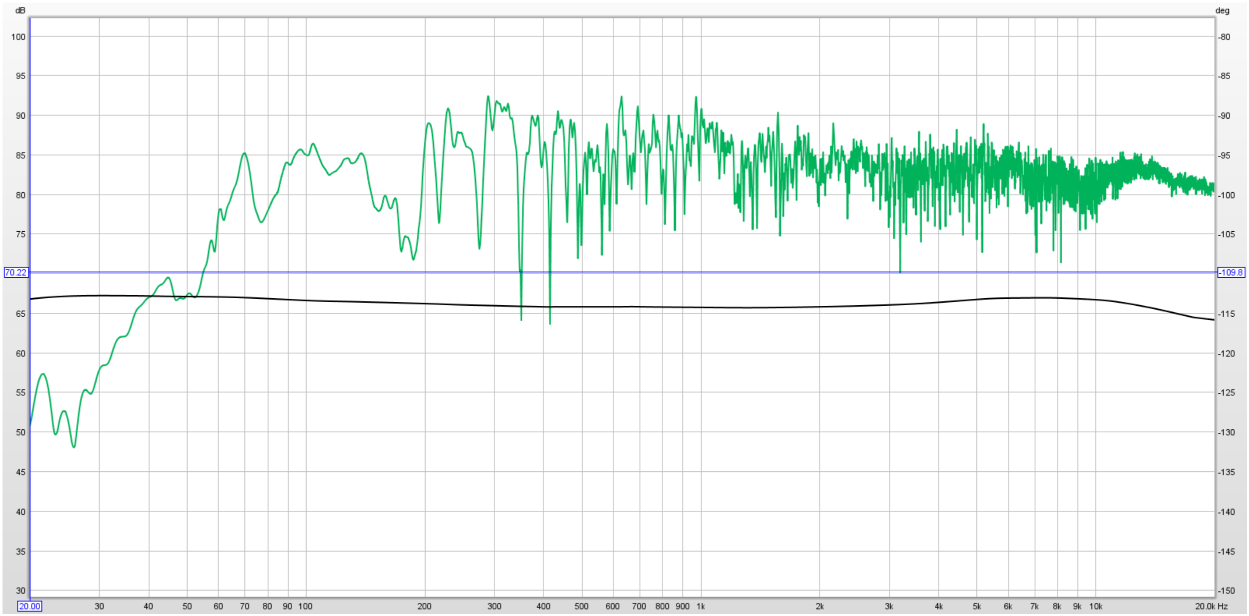


Figure 2.13 Studio Treatment Test 1 Frequency Response

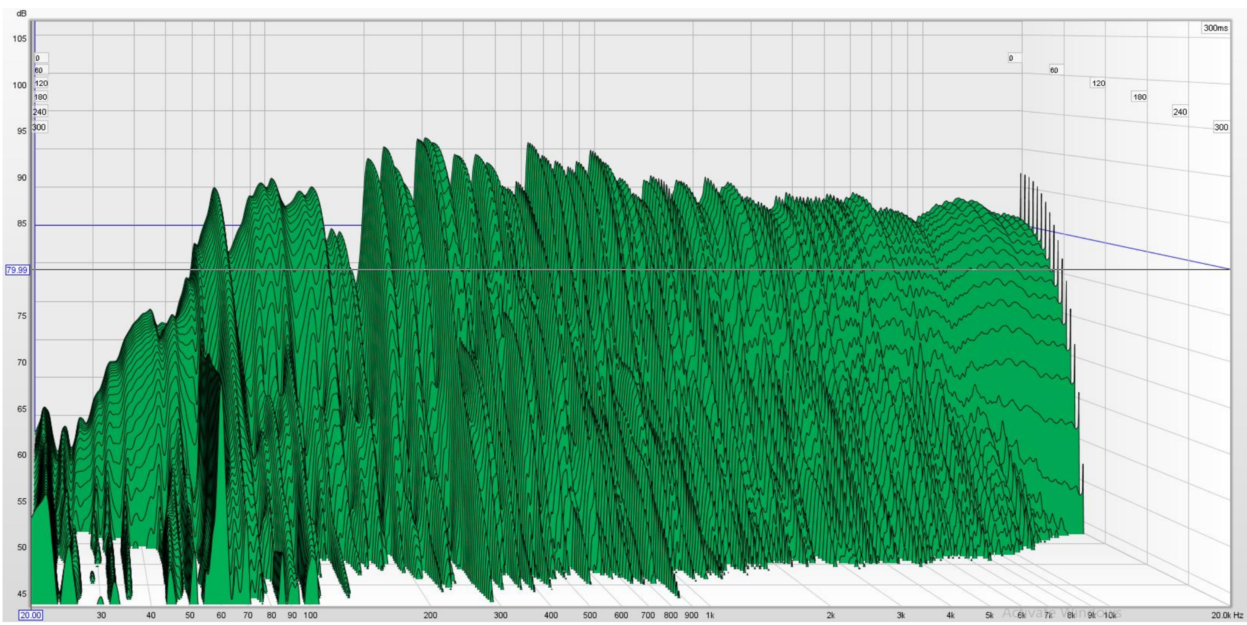


Figure 2.14 Studio Treatment Test 1 Waterfall Graph

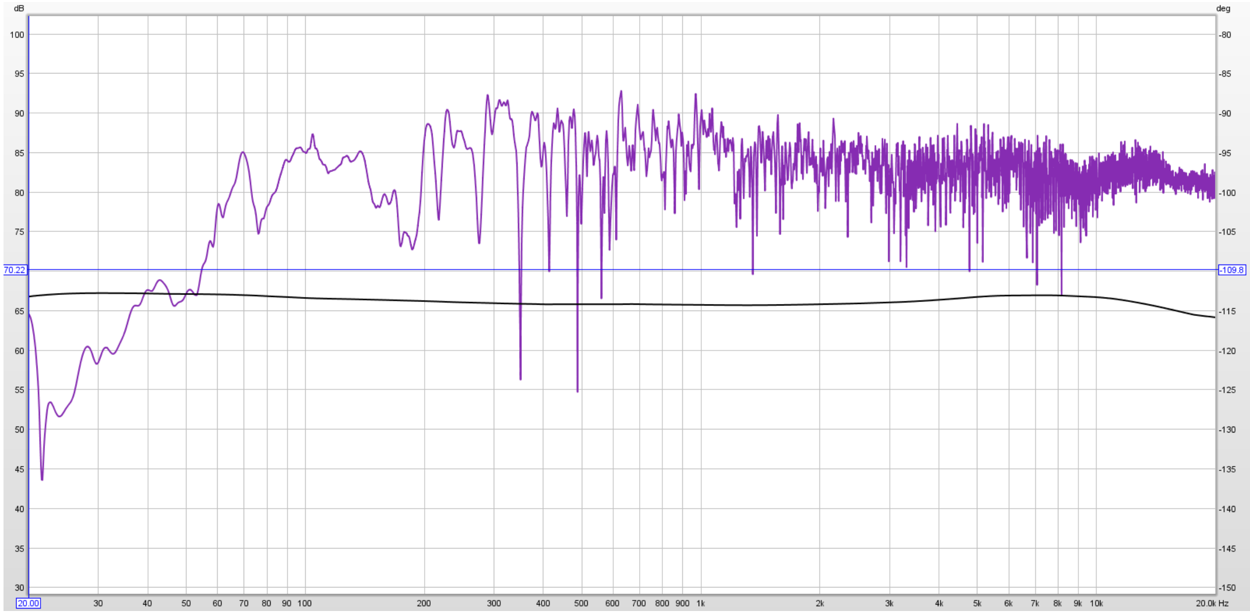


Figure 2.15 Studio Treatment Test 2 Frequency Response

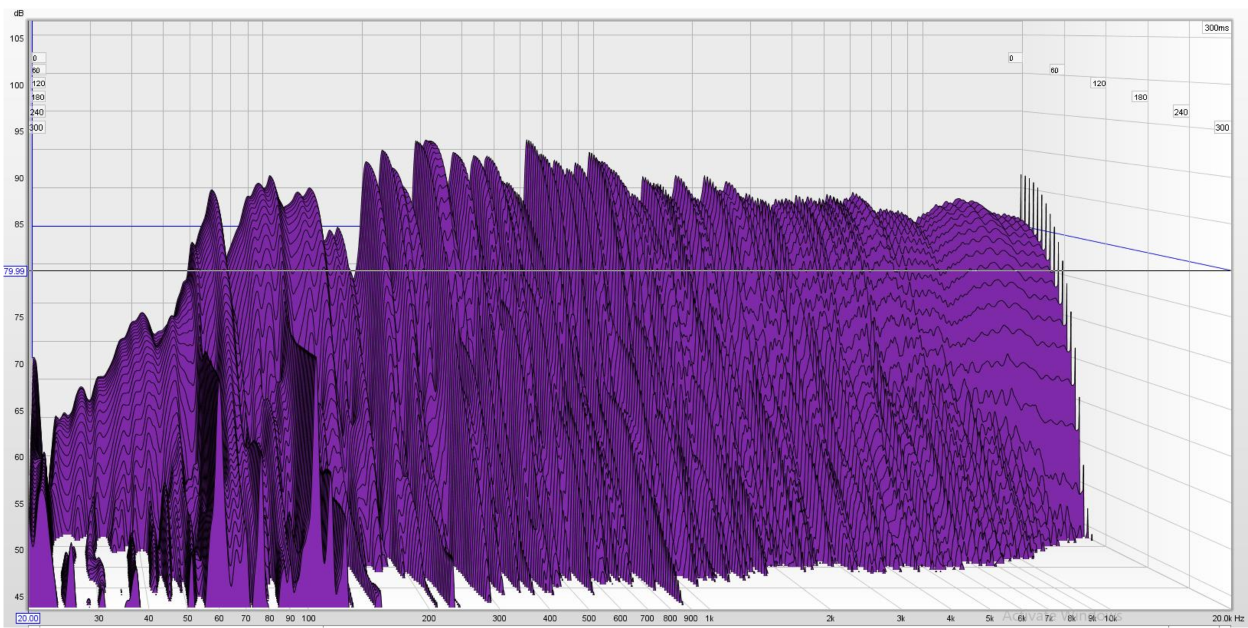


Figure 2.16 Studio Treatment Test 2 Waterfall Graph

Figure 2.17 Studio Treatment Test 3 Frequency Response

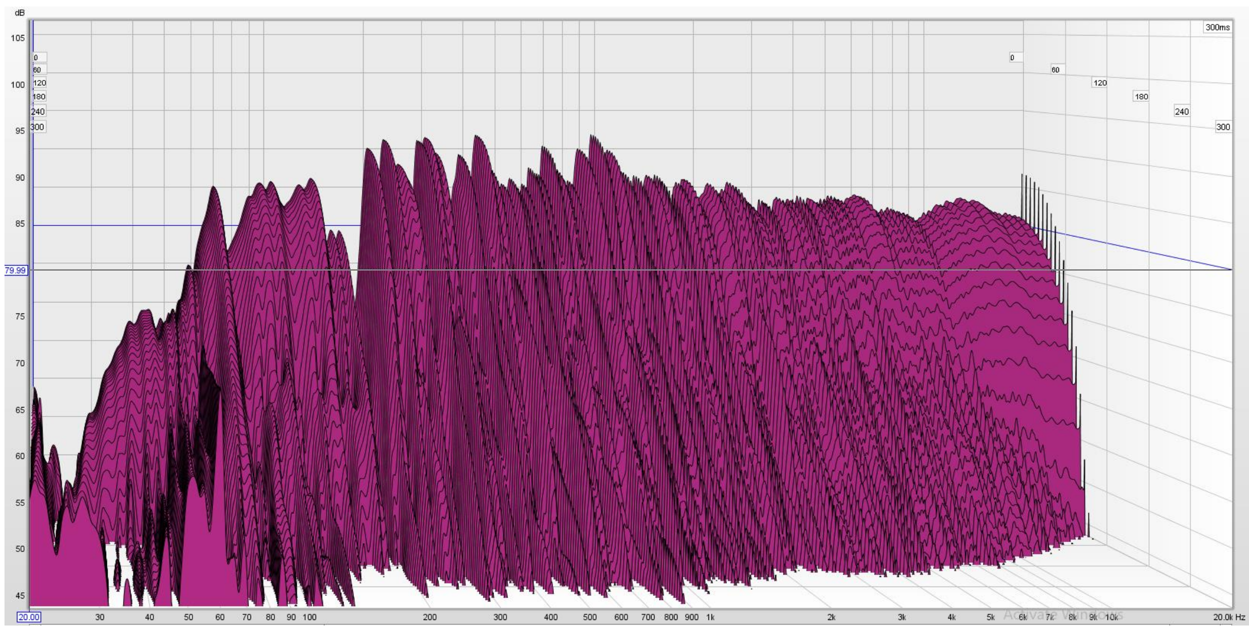


Figure 2.18 Studio Treatment Test 3 Waterfall Graph

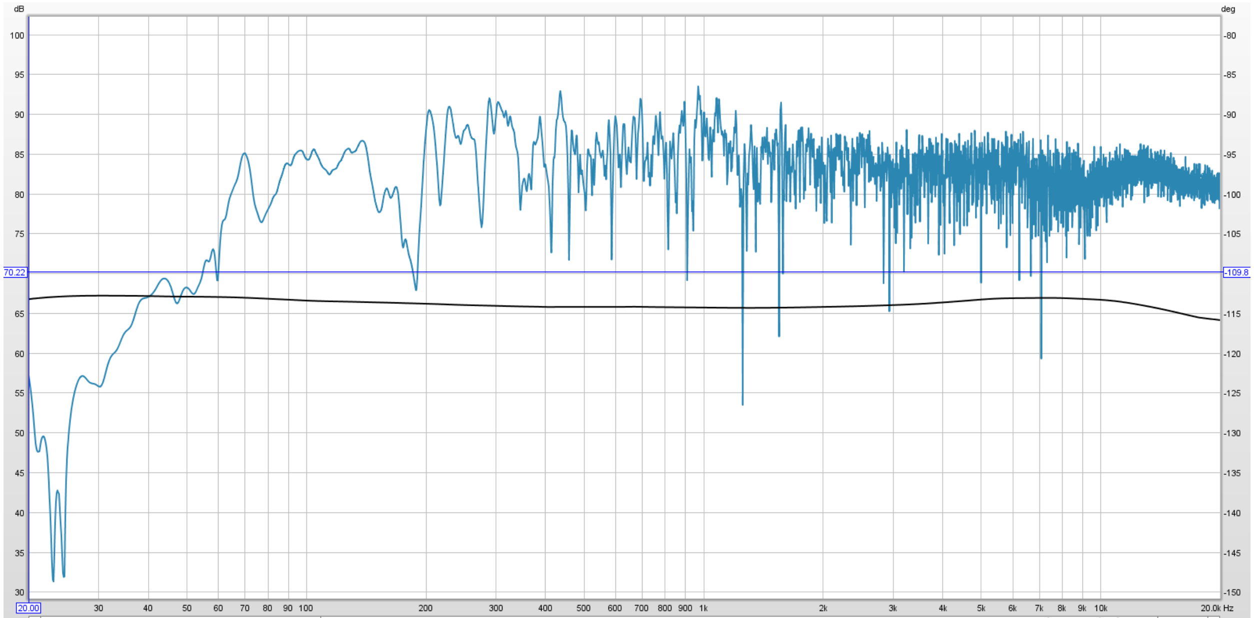


Figure 2.19 Studio Treatment Test 4 Frequency Response

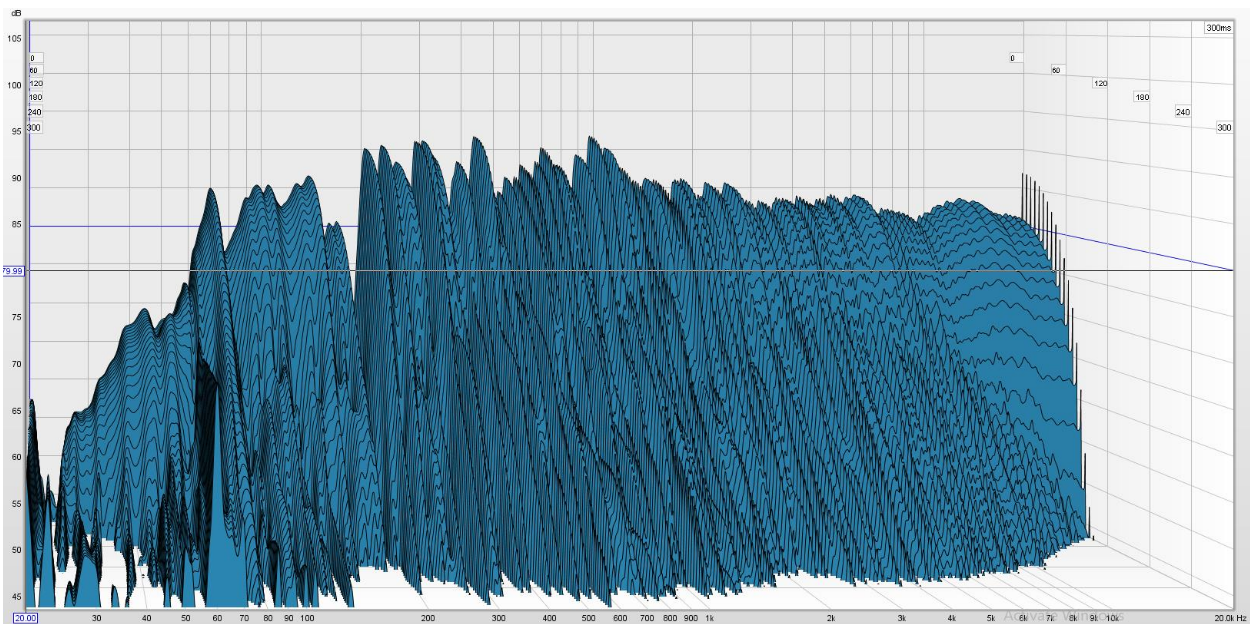


Figure 2.20 Studio Treatment Test 4 Waterfall Graph

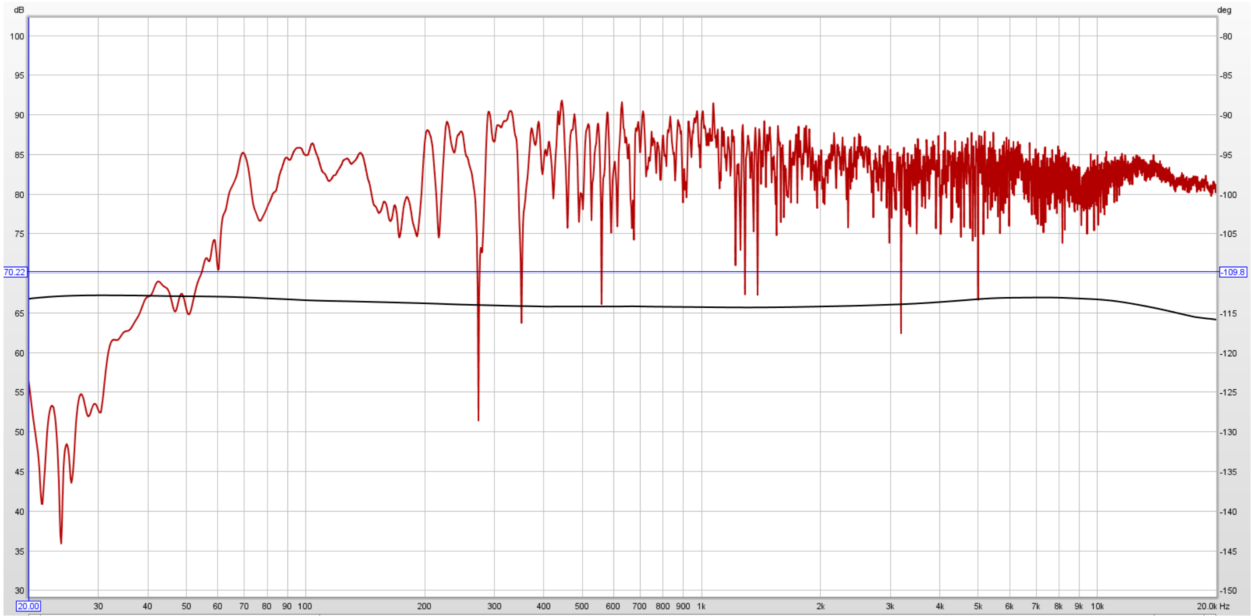


Figure 2.21 Studio Treatment Test 5 Frequency Response

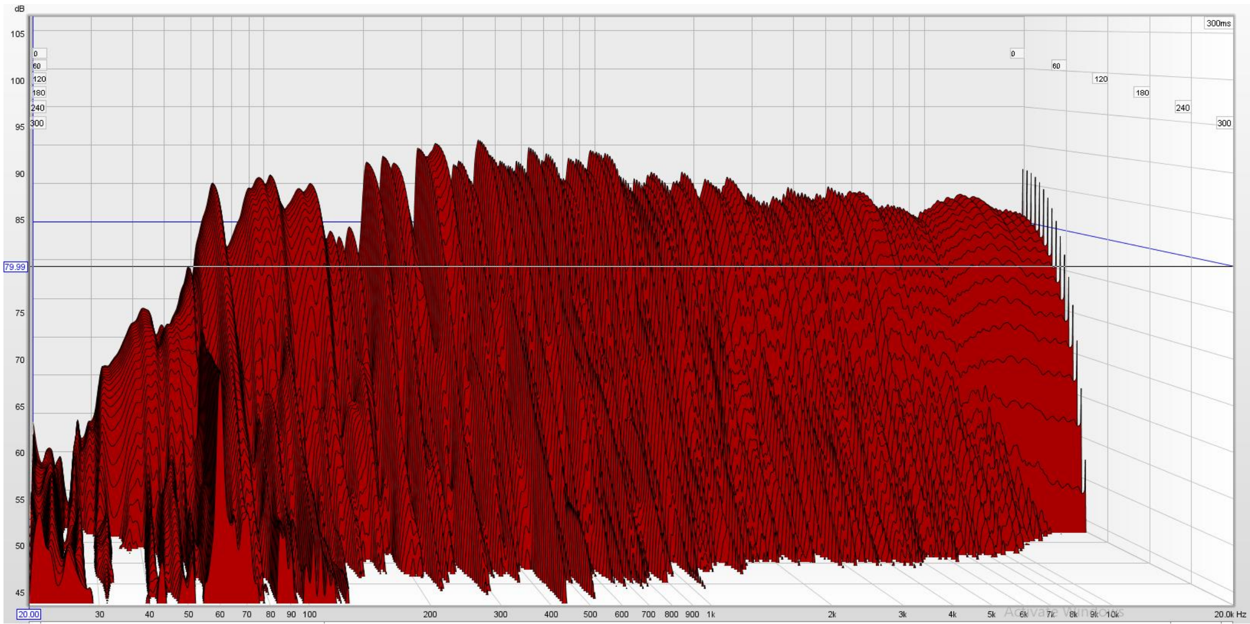


Figure 2.22 Studio Treatment Test 5 Waterfall Graph

The Living Room

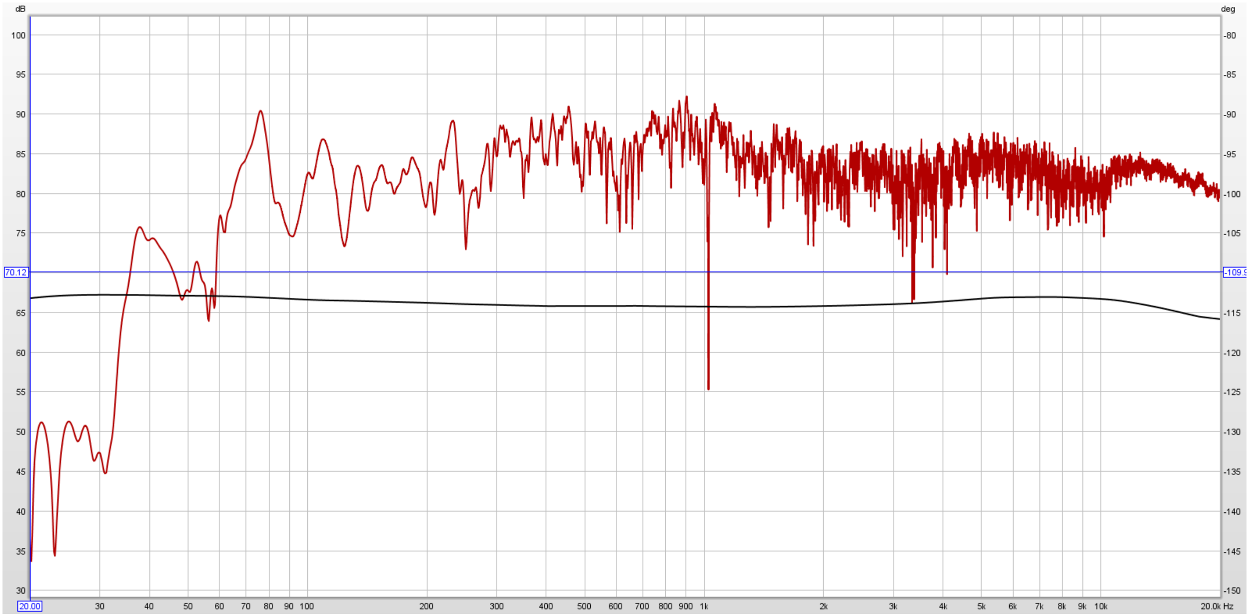


Figure 3.1 Living Room Initial Frequency Response

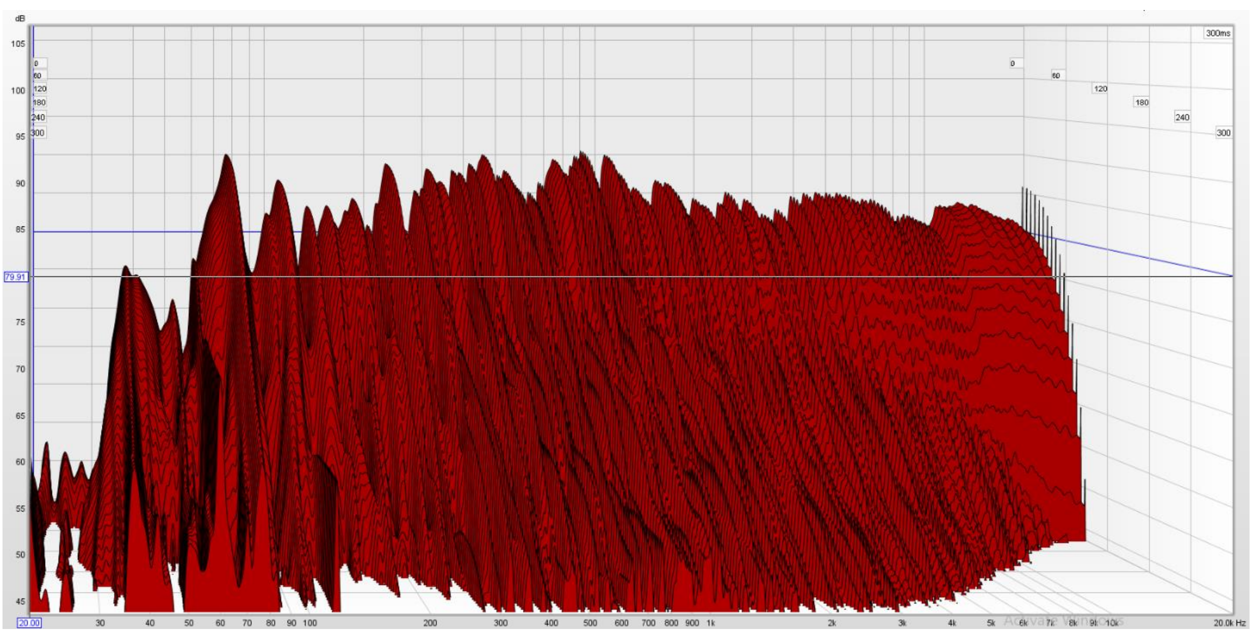


Figure 3.2 Living Room Initial Waterfall Graph

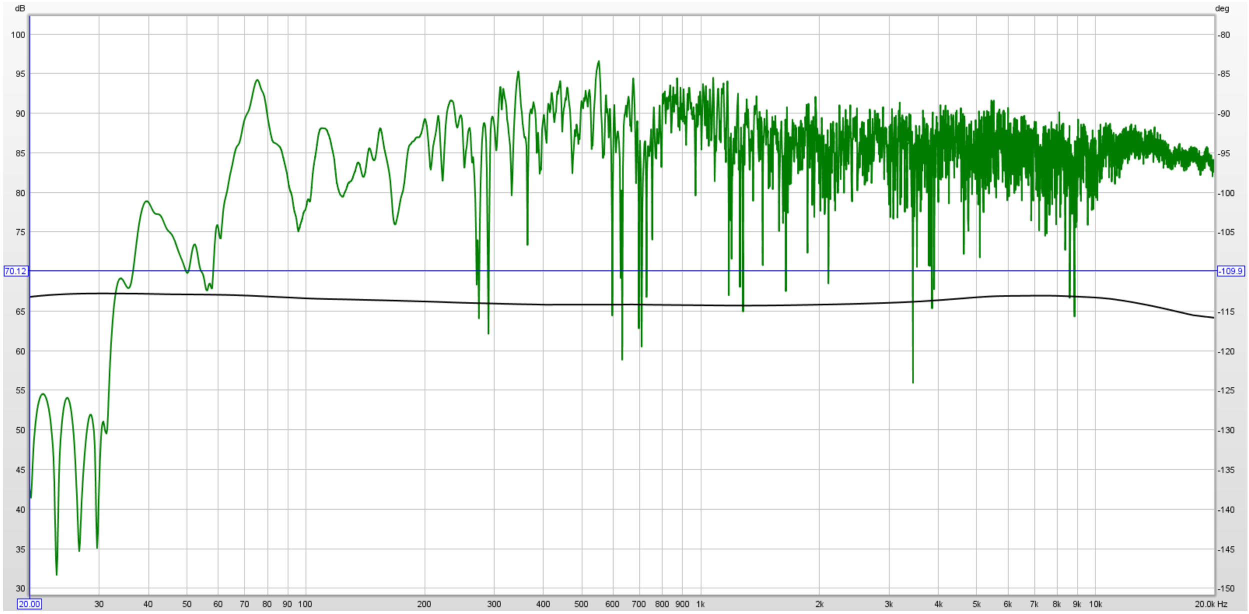


Figure 3.3 Living Room Test 1 Frequency Response

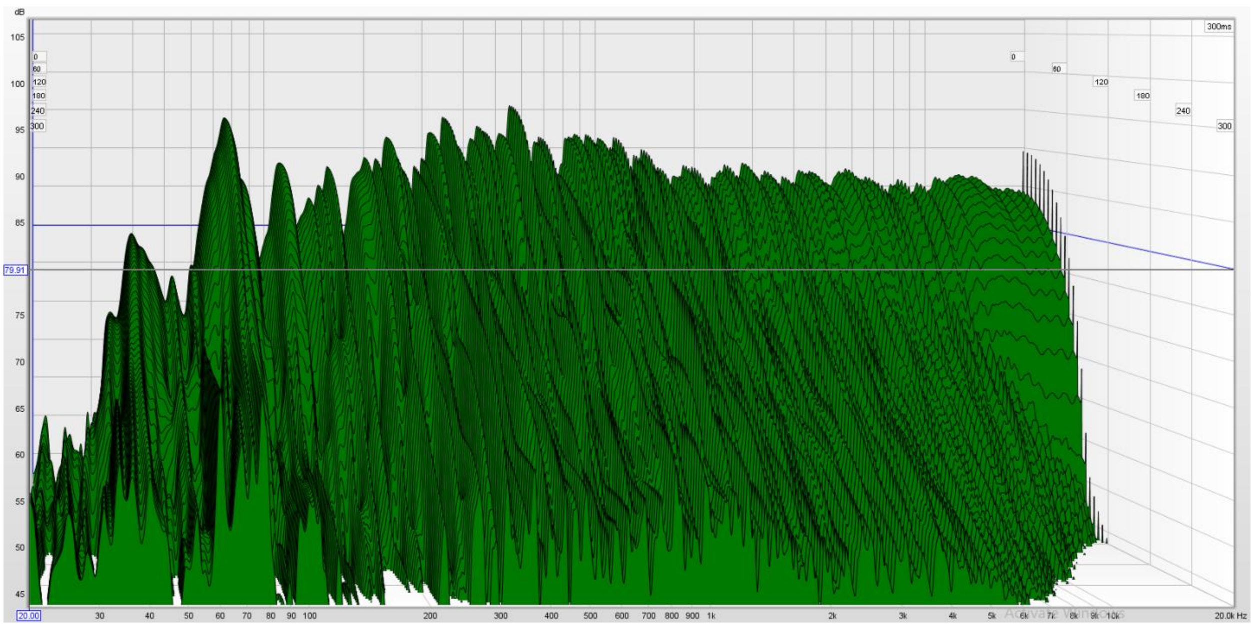


Figure 3.4 Living Room Test 1 Waterfall Graph

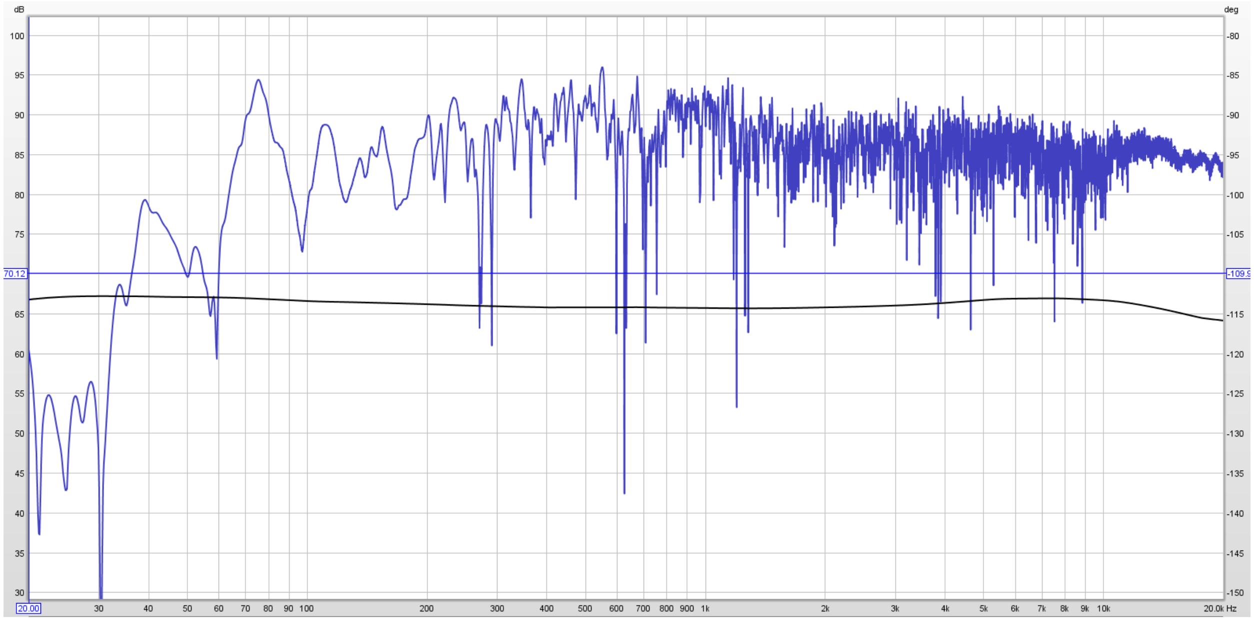


Figure 3.5 Living Room Test 2 Frequency Response

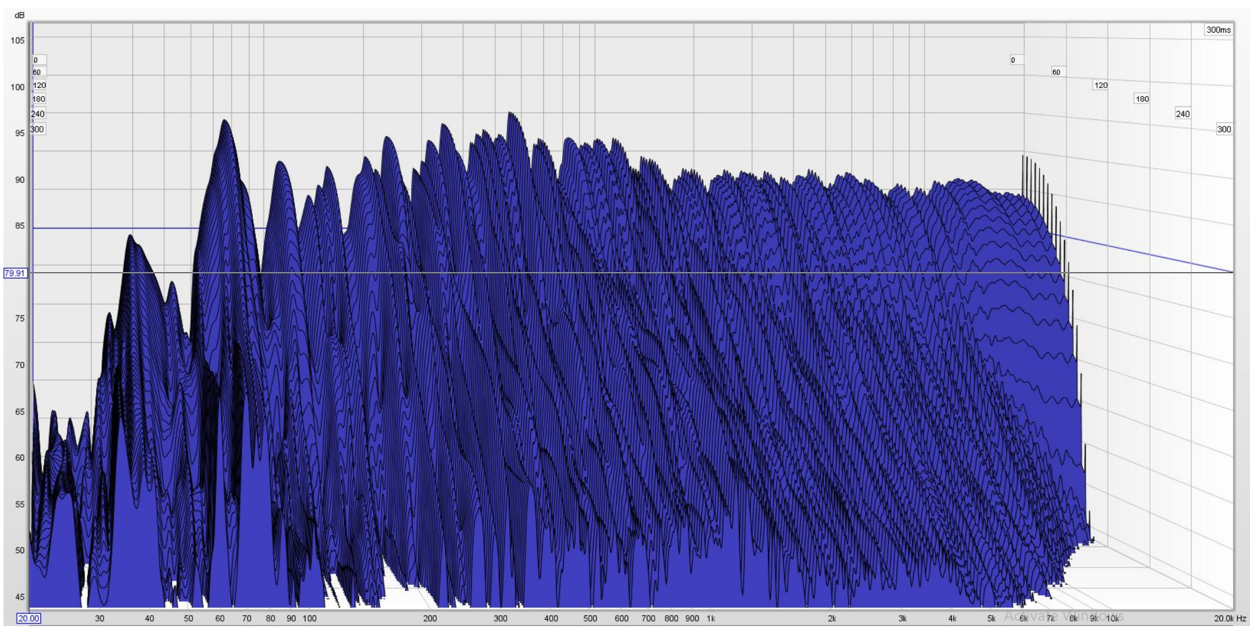


Figure 3.6 Living Room Test 2 Waterfall Graph

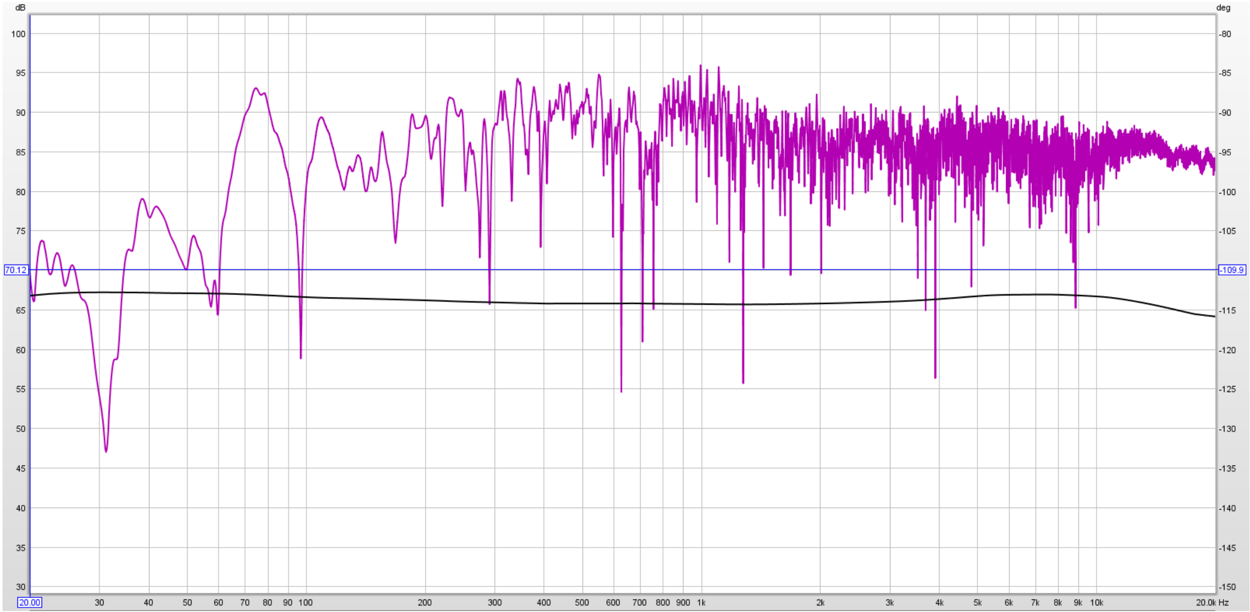


Figure 3.7 Living Room Test 3 Frequency Response

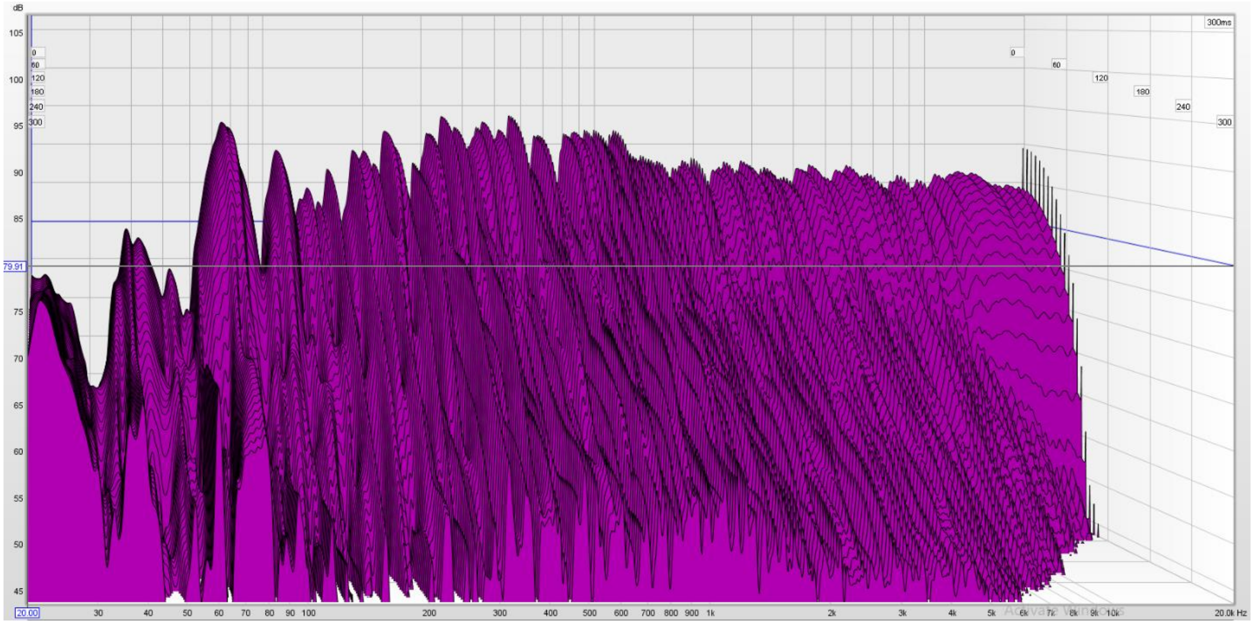


Figure 3.8 Living Room Test 3 Waterfall Graph

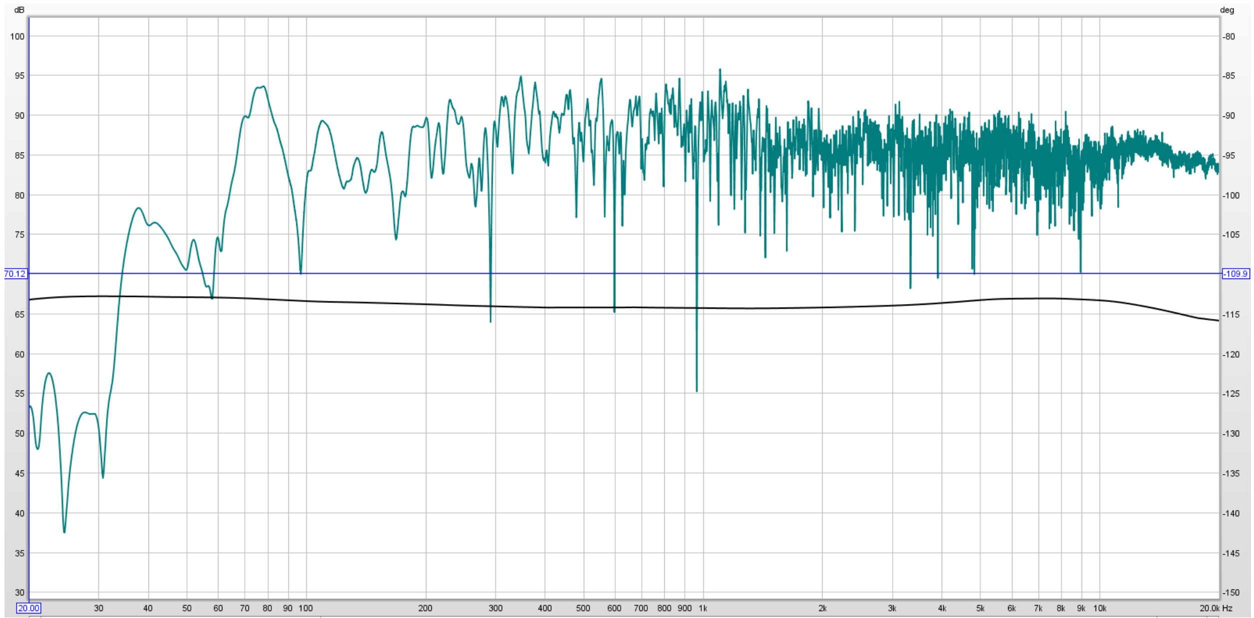


Figure 3.9 Living Room Test 4 Frequency Response

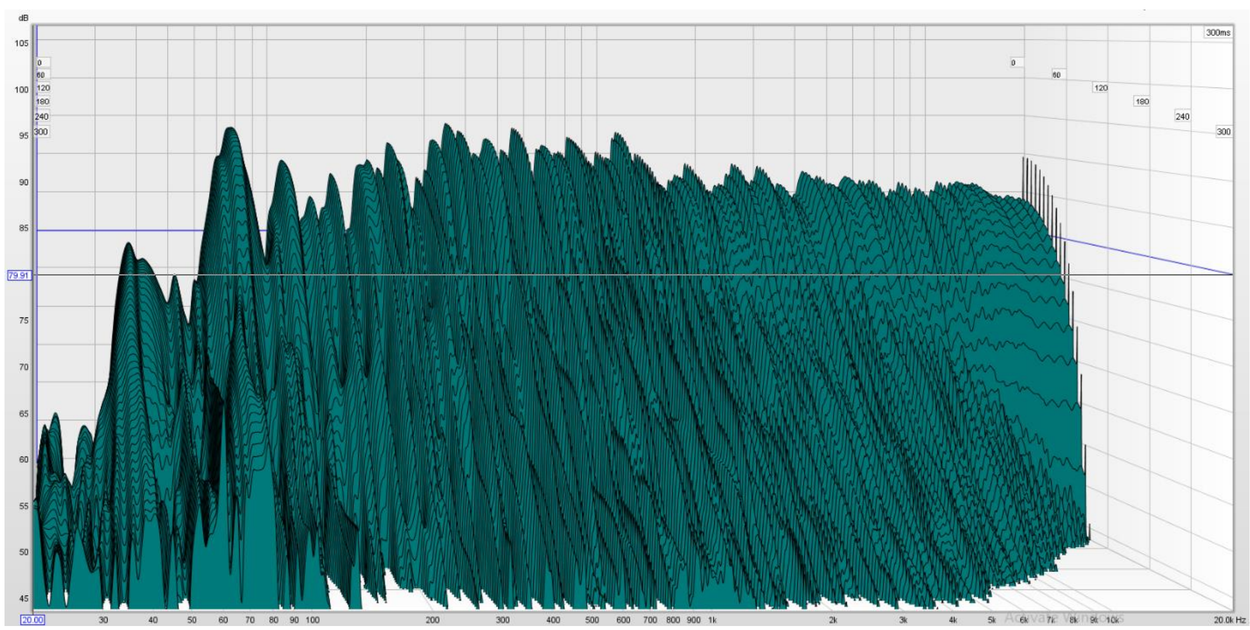


Figure 3.10 Living Room Test 4 Waterfall Graph

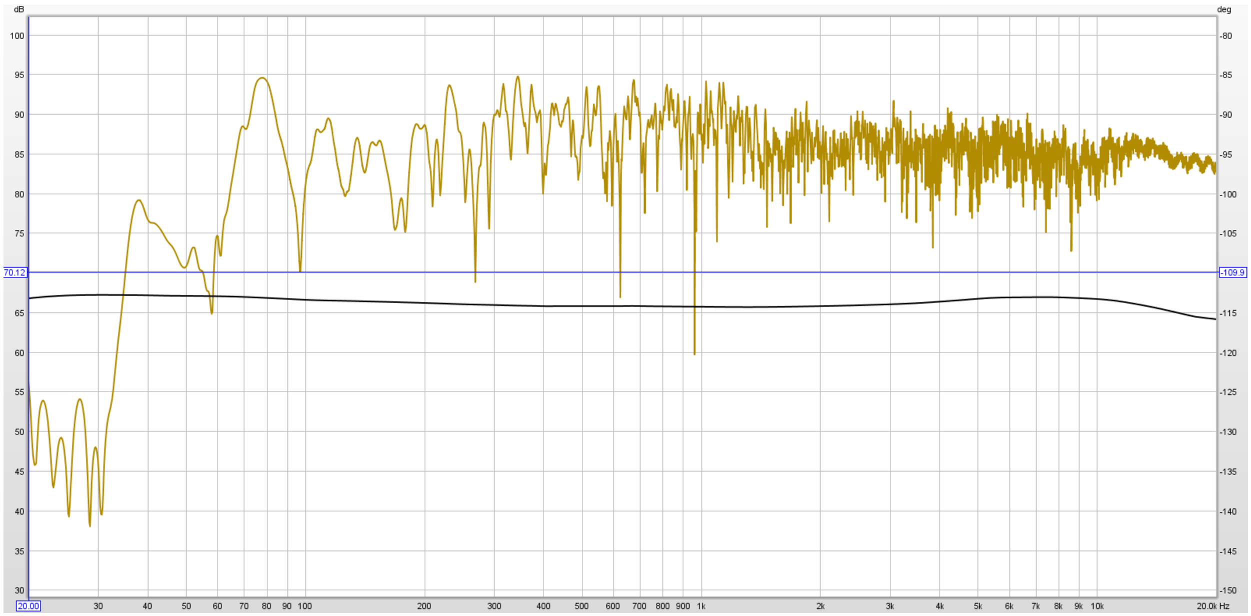


Figure 3.11 Living Room Test 5 Frequency Response

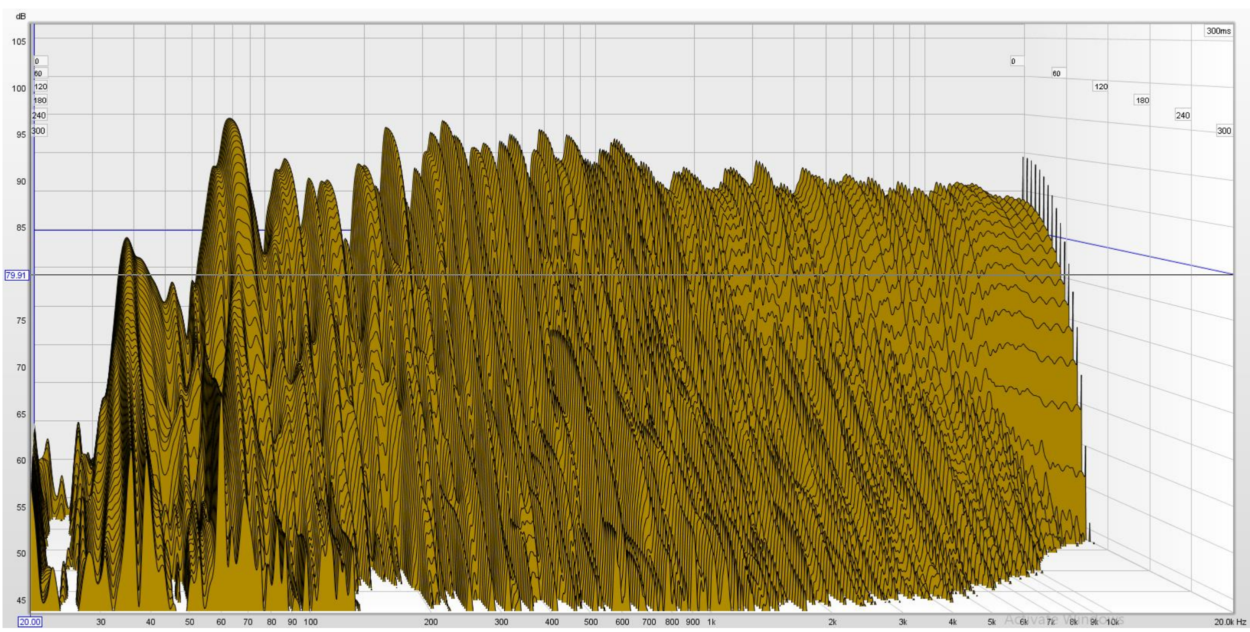


Figure 3.12 Living Room Test 5 Waterfall Graph

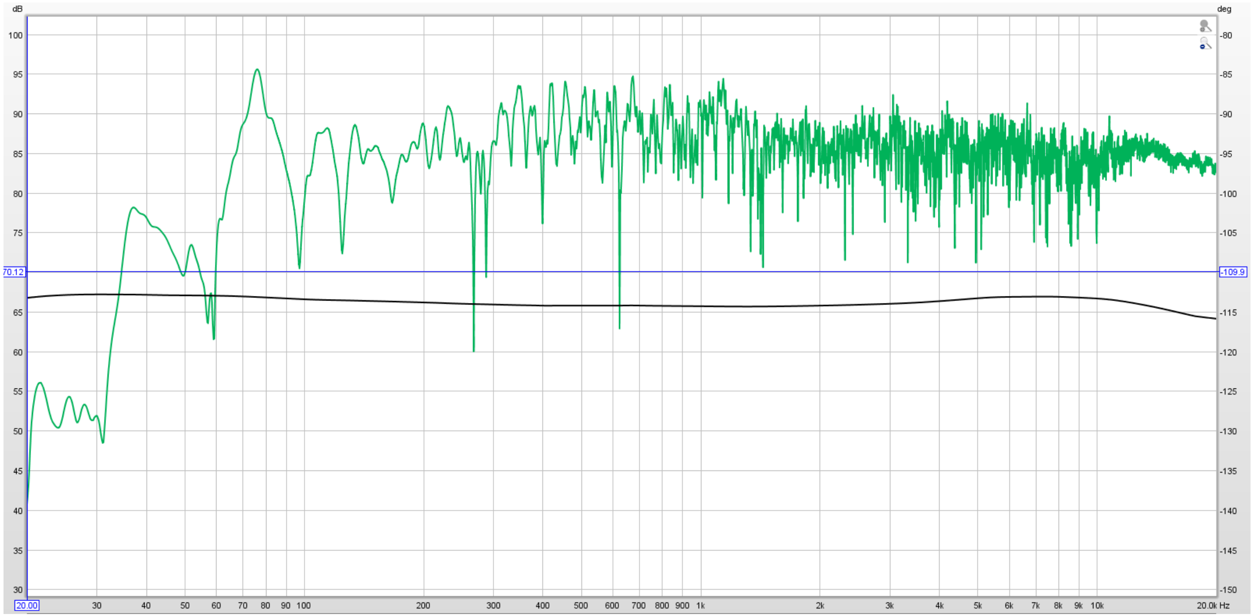


Figure 3.13 Living Room Test 6 Frequency Response

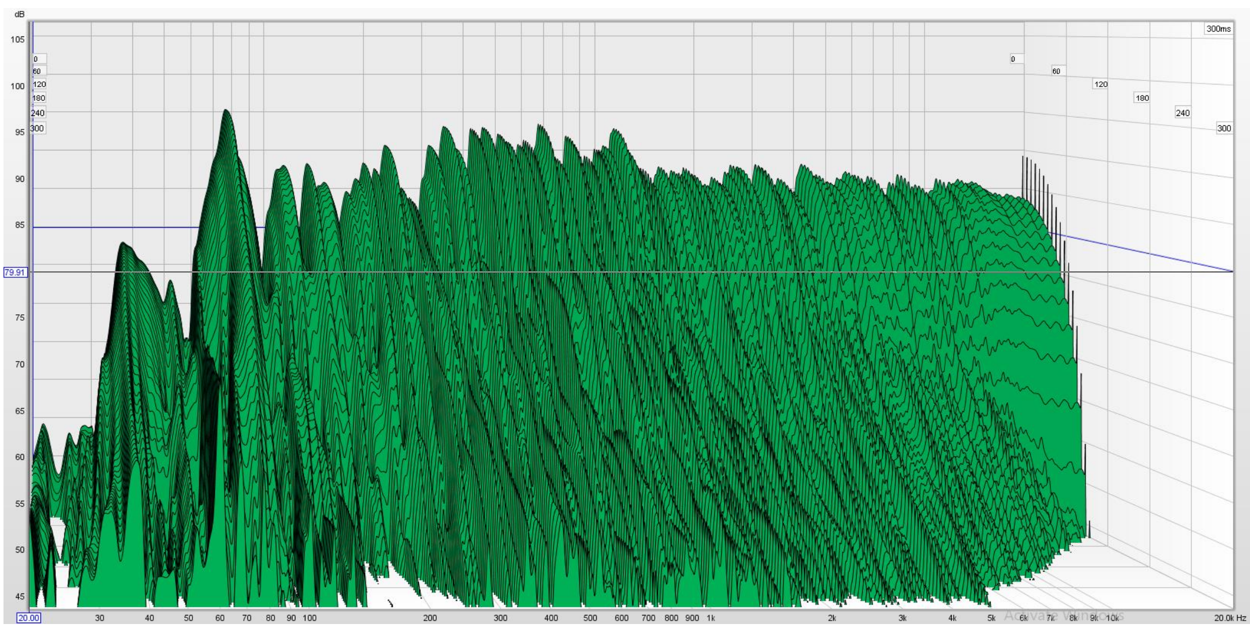


Figure 3.14 Living Room Test 6 Waterfall Graph

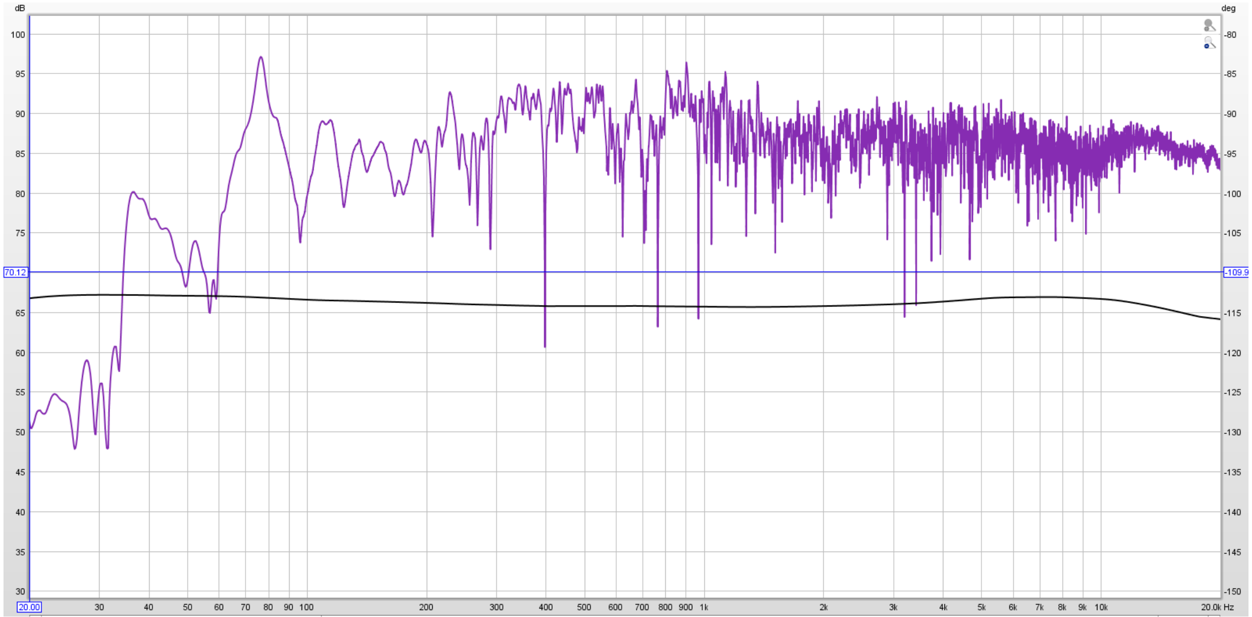


Figure 3.15 Living Room Test 7 Frequency Response

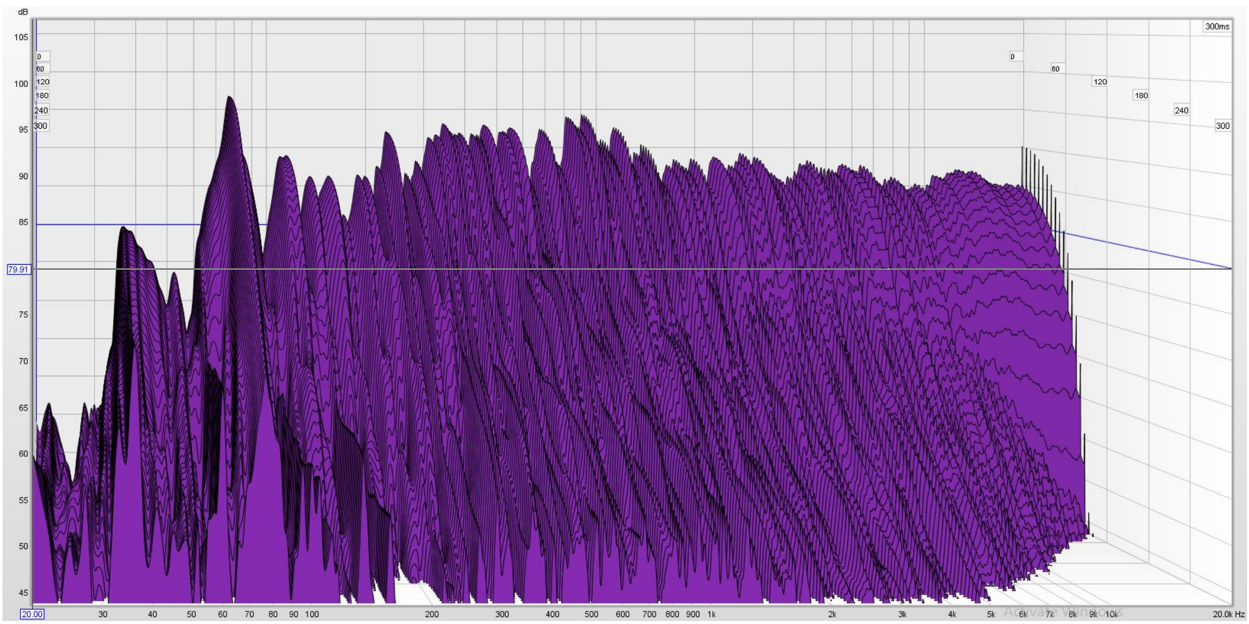


Figure 3.16 Living Room Test 7 Waterfall Graph

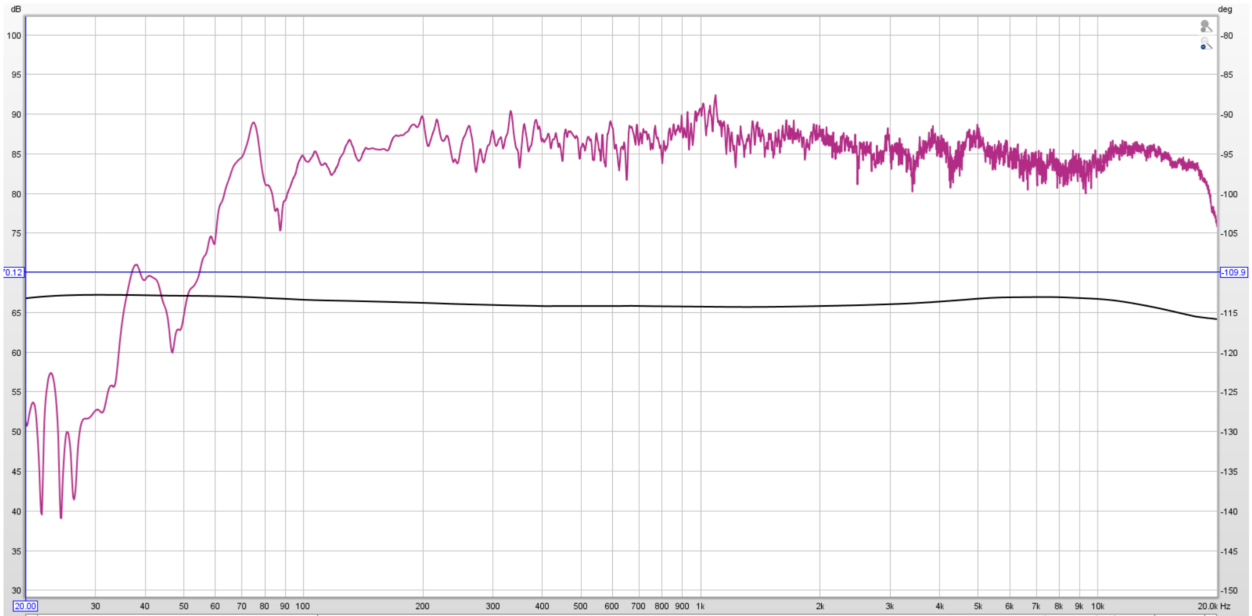


Figure 3.17 Living Room Treatment Test 1 Frequency Response

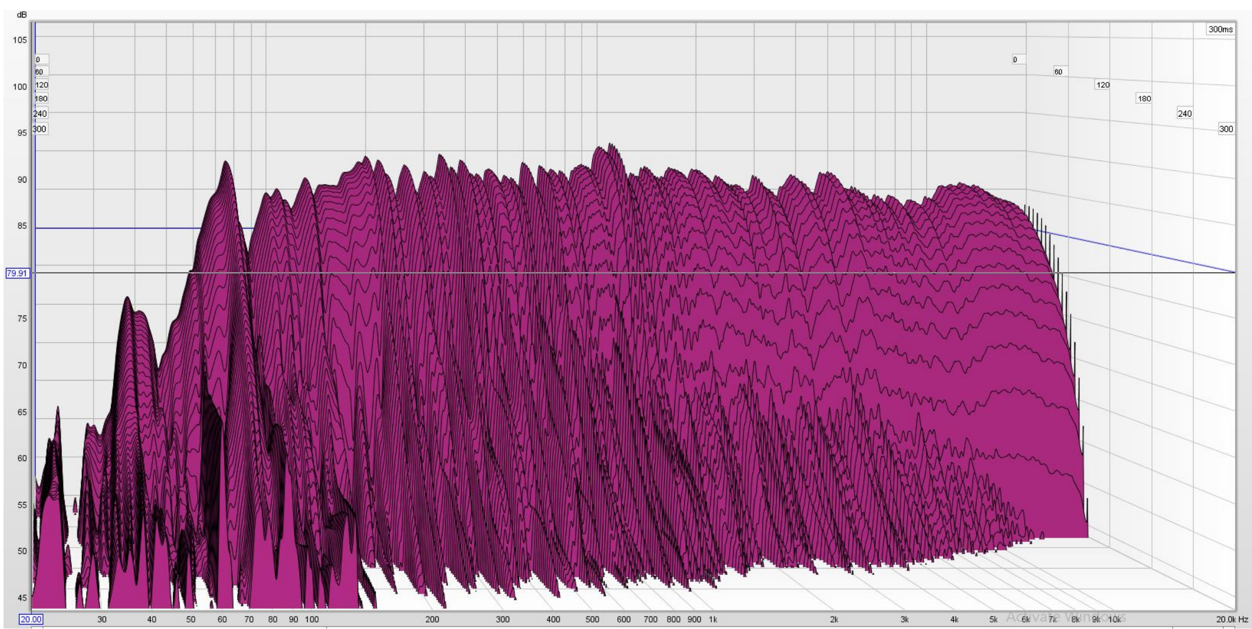


Figure 3.18 Living Room Treatment Test 1 Waterfall Graph

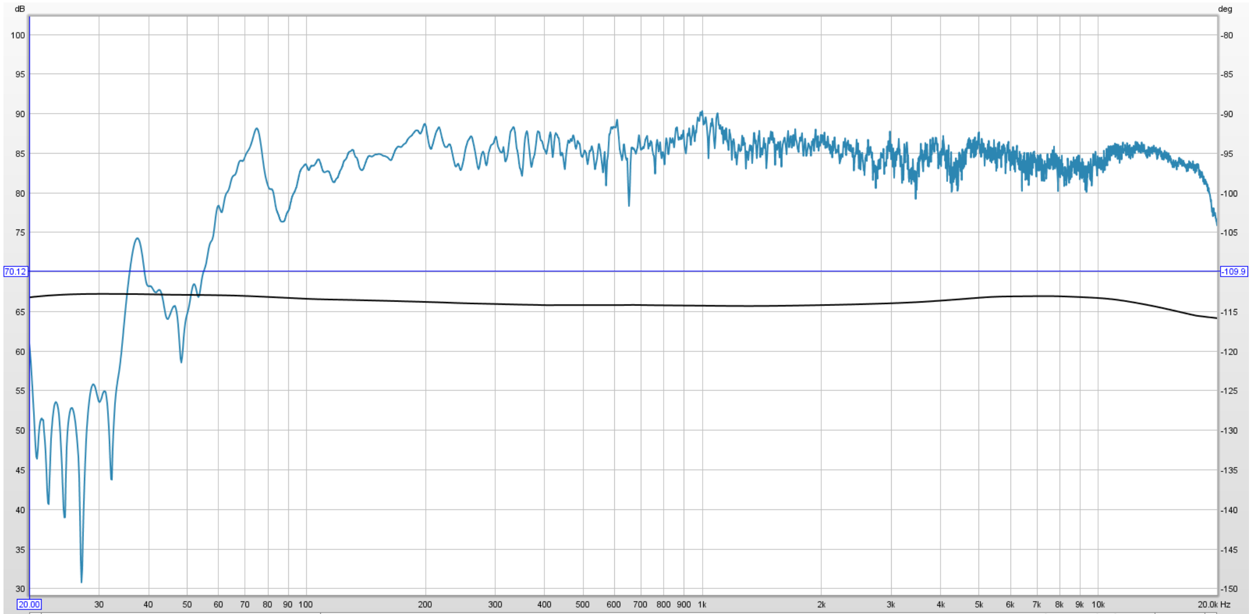


Figure 3.19 Living Room Treatment Test 2 Frequency Response

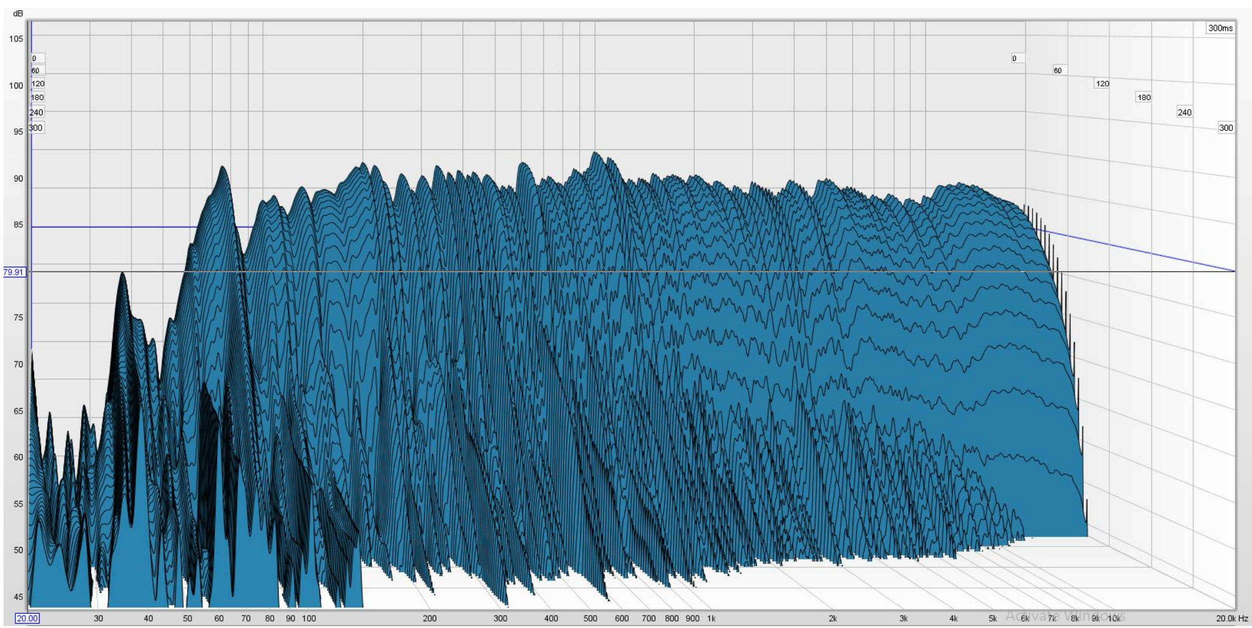


Figure 3.20 Living Room Treatment Test 2 Waterfall Graph

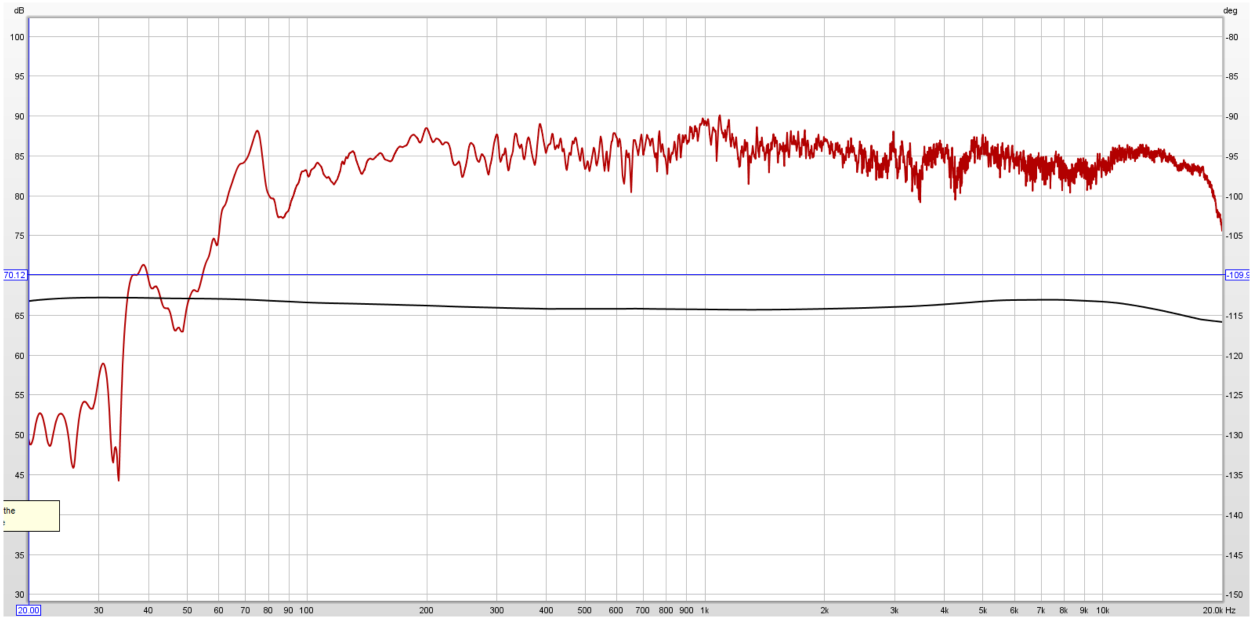


Figure 3.21 Living Room Treatment Test 3 Frequency Response

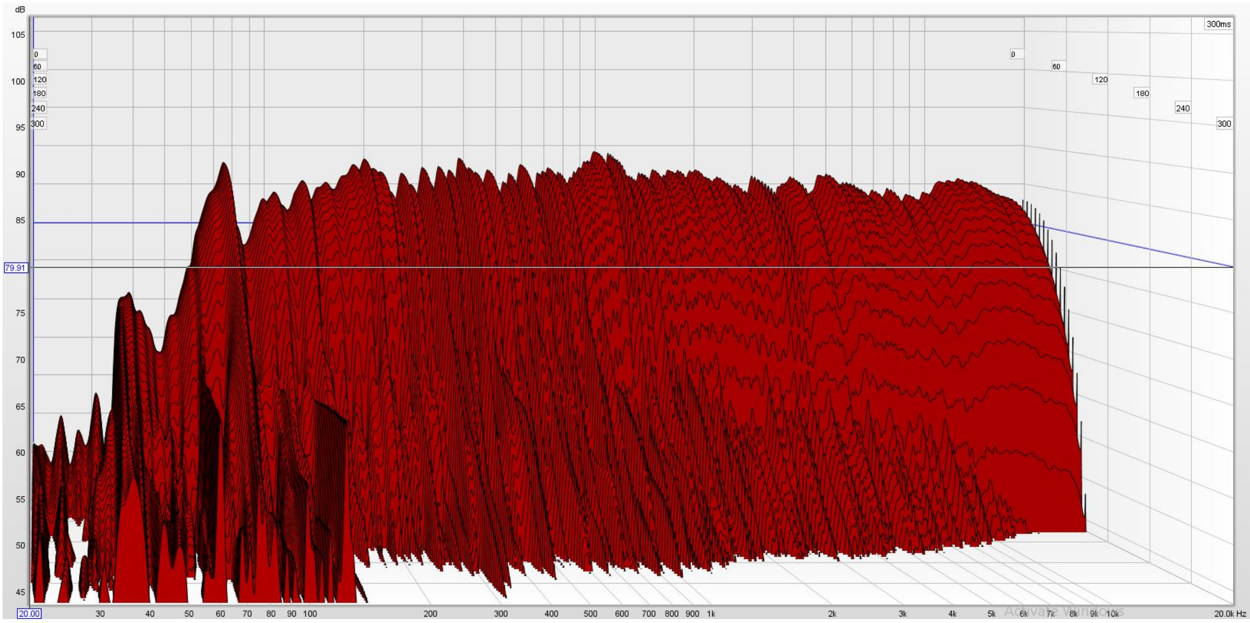


Figure 3.22 Living Room Treatment Test 3 Waterfall Graph

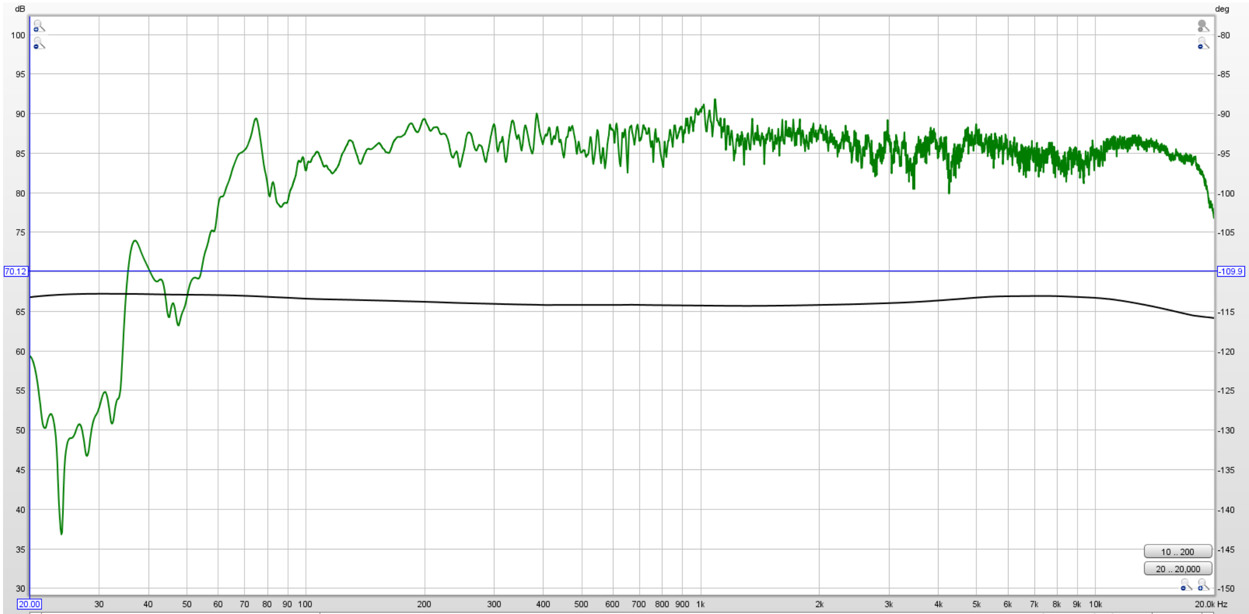


Figure 3.23 Living Room Treatment Test 4 Frequency Response

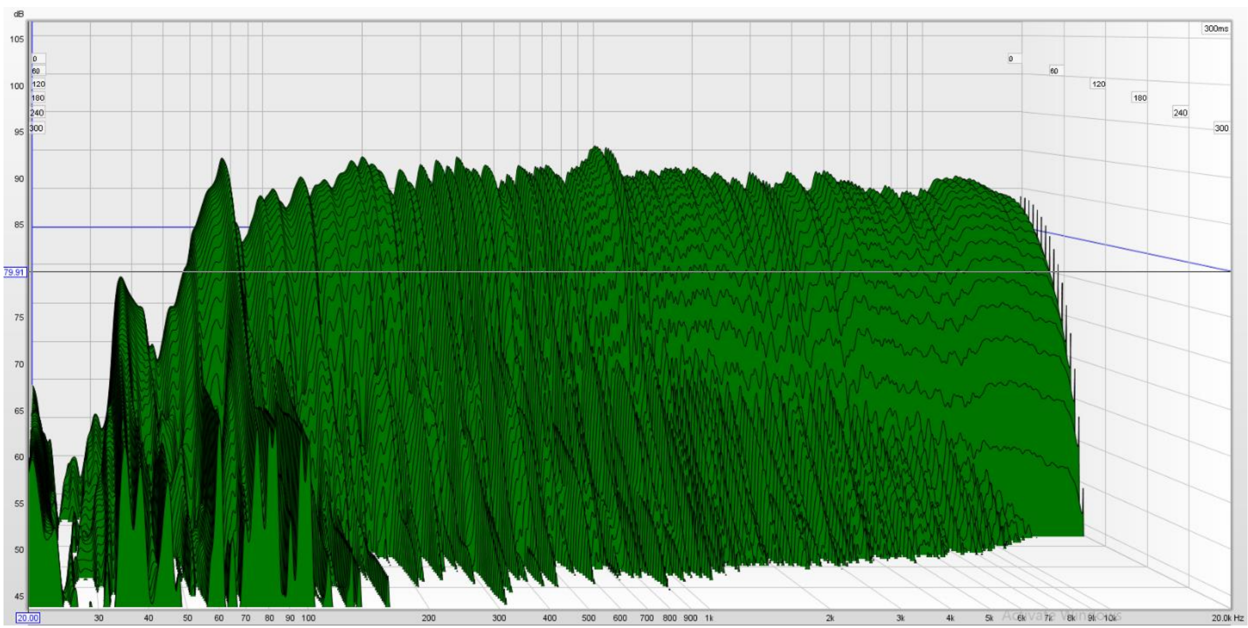


Figure 3.24 Living Room Treatment Test 4 Waterfall Graph

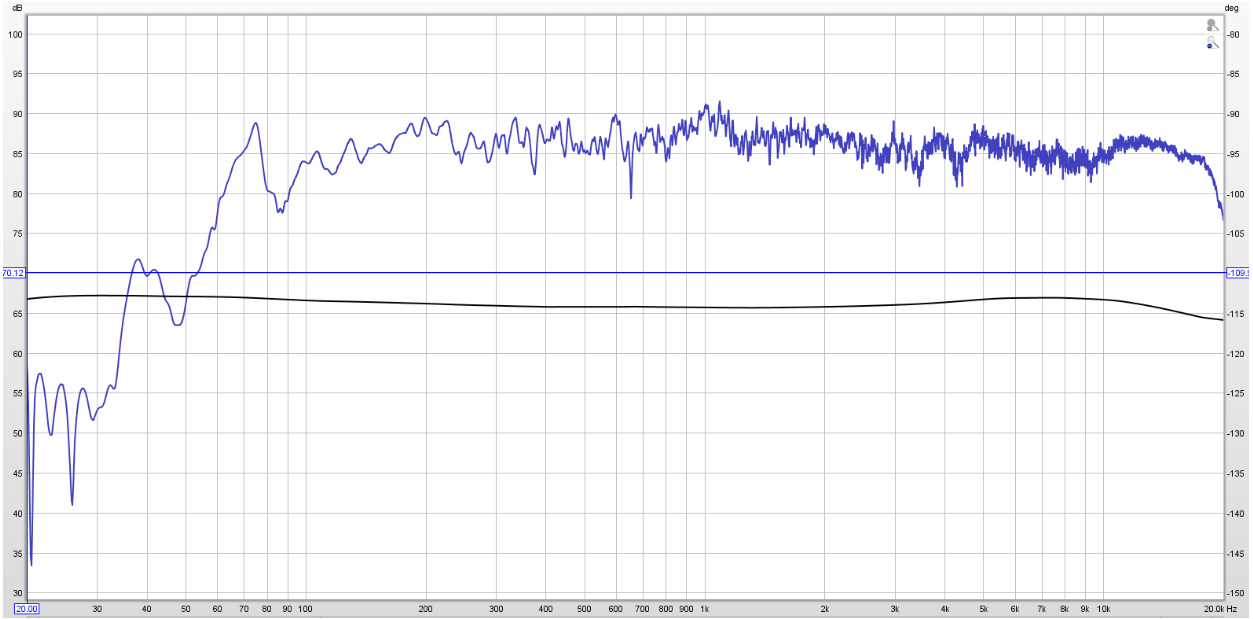


Figure 3.25 Living Room Treatment Test 5 Frequency Response

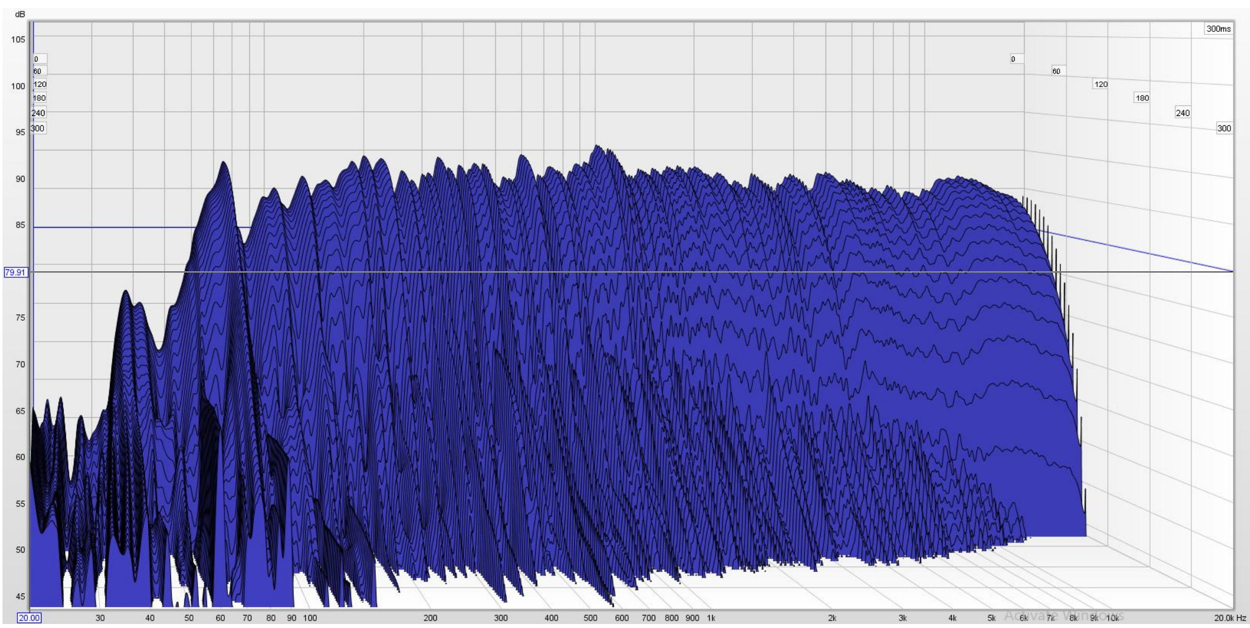


Figure 3.26 Living Room Treatment Test 5 Waterfall Graph

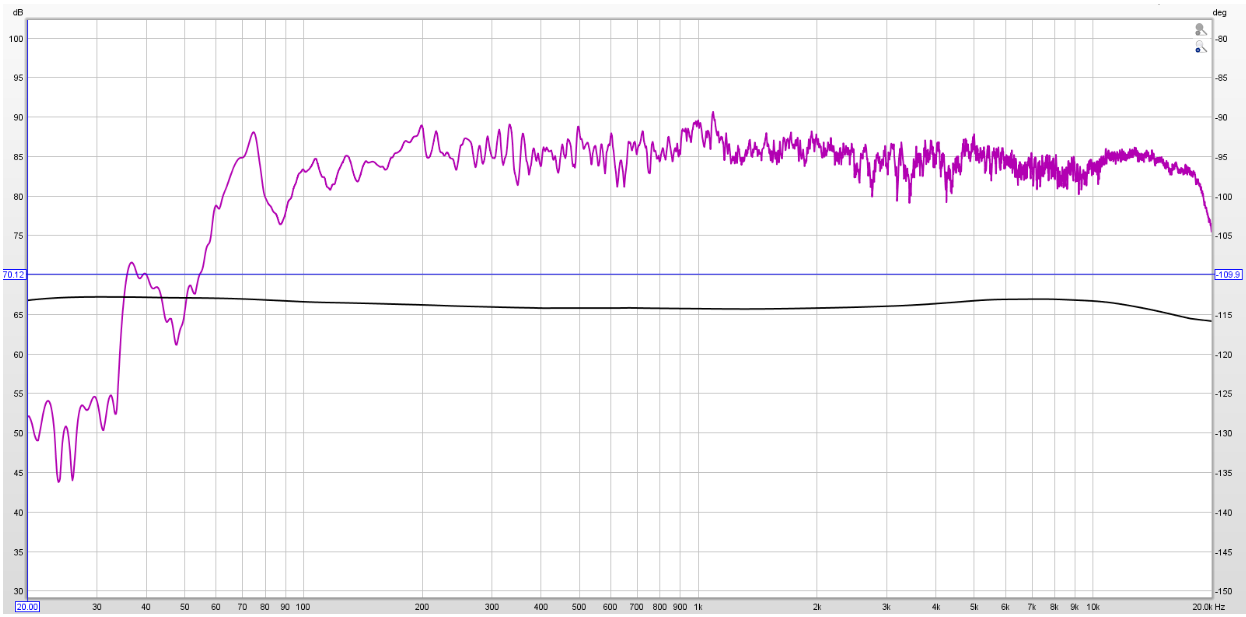


Figure 3.27 Living Room Treatment Test 6 Frequency Response

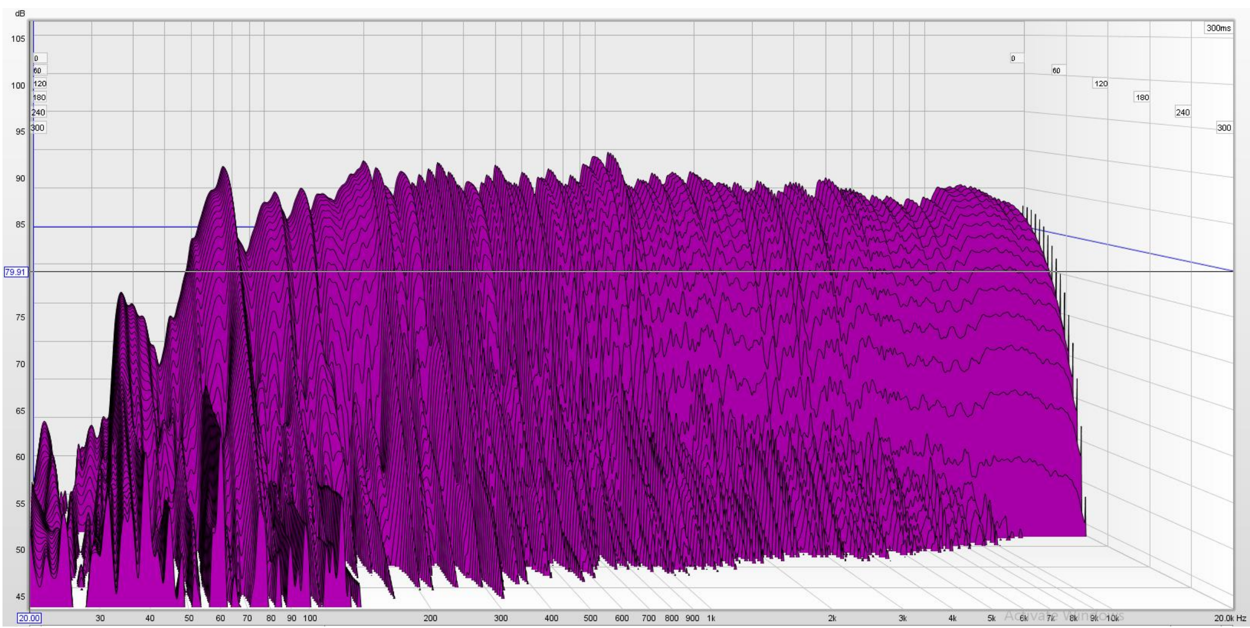


Figure 3.28 Living Room Treatment Test 6 Waterfall Graph

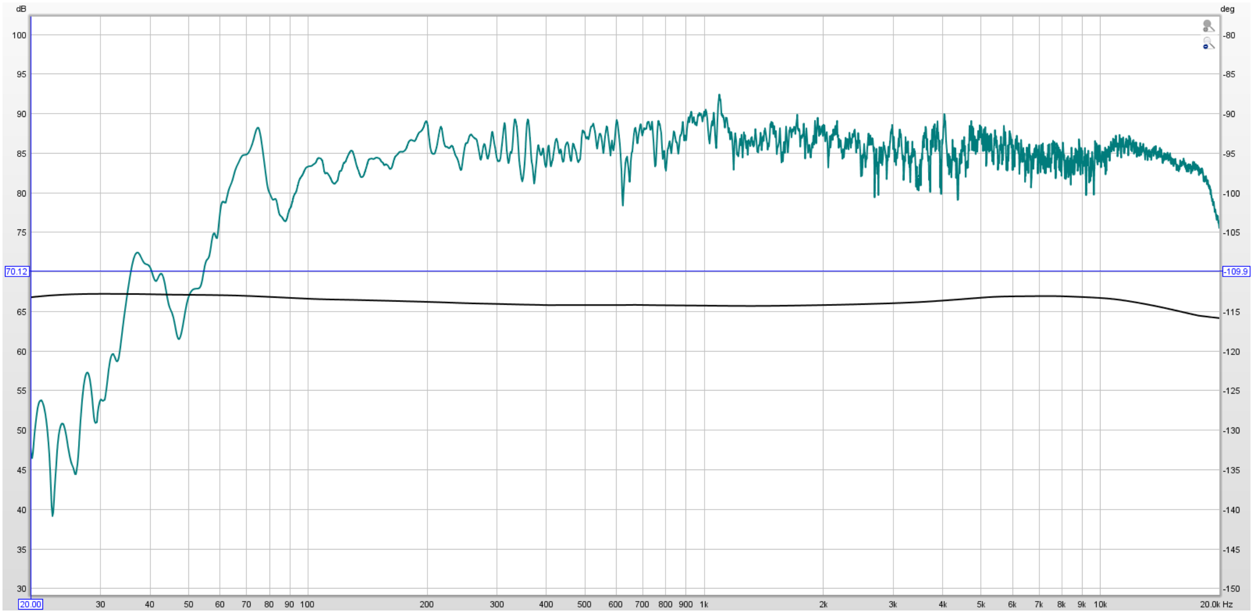


Figure 3.29 Living Room Treatment Test 7 Frequency Response

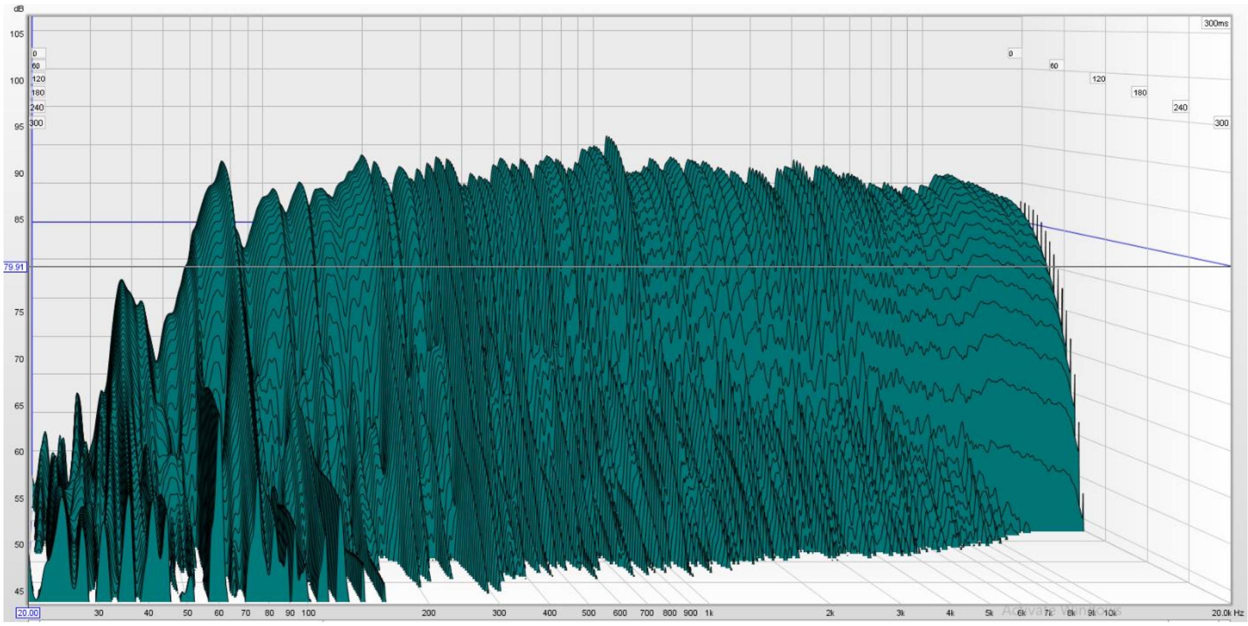
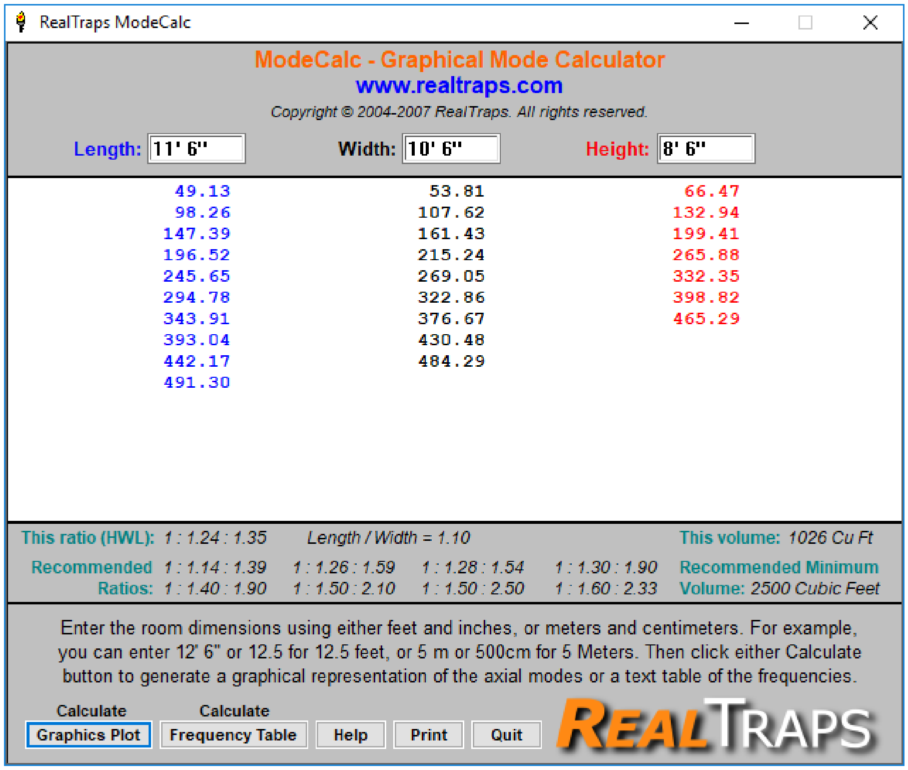
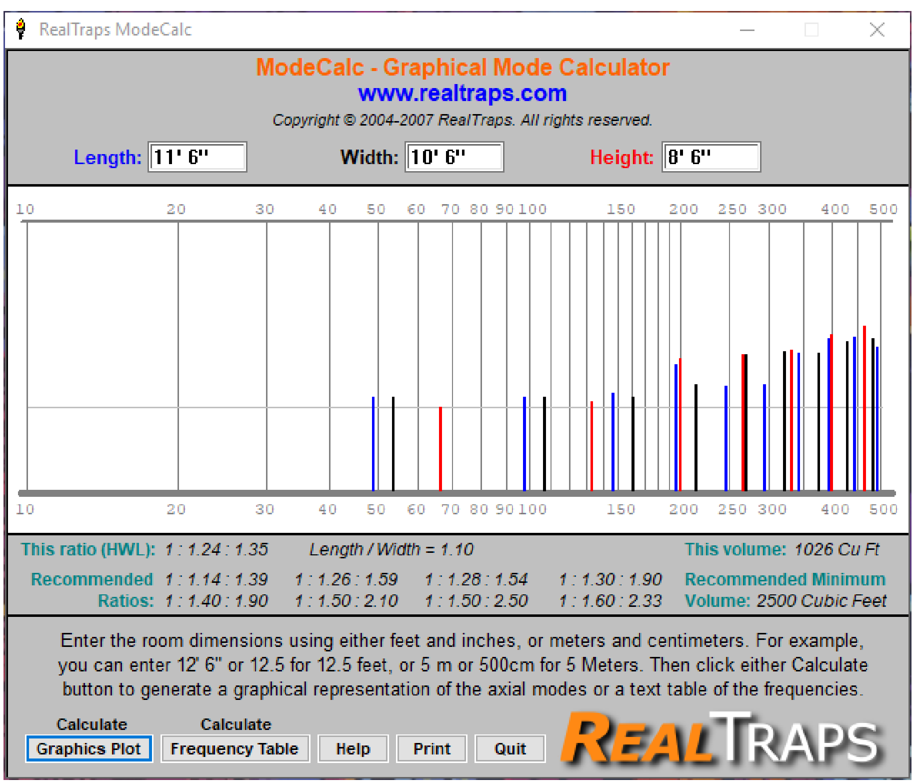


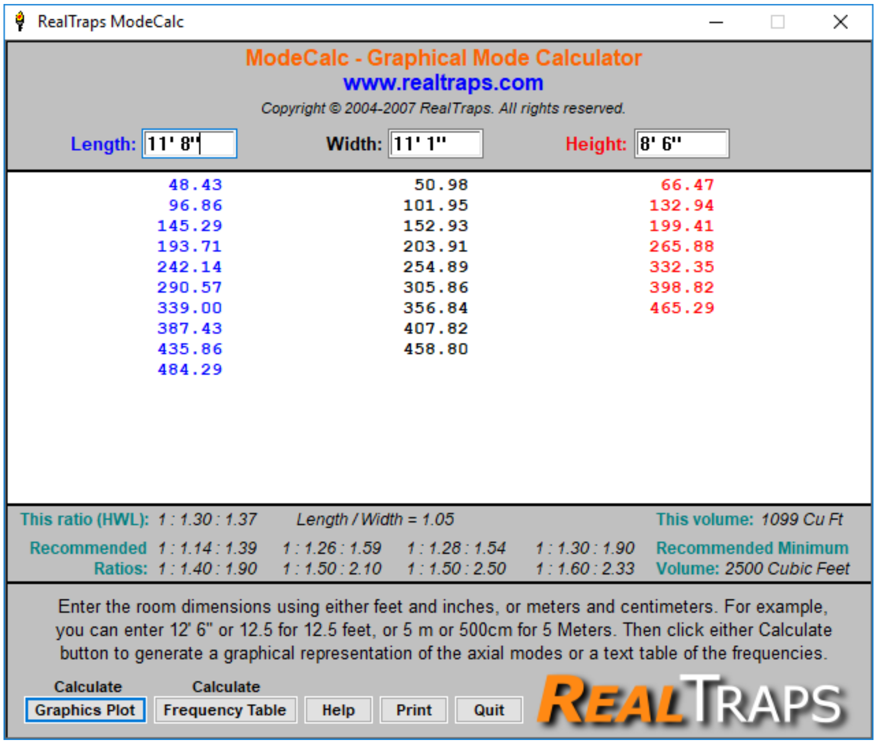
Figure 3.30 Living Room Treatment Test 7 Waterfall Graph

Appendix B: ModeCalc Tables and Graphics Plots

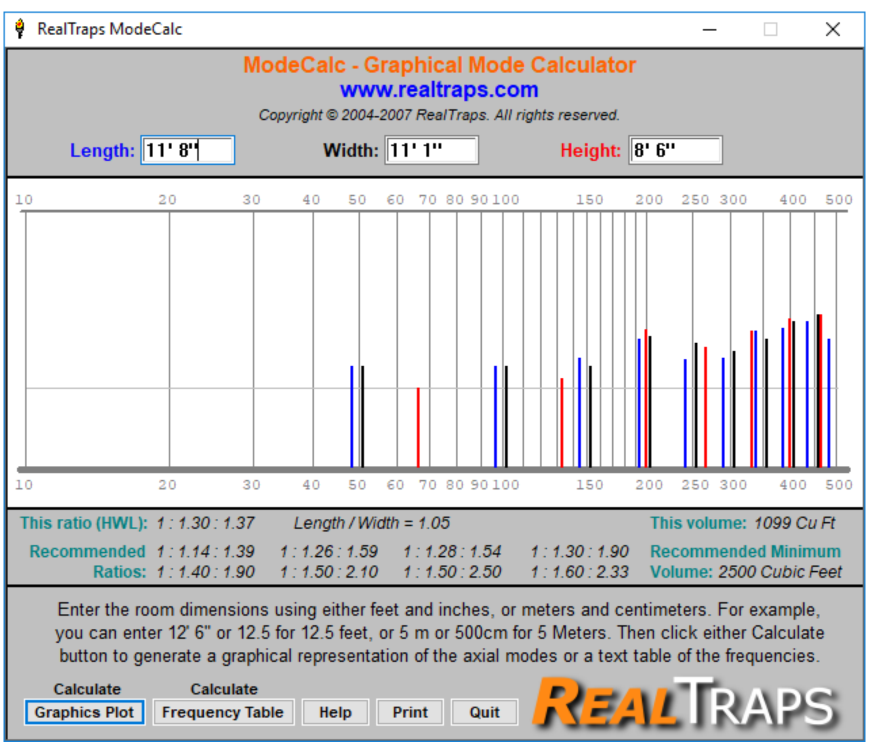


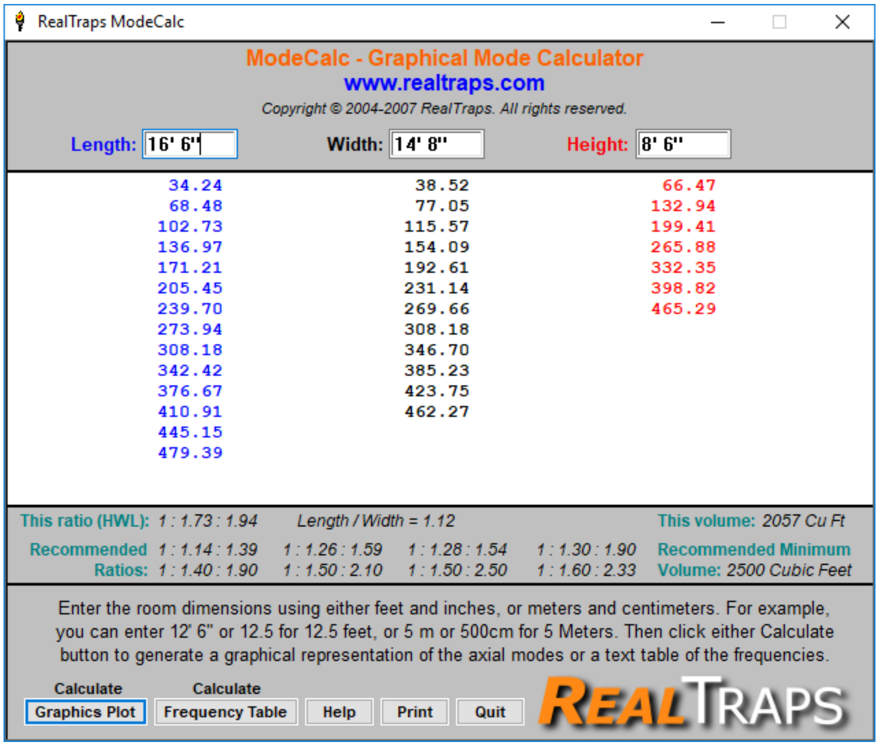
Bedroom Room Mode Table and Graphics Plot





Studio Room Mode Table and Graphics Plot





Living Room Mode Table and Graphics Plot