Acoustic Space Analysis

An Interactive Qualifying Project
Submitted to the faculty of Worcester Polytechnic Institute
in partial fulfillment of a Bachelor of Science Degree

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Abstract:

When a musician wants to either share a composition with others or sell it for monetary gain, they typically would go to a recording studio to have their music recorded and mastered for distribution. Within the past decade many artists have gained the ability to record and mix in their own home, and many are taking advantage of this strategy not only to save money but to have more control over the recording process as a whole. This is causing an overall downward trend in the number of what is traditionally referred to as recording artists, those who use professionally built studios usually supplied by a recording label, and instead causing a massive rise in independently recording artists. This project addresses architectural acoustic problems in these independent spaces.

Acknowledgments:

The Acoustic Space Analysis team would like to thank the following people and organizations for their time and valued input into our project. First, the WPI recording club, for the use of their equipment, space and expertise. Second, our case studies and interviewees, namely Joseph Chilorio and Mechanics Hall, Lou Clark, Dan Foley, Jeremie Inhaber, Ethan Winer and Jim Matus for their time and resources. We also would like to thank our advisor, Professor Scott Barton of the WPI music department, for his consistent dedication to the project.

Executive Summary:

Recording studios are places where a musician may record and perfect their work for distribution to others. The recording studio usually consists of the live room, where the music is played and recorded, and the control room where it is mixed and mastered. The acoustics of these spaces are crucial to these processes due to their inherent effect on the artist's music as it is played in the recording and listening space. Typically due to the acoustic qualities and professionalism of recording studios, musicians will pay recording engineers to record and mix their music. However, with advances in technology artists have gained the ability to record and mix in their own homes. Despite this ability, many of these attempts fall short of the professional quality of the traditional recording space because the musicians lack the appropriate acoustic attributes in the space that they record and listen in. Many believe that the process of obtaining the proper acoustic treatment would be too costly or laborious and turn to electronic methods of solving this problem, often degrading the quality of their work in the process.

This project set out to demonstrate cost effective methods of acoustic treatment for independent and at-home recording artists that they could easily incorporate in their space. It is essential that the report focus on spending as little money as possible in order to align itself with the position an at-home recording artist would find themselves in. This project utilized the Riley Hall Recording rooms located in the basement of Riley Hall on the campus of Worcester Polytechnic Institute to serve as model live and control rooms. All acoustic tests and treatment were used in our model rooms.

First the team sought to investigate the problems that many of these musicians may face in a typical home environment. These issues include, improper frequency response, echos and standing waves caused by early reflections, lack of background noise control, and nodes present in the space. These issues must not only be treated properly, but also identified properly for the musician to be effective at treating them. Therefore, the report first defines the process of identifying the problems and then the process of correcting for the identified issue.

Next the team sought to define a methodology that any person could use to test and verify the properties of their room. Due primarily to conflicting sources of information the team's methodology underwent a long evolution until the current methodology described below was achieved. The team stands by this methodology as a concrete way to test the acoustic properties of any room and has also shown ways that one could alter the methods if the need arrises.

From this the team was able to generate a set of data about the rooms that directly correlated to the quality of the acoustic spaces. This data was able to guide the team in the direction of the construction of acoustic treatments that should have influenced and improved the sound quality in the room. The team was then able to treat the room with said constructed treatments and observe their effects on the sound quality of the room as a whole. This provided useful insight into how the sound behaves in the room and how a musician may go about influencing the acoustic properties of the rooms they work in.

Although not all of our tests provided encouraging evidence that our treatment was effective in every scenario, these tests were useful in determining the cost effectiveness of said treatment as overly expensive treatment with little effect was identified for the musician. The iterative process of our testing further added to the reliable testing methodology. This methodology provided us with reliable results and could, in the future, provide a musician with similar results. Similar methods using commercially available computational technology could also be employed by the home musician for little or no cost. The team was able to test these methods and found that they yielded similar results to our professional quality measurements.

The team was able to conclude that many of the common methods that were discussed and implemented by the home recording community are not effective on a small scale. The team's results also suggest that room treatment is not as effective as simple room configuration adjustments, which can be costless. The team speculates that our limited positive results could have been due to the large size of our rooms with respect to the amount of treatment applied and believes that with more attention to the amount of treatment and the overall size of the treatment, the tests could have yielded different results. Regardless, the team's tests and research is of value to the home recording artists who wishes to better the quality of their recording.

Authorship:

Although all group members contributed to the drafting of all sections equally, the following is a breakdown of the members that took leading roles in creating the associated chapter.

Chapter 1 - Harrison Williams

Chapter 2 - All Members

Chapter 3 - Alexander Klose

Chapter 4 - Colin Cunningham

Chapter 5 - Alexander Klose, Harrison Williams

Table of Contents:

Listing of Figures:

Chapter 1 - Introduction:

When a musician wants to either share a composition with others or sell it for monetary gain, they typically would go to a recording studio to have their music recorded and mastered for distribution. Within the past decade many artists have gained the ability to record and mix in their own home, and many are taking advantage of this strategy not only to save money but to have more control over the recording process as a whole. This home recording space is typically made up of one or two rooms that the artist can dedicate to recording their music and typically have better acoustics than a normal room either because of the original design or modification of the existing structure.

The world of music recording has greatly benefitted from the recent improvements in inexpensive high quality technology. "Over the past decade, technological changes for recording music in a digital, instead of analog, format, along with digital distribution on the Internet, are changing the costs of producing and releasing records, thereby changing the dynamics of the relationship between artists and their labels." states Richard Busch. [1] This has provided the means of recording to many amatuer artists like never before. The artists themselves are going less often to professional recording studios and instead taking up the task of recording in their own homes. This is causing an overall downward trend in what is traditionally referred to as recording artists, those who use professionally built studios usually supplied by a recording label, and instead causing a massive rise in independent artists, who record using private resources, of over 71% in the past 9 years. [2] These independent artists, lacking professionally designed recording and mixing spaces, are increasingly aware that their recordings differ significantly in sound quality when compared to professional recordings. [3]

Many architects and building designers are taught the implications of their designs with respect to sound and auditory clarity especially in the noise insulation and projection field. Little effort, however, has been expended in the area of helping a homeowner or musician configure an existing room to be acoustically balanced and well sounding, especially not with the idea of using the room as a recording space. A rudimentary search for guides on acoustic treatment are few and far between, with most simply claiming that all you need is acoustic absorption foam. Further many guides suggest electronic solutions to recordings without even mentioning the physical characteristics of the space. Very little of this work focuses on the nature of recording in these rooms, and how to mitigate issues with inherent architectural or structural elements in the original design of the room.

Many variables come into play when analyzing the acoustic characteristics of a space, especially one that it not designed with acoustic considerations. Wall placement and size can be major factors in this kind of analysis, but also finer details such as the humidity and placement of ventilation systems can negatively affect a recording's quality. Also the concept of perceptual versus empirical measurements can lead certain artists awry with false impressions of the actual auditory problems in the room. With this in mind, the project will focus primarily on the architectural aspects and how an artist can change or modify a room set up in order to help with their musical sound and conditions. Special attention must be paid to ensure that solutions to auditory clarity problems reflect the fact that many rooms being used to record in are not designed to be such, and that inherent structural or architectural factors might also come into play.

The ability to identify how a room sounds is a crucial step, without which one would either improperly apply a correction, making the problem worse, or not apply any correction and leave an issue completely unaddressed. The project will focus on how to identify the actual problems with the sound of a room and how to treat the acoustic issues in the rooms that artists work.

The main problems that this project will focus on will be those issues experienced by the amateur musician as they work to create or improve the space in which they will be recording and mixing in. The specific issues presented by each and every different acoustic space will be unique, but the principles and science that underlie them can be identified and a generalized approach to solving these acoustic space issues can be created. The project will use a combination of software simulation and actual testing of lab based materials to determine the inherent acoustic properties of a space.

Chapter 2 - Background Research:

In order to provide musicians with accurate information about creating a recording space at home, a large amount of background research was needed. In the following sections common problems with current home recording studios as well as common solutions are discussed. Potential pitfalls that a home recording artist might run into are shown and some basic information about how to avoid them is also included. A large section is dedicated to the various interviews and case studies the team performed over the course of the project as well as the modifications and changes made to the project based on those aforementioned interviews and case studies.

A majority of the background research is a reflection of the complexity and existing contradictions of “appropriate and effective” acoustic treatment. The goal is to highlight the essentials for what makes a “good” recording space. It is of course in the opinion of the artist and engineers what qualifies the recording space as appropriate or not for the music they wish to produce. Therefore our research was conducted to find what the most common professional studios encompass and how to best emulate them in an affordable and efficient method for beginning musicians or engineers.

2.1 - Problems with Current Home Recording Studios:

Acoustic quality is a necessity in recording studio space as this can have a dramatic effect in the quality of the recorded work. This means that the musician or owner of the space is then responsible for acoustic treatment beyond that required by law, and thereby making the adjustments and modifications in order to create a quality recording environment. Unfortunately many independent artists are not aware of the influence of architecture on acoustic quality. One responder on a home acoustics site states: "*The only acoustic treatment, i will ever need, as long as I'm a home-recordler, and dont have somebody to build a studio professionally from scratch… is the IK MULTIMEDIA ARC,*" [4] in reference to one of the many equalization systems that attempt to account for acoustical problems. Many assume that electronics are among the most effective ways to improve their sound quality or don't know how to approach other alternatives. While electronics are vital to the any recording studio they are not the only means to improve the overall sound quality. In many cases, sound quality is limited by poor architectural acoustics.

When the musician is made aware of the effect of architecture on quality he or she will most probably seek help online in articles or forums, in magazines or by word of mouth. Contradicting sources are a common occurrence, one popular forum, gearslutz.com, is slandered by another popular acoustic guitar forum, saying that they deliver "95% bad information - magic boxes, poorly designed comparisons, anecdote offered as proof." [5] It is difficult to determine which source is more valid and to what degree. An indicator of the public's view of acoustics versus that of electronics is Sound On Sound's, "50 smart studio buys," a list of 50 things every studio supposedly needs, only one of which, a quilt, is related to acoustics. [6] This shows that most consumers are primarily interested in electronic equipment and instrumentation rather than acoustic treatment.

2.2 Common Problems with Architectural Acoustics

Many of the problems discussed in this project have to do with architectural acoustics or the influence a building's design or configuration has on a sound or music played within it. These problems can vary from building to building with varying intensity and can even interact with each other. In this section some of the most common architectural acoustic problems are discussed and their root causes identified. Being able to correctly identify an issue with a room's acoustics is crucial in determining a solution or solutions to correct for said issues.

Reverberation is the continuation of sound after it has been created. This can be quantified by measuring the time it takes a sound signal to attenuate by 60dB, this time is called the "reverberation time". [7] This continuation of sound is attributed to its reflections from objects in its environment. Attenuation time is affected by the distance sound travels and number of reflections. This is determined by the geometric properties of the room, which are quantized by the scattering coefficient of the materials used of the and the frequency dependent energy absorption characteristics of the solid bodies. [8] Thus, reverberation is the perceived effect of the combination of scattering and reflection. Reverberation is often highly sought after, by some it is even hailed as the, "most important effect,". [9] It can, however, be detrimental. Too much reverberation can lead to atonalities and misconstrued musical phrases due to the interactions of reverberating sound and that from the emitter.As an example, if two atonal notes are played in quick sequence, they may overlap if the reverberation is too long. It is desirable then to have controllable reverberation. The usual approach in a studio setting is to eliminate reverberation to about a quarter or half second, and then add it in when necessary, either by simulating it electronically or otherwise. [10]

Reflected sound can cause another issue that does not have anything to do with reverb. As the waves move from wall to wall they may encounter each other and via superposition, interfere. This interference can be either constructive or destructive, meaning that it waves can either build on top of each other or eliminate each other. If a wave is reflecting between two walls that are separated by a distance that is a multiple of half a wavelength, the wave may reflect back upon itself. Since the waves travel at the same speed they will form a wave that appears to be stationary. These "standing" waves can cause different parts of the room to have different gains and attenuations at different frequencies, depending on where the source is and the dimensions of the room. This issue is often problematic for the home based musician.

Room modes are those standing waves caused by reflections off the room walls. Since the walls are large and generally reflective, these standing waves are often prominent and are therefore of concern. The distance between the walls determines the wavelength and therefore frequency at which a standing wave will build. Whenever the distance between surfaces is a half wavelength or multiple thereof, a standing wave will be able to form. These distances are measured, their resonant frequency is calculated knowing the nearly constant speed of sound. These frequencies comprise the modes of the room. At each of these modal frequencies, antinodes are found at the walls and every half wavelength in between. Nodes exist a quarter wavelength from the walls and every half wavelength thereafter.

Due to the frequency dependence of these reflections and standing waves, each room configuration will have a unique frequency response characteristic. This means that different frequencies will be attenuated and amplified differently due to reflections. The frequency response of a room from is extremely important. A flat response across the audible spectrum is desired. This response can be accurately measured by creating varying frequency controlled noise at the location of the sound source then recording at the collector location. [11] The recorded sound will have inherited the frequency response of this room configuration. This recording is then viewed in the frequency domain with a computerized Fourier transform. Reverberation characteristics are also sometimes recorded. This is a simple test that many home recorders use to quantify the frequency response characteristics of their spaces to pinpoint their room's acoustic problems. Often, however, these tests are performed incorrectly or their results are incorrectly interpreted. Such is the case on one forum discussion on gearslutz.com. [12] A member of the forum submits a graph of the frequency response of his room, it does not appear linear. After another user recommends that he configures the test differently, he posts another graph which looks entirely different than the previous. This happens a second time and the results differ again. This serves to illustrate the confusion that some face as they attempt to diagnose and solve problems pertaining to their room's frequency response.

Another, although lesser, acoustic problem that arises is the presence of resonant objects in the studio. These objects may, by coincidence, have natural frequencies close to that of a musical note or one of the desired recording frequencies. The natural frequency of an object is the frequency at which its vibration is least impeded by waves inside of the object. In effect, it is when a standing waveform is created within the object. This leads to the object vibrating at some frequency at or near that of the note played. This is usually audible and detrimental to the quality of the recording because, along with the base frequency, the resonation of the object may produce other vibrations. This effect occurs commonly when people place picture frames and ornaments on a piano, which as the original resonator, pronounces the effect. These ornaments are usually metallic and rigid in nature, making them ideal candidates for higher frequency vibrations. The player will notice that on one particular note, a certain ornament will cause a ringing vibration. These elements are usually passive in that they do not add energy to the system, but they can still modify the sound by resonating at frequencies slightly different than those desired. Other, similar issues can occur from active objects such as feedback loops through recording equipment. Issues with normal resonators can sometimes be solved by simply removing them from the room or moving them while feedback loops may be more difficult to solve.

2.3 - Current Solutions for Architectural Acoustic Problems:

There are many options available to the household musician to improve the sound quality of their rooms. Many methods can be found with a simple search through the internet, but not all of these methods are effective or known to most musicians. In fact, some of these methods may be detrimental to the quality of the recordings. It will be the purpose of this report to identify the methods that are most effective and where a musician or home recorder can focus in order to have the most acoustic improvement in their recording space with cost and time constraints.

There are current architectural solutions being used today by some home recorders, but the solutions can be costly and many artists may not fully understand the techniques they are implementing or how to use materials they have. Many home recorders think they need to use the materials seen in commercial recording studios to absorb and manipulate sound, but this can be extremely costly. Take, for instance, a 2'*4' sheet of "Echo Absorber Acoustic Panel" from soundproofcow, an online acoustics store, costing $34.99. [13] If we assume an 8' ceiling height and a 10' by 10' room, a bare minimum for a studio, the area of the walls would be 360 ft^2. According to an article in Sound on Sound, about 40% of an average home recording studio should be covered. [14] At $4.37/ ft^2, the total cost would be $629.82. Keep in mind that this is a restrictively small space and that only the four walls are covered. Also bear in mind that as the length and width of the room both increase, the price will increase quadratically not linearly. Further, according to the spec sheet on this material it would only be effective in the mid to high frequency range. It becomes clear that this is not a cost effective strategy.

Noncommercial acoustic materials should be considered by at home recording artists before turning to higher priced "engineered" solutions. Raw materials that can be bought at a hardware store or other shops will inevitably be cheaper as they are not processed and marked up by the manufacturer. Returning to the previous example room we can further research the material that soundproofcow is selling. According to the data sheet it is made out of 2" thick, "cotton fibers." At The Home Depot this material is sold as insulation. [15] They sell a six pack of 16"*48"*2" rolls for $36.00, coming to $\$1.20/ft^2$, nearly a quarter of the price. These are both the same material, 1.2 pounds per cubic foot cotton fibers. While these materials may be a cheaper alternative to commercial materials, they may not be considered by the home musician. It is also important that these materials be used wisely, so that less bulk and expense is required. Some of these strategies may be well known to acoustic architects and engineers, but not to most musicians.

While materials can be used to help acoustically treat the room, another common method to flatten the frequency response of a room is to use electronic equalization. This method involves filtering and amplifying different frequencies to account for inconsistencies in the frequency response of a room. [16] The downside to this is that with this filtering the signal accumulates noise, phase shifts and distortion. Also, when a signal is amplified, noise is always amplified alongside it. Additional quantization noise can be added if the signal is digitized for the equalization process. [17] These effects are detrimental and may be critically so depending on the equipment used. It is commonly thought that all shortcomings of a room's acoustics can be removed with equalization. The previously discussed quote about the "*IK MULTIMEDIA ARC*," [4] exemplifies this philosophy of electronically based solutions where architecture and room configuration could provide a much higher quality option.

2.4 - Recommendations from Case Studies and Interviews:

We interviewed Dan Foley, an audio test engineer, and Lou Clark, a professional studio designer. Mr. Foley gave us valuable insight on the impracticality of testing for absorption coefficients, but also on how to use the real time analyzer referenced later in this section (see section 3.2). Mr. Clark on the other hand talked about his experience designing home recording studios. We asked if less expensive materials such and insulation or blanketing can be used as a substitute for expensive absorbing panels, he said they could, and that he has used less expensive materials in his studio designs. He also spoke on how many of his clients prefer rooms that have modifiable acoustics, and how this may be difficult for the designer. The idea is that panels can slide out and mobile walls can be moved around with different absorptive surfaces and diffusive properties in order to create desired effects. We discussed the possibility of replicating this for less money and we are considering using mobile walls in the room with various surface properties. When asked about absorption and diffusion he said that he uses both in his studios for different scenarios but largely diffusers. For cost reasons he usually uses parabolic diffusers instead of more expensive mathematical diffusers, seen in larger concert and lecture halls. While he usually uses diffusion for his higher end projects he stated that in a smaller room the reverberation time is of little concern. He was of the opinion that limiting early reflections via absorption would be the most effective use of time and resources in a smaller room.

After Mr. Foley and Mr. Clark we interviewed Ethan Winer, a Studio Designer with a large web presence. It was from this interview that we learned the necessary characteristics of a "good" home recording studio. Mr. Winer explained that in small room acoustics at home you want a flat frequency response across the spectrum (20Hz-20kHz) with a reverberation time of half a second or less. After this is achieved a recording from this environment can be modified through mixing and mastering to add desired effects such as more reverberation time or "reverb". He explained the reason that this is best is because changing the small room acoustics, especially on a small budget is almost impossible and may make the room sound worse rather than better. Also if the room has very strong characteristics such as extremely large low frequency response or a long reverberation time, it would be hard to record something that a musician wishes to have a short reverb and higher frequency response. This is opposed to a room that starts at a neutral level. A neutral room makes creating multiple types of music and recording different sets of instruments and ensemble sizes more attainable. Lastly he explained that the best way to alter early reflections was also through absorption by placing materials to absorb all frequencies to the half second. He said that diffusion would not be as effective as absorption in smaller rooms. This is because the rooms are small enough already, as Mr. Clark said, thus diffusion is obsolete and absorptive surfaces will lower the amplitudes of the waves and decrease reverberation time further as waves are absorbed by them.

Our first case study was in Mechanics Hall with technical director Joseph C. Chilorio. Particularly we studied their listening and control rooms, here we learned that 1/4 to 1/3 second reverberation time is optimal in a small listening room or control room, and to accomplish this you must both absorb and scatter the sound waves in the room with a combination of hard irregular surfaces and absorbing surfaces. Just as Mr. Winer said, Mr. Chilorio stated that the best way to balance the room and lower the reverberation time in a small room is through absorption. The listening room and control room's walls were covered with various materials including poly-cylindical absorbers and a slat absorber which acts as a helmholtz resonator in order to absorb a specific low frequency. Mr Chilorio confirmed our research on speaker placement in the control room with the recording engineer seated at the apex of an equilateral triangle formed by the left and right loudspeakers and the engineer seated between them, in the middle of the room (see section 2.8). He also recommended we use an assortment of speakers to emulate various peoples systems based on cost. Lastly he talked about the NC Level (background noise level) of the listening or control room must be lower than that of the live (studio) room so that you can hear the softest sounds coming from the live room over the monitor loudspeakers and not have these softest sounds masked by noise originating in the listening room. This case study clarified and reinforced what we had researched about control rooms and their relation to live rooms. Our interviews coupled with our research helped us understand as well as verify our previous research of the acoustic properties of a great home recording studio.

Our second case study was Jeremie Inhaber, a mobile recording engineer and student at the University of Massachusetts. In contrast to Mechanics hall he operates on a low budget and is therefore more relevant to this study. From his interview we gained valuable knowledge about what techniques a beginning recording engineer uses and his knowledge of acoustics. As a mobile recording engineer, it is the responsibility of Mr. Inhaber to set up a recording environment in about two hours before an event. To accomplish this he first makes sure the speakers are properly placed, then he uses absorptive packing blankets to limit early reflections off sidewalls. Often times he is forced to circumvent room acoustics entirely by either close micing or, if the source is electronic, taking the signal directly from the instrument instead of using a microphone. This is because he does not have the time or the resources to improve the room response. Low frequencies are particularly problematic for him. He does not have any form of bass trap as they are limited in mobility and instead is forced to equalize during mastering. Software is used to achieve desired reverberation effects. A common problem for him is that the customer desires a longer reverb time than that possible in the space given. To accomplish this he usually eliminates the room sound with "close micing" the use of a microphone extremely close to or possibly mounted on the instrument on or in a sound source (i.e soundboard) and uses a software plugin to add the desired reverberation.

For our final case study we interviewed Jim Matus at his recording studio that he built in his house in western Massachusetts. Matus achieves a relatively high signal to noise ratio from his studio due to it's location away from main roads and the noises of the city proper and his self installed acoustic treatment. Although he has never had the room RTA tested, he has had good reviews from his customers about the low noise and good sound of both the space and the recordings. The silence is immediately noticeable to even the casual observer. He attributes much of the studio's success to his careful selection of it's location. The studio is located at a residential house in a rural area. The house itself is several hundred feet from the road and it's nearest neighbor. The only major source of background noise is from farm equipment behind the building. Matus' treatment and layout of the studio are also key factors to its success. There is a traditional control and live room layout with the addition of a smaller recording room which he uses to record vocals or amps. This smaller room is the most isolated and well treated room. He uses this room to isolate the sound source and also to gain some reverberation by distancing the mic from the source. All of the rooms are treated with a hard pegboard like material bought from a local lumber yard, this is not intended as a major absorber, it is more to isolate the rooms from each other and from the outside to limit background noise. He uses movable sheets of the same material to eliminate crosstalk between microphones of nearby instruments. He also uses some carpeting as an absorber in the high frequency range. When more reverberation is required than the live room can offer, Matus uses a Alesis HD 24 channel ADC converter from the mid-1990s and adds digital reverberation after the fact. He says that there is little significant noise added from this process.

From our case studies and interviews we learned how high budget and low budget recording spaces are currently made. We also learned about the equipment used, both in recording and in simulating and designing recording spaces.

2.5 - Role of Absorption and the Absorption Coefficient:

As our research shows absorption will play the greatest role in the architectural quality of a room. Ethan Winer stated that a flat frequency response and a reverberation time of about ½ a second are usually desired in a recording space. This creates a room with a "neutral" response and makes recordings "clean" for electronic manipulation. According to our research and recommended by both Mr. Winer and Mr. Clark, a flat frequency response can be obtained by placing appropriate absorptive materials in the room. Also both stated the size of the room alone should create the desired reverberation time and diffusion material is not necessary unlike in larger spaces and the absorptive materials placed alone will be enough to regulate reverberation time.

Creating a good home recording studio is achievable by the average musician through reasonably priced and well implicated absorptive materials. Ecophon Saint-Gobain explains sound absorption as,

> "When a sound wave strikes one of the surfaces of a room, some of the sound energy is reflected back into the room and some penetrates the surface. Parts of the sound wave energy are absorbed by conversion to heat energy in the material, while the rest is transmitted through. The level of energy converted to heat energy depends on the sound absorbing properties of the material." [18]

Acoustic absorption of materials is characterized by its "sound absorption coefficient". "The sound absorption coefficient indicates how much of the sound is absorbed in the actual material." [19] This is determined experimentally in order to quantify the reduction in sound pressure level of a sound wave after it impacts the material at 125Hz, 250Hz, 500Hz, 1000Hz, 2000Hz, and 4000Hz for construction materials. [20] For materials specifically designed for acoustic absorption the range of frequency absorption is specified.

2.5.1 - Determining the Absorption Coefficient:

There are three primary ways that the acoustic absorption coefficient of a material is determined, a reverberation chamber, an enclosed testing space, or with the Brüel & Kjær Standing Wave Apparatus Type 4002.

A reverberation chamber is, "... a special room··· that is very reverberant at all frequencies." [21] The idea here is that you take a room with very flat walls and non-absorbent materials for the walls, floors, and ceiling. The test is first done empty, and then with the materials in the room. The results of both tests are compared. In essence:

> "The reverberation time is measured in the empty room when the sound is switched off. The reverberation time is the time taken for the sound level in the room to decay by 60 dB after the sound source has stopped. The test specimen or test items are then placed in the room and the reverberation time is measured again. Because of the sound absorption, the reverberation time is now shorter. From these two reverberation times, the equivalent sound absorption area of the test specimen, A_T, is calculated by using Sabine's equation." [22]

An advantage of this method is that it is tested in a room rather than a small chamber, testing materials in an open space simulates the size of a real room environment, but there is a downside to this method as well:

> "The coefficients measured by this test method should be used with caution because not only are the areas encountered in practical usage usually larger than the test specimen, but also the sound field is rarely diffuse. In the laboratory, measurements must be made under reproducible conditions, but in practical usage the conditions that determine the effective absorption are often unpredictable. Regardless of the differences and the necessity for judgment, coefficients measured by this test method have been used successfully by architects and consultants in the acoustical design of architectural spaces." [23]

SoundProofCow.com uses a different method for testing. They use a speaker and a microphone in a fully enclosed room with almost no reverberation time. and emit a frequency signal sweep similar to that used in the previous method. They first test the space with no material, and then place a material standing up off the floor between the speaker and microphone and compare the results. [24] This method directly through the material so the absorption coefficient is less dependent upon the shape or size of the room. This is good for consistent and direct results that can be applied to a room later. The only con of this test is that there is no record of absorption of the material outside the chamber in a simulated room environment.

The last method is a measurement of absorption and impedance using the Brüel & Kjær Standing Wave Apparatus Type 4002. The idea is that a loudspeaker produces a sound wave which travels down a pipe with material on the other end and phase difference between initial and reflected waves will create a standing wave and the amplitudes of the different waves are recorded by pressure in the tube. The amplitude difference is a result of the material absorption. [25] Again the only con of this being it is not clear how the absorption would differ outside the small chamber.

After considering these testing methodologies and their requirements in terms of equipment and time, we decided not to test for absorption coefficients of different materials. It was also determined that absorption testing was not an effective use of our time because of its difficulty, inaccuracy and limited necessity. Our interview with Mr. Foley confirmed this decision. It was his opinion that testing specific materials was redundant because these values have already been determined and are easily available in tables created from rigorous professional testing using these methods. Also, according to Mr. Clark the sound characteristics of smaller rooms are predominantly influenced by early reflections rather than total reverberation time and we should be more concerned with eliminating early reflections with known absorptive materials than we should be with determining absorption coefficients of new materials. Further demonstrating that it would be more valuable to the project to start testing room acoustics rather than verifying previously known absorption coefficients which we will instead look up in published tables.

2.6 - Background Noise:

Lastly, aside from the architectural properties within the room, lack of noise insulation or control of background noise elements can also attribute to a poor recording/listening environment. Background noise is caused by HVAC units, heaters, electric lighting, transformers and the outside environment. Average ambient noise for a suburban house is about 50 dB. [26] This noise can be mixed into the recorded sound and heard by the listener. It is even believed that this level of noise can increase stress and the risk of mental illness over the long term. [27] Background or "ambient" noise is simply sound being produced by a different source than that being recorded.

Background noise is also often present in populated areas where buildings have less space between them. If it is possible to select the location of the studio, it is extremely advantageous to select a quiet location in a non residential area. This will limit the amount and cost of soundproofing necessary so that more effort can be given to acoustically treating the room. Soundproofing is the act of acoustically isolating the control and live rooms from the outside environment and from each other. [28] During our interview with Jim Matus, we discussed background noise and soundproofing. Matus chose the location of his studio specifically for its lack of background noise. He then insulated the walls in his recording rooms and control room with solid boarding and sealed the windows and doors. It was only after this soundproofing that he began treatment using carpeting and other absorption techniques.

In our study of Mechanics hall we discussed in greater detail the measures that were taken to avoid background noise. Even in 1857 when the hall was built, background noise was of the utmost concern. The building was heated and cooled using a steam pump located outside of the building which pumped air through a long wide duct that ran behind the audience. Hot air rises and is allowed to escape through openings in the ceiling. The system has been upgraded since then but some of these vents are still in use. The hall was also built with a thick double brick wall which isolates it from the surrounding city. When electric lighting was installed, it introduced an entirely new source of noise. In order to eliminate this noise, fist sized inductors were installed on each set of bulbs to smooth the current. The result of all of this engineering and reengineering of the space is a room in which the only noticeable background noise is the murmur of wind as it blows over the roof, vibrating it's surface.

Many people have tried really hard to create noiseless rooms and the process is generally very expensive. There are methods, however, by which a home recording artist may greatly decrease background noise. The first and easiest is the location of the studio. In some situations it is possible to select the location of the building, even if this is not possible it is usually possible to select in which rooms the control and live room are built. When making this selection, background noise should be a primary deciding factor. Ideally, rooms should be far from major piping and ductwork. As HVAC systems are included in most public buildings and in a few residential buildings it becomes necessary to accommodate for them. In a professionally designed studio the HVAC systems are specifically designed to eliminate noise. They are lined on the interior with sound absorbing materials and are increased in cross sectional area to reduce the air velocity. Lou Clark recommends keeping the air speed in ductwork to below 300 feet per minute in and near the studio. If it is possible to redesign the ductwork to meet these criteria then it is advantageous to do so. Most home recording artists, however, are not afforded this luxury. A possible alternative would be to simply turn off the environmental systems for the recording time, although this could become impractical for long recording sessions.

Another important element of noise control is soundproofing. In order to isolate the room from its surroundings it is necessary to seal it with thick high density materials. [28] The objective of soundproofing is to either absorb or reflect sound in order to prevent its transmission through the material. This sound reduction is quantified by the sound reduction index R, which is simply an approximation of the attenuation that a sound wave undergoes when it passes through a solid boundary. The value of R is generally logarithmically dependent upon both the frequency of the sound and the mass per surface area of the wall. In order to prevent sound from passing through flat surfaces it is beneficial to increase the mass per unit area of the wall. The material for this does not matter, so it is advantageous to obtain the cheapest and densest material possible. It is important to mention that most of these materials are reflective as opposed to absorptive, creating the necessity for further internal treatment of the room. Sealing open spaces in the room is also vitally important. Open spaces like cracks in windows and doors allow sound to enter and exit the room unimpeded. Windows and doors are often problematic, they both can be sealed using methods similar to those used to insulate for heating purposes. Single glazed windows should be replaced with double glazed as they are often a cause for concern acoustically. Alternatively they could be boarded or otherwise sealed.

Another often problematic background noise consideration is noise from electrical devices. Electrical noise can come from several sources including computer fans, hard drives, lights and transformers. Modern computers are extremely efficient and usually solid state thus eliminating the hard drive problem. Some are even designed without a fan, eliminating this noise as well. In any case the noise from computers can be controlled by the addition of quieter fans or by limiting their use, at least in the live room. [29] Transformers and lights, however, can create significant amounts of background noise. Transformers vibrate from magnetic forces inherent to the device, silencing these transformers requires acoustically insulating the interior of the device, a task which may prove difficult in smaller modern electronics. Lighting is also a source of noise, both the lights themselves and rheostats can cause unwanted noise. Many home recording studios do not use regular lighting methods, some use low wattage bulbs such as christmas lighting. Another method would be to use LED lighting with an AC to DC transformer in another room to eliminate the noise from the power converters. Other electronic "noise" may not start as noise at all, but may instead be due to magnetic coupling of the signal wires with power lines or other lines. Although this is not in the scope of acoustics, it is important to mention as it is a common cause of noise in recordings for home musicians. To eliminate this coupling, the signal wires should be separated from the power lines and shielded.

2.7 - Properties of the Live Room:

The problematic acoustic properties mentioned discussed in our background research need to be tuned in the live room so that the sound from the musicians is accurately received by the microphones and can be processed electronically in the control room. From our case studies and background research of problems and current solutions with recording environments we have outlined what the essential acoustic properties of a professional live room are (aside from background noise control)； a flat frequency response and a short reverberation time with control of early reflections, both achieved by appropriately placing absorptive materials (see section 2.5).

First, in order to determine what materials must be placed and where, a room must be analyzed in one or many of the methods outlined in section 2.9-10, then the required absorption to "treat" the room can be determined in order to create a level frequency response. It is after this that material is placed in the room. Typically material is placed on the modal axes of the room, but it is also placed where engineers determine are necessary to eliminate standing waves based on various size properties of the room (see section 2.2). It is from this base level room with equal sound pressure level response that engineers and musicians can start to alter other properties of the room like early reflections and reverberation time to create desired sound.

2.7.1 - Properties of Our Model Live Room

We used the recording live room in the basement of Riley Hall at Worcester Polytechnic Institute as a mock at-home recording space. The room is appropriate for the study due to the its size and material characteristics (See Appendix 2 for pictures of the room). Due to the early reflections and the in-balance in absorption, the recording qualities of the room are very poor. These qualities are also expected to be similar to those of a common household, thus the room is a relevant example of a possible untreated recording space from an at-home recording musician's perspective.

Currently from our live room experience little absorption based on the amount of concrete in the rooms. Concrete has very low sound absorption coefficients across a range of frequencies. The gypsum board also will be fairly absorptive in mid to high range frequency ranges, but nothing like that of thick fabric. The wood on the bottom half of the room does help attenuate the midrange to high frequency sound absorption low to the ground. Lastly there is very little glass in the rooms especially in the live room, although the glass that is present will absorb low frequencies, as shown in figure 2.7.1 below, due to the amount in the room however, this is almost negligible. In general the biggest problem we faced in the room was the absorption at high frequencies and lack of absorption at low frequencies.

	A	B	C	D	E	F	G
1	**Frequency**	**125**	**250**	**500**	**1000**	**2000**	**4000**
2							
3	**Marble or glazed tile**	0.01	0.01	0.01	0.01	0.02	0.02
4	Reflections dB down	**0.04**	**0.04**	**0.04**	**0.04**	**0.09**	**0.09**
5							
6	**Concrete sealed or painted**	0.01	0.01	0.02	0.02	0.02	0.02
7	Reflections dB down	**0.04**	**0.04**	**0.09**	**0.09**	**0.09**	**0.09**
8							
9	**Vinyl tile or linoleum on concrete**	0.02	0.03	0.03	0.03	0.03	0.02
10	Reflections dB down	**0.09**	**0.13**	**0.13**	**0.13**	**0.13**	**0.09**
11							
12	**Wood parquet on concrete**	0.04	0.04	0.07	0.06	0.06	0.07
13	Reflections dB down	**0.18**	**0.18**	**0.32**	**0.27**	**0.27**	**0.32**
14							
15	**Wood floor on joists**	0.15	0.11	0.10	0.07	0.06	0.07
16	Reflections dB down	**0.71**	**0.51**	**0.46**	**0.32**	**0.27**	**0.32**
17							
18	**Glass small pane**	0.18	0.06	0.04	0.03	0.02	0.02
19	Reflections dB down	**0.86**	**0.27**	**0.18**	**0.13**	**0.09**	**0.09**
20							
21	**Gypsum board on masonry**	0.01	0.02	0.02	0.03	0.04	0.05
22	Reflections dB down	**0.04**	**0.09**	**0.09**	**0.13**	**0.18**	**0.22**

Figure 2.7.1 taken from Ethan Winer's website shows the higher levels of absorption of low frequencies below 500 Hz. [30]

The overall lack of absorption will cause tones in the room to be unclear in the recordings as the sound source produces a set of waves and some are absorbed more than others (see section 2.5). Another feature of the room it its lack of diffusing or scattering materials. The walls are not only hard and dense, but also flat causing strong early reflections. The rooms are small however, so reverberation time should not be problematic. We predicted the flatness would create standing waves and echoes. In our study we attempt to create a neutral spl absorption level in our recording space.

With neutral response from the room, placement of the microphone, primarily the distance from the musician but also the height in the room, can then be adjusted to alter the reverberation time, and early reflections that have not been reduced due to absorption, all the while keeping the frequency response the same. The greater the distance between the player and the microphone the greater the reverb, the closer the less. Many engineers like Mr. Inhaber use close mic'ing as this lessens the effect of room acoustics on the recording. This type of recording is especially useful in extremely large or small rooms when the musician does not want much of the room characteristics in the sound, or in any situation when the musician does not like that properties of the room. These are examples of how we will manipulate physical aspects of our room, which will be seen in the results section. It is after the recording is made in the live room that it is then electronically edited or "mixed" in the control room to create the desired sound for the musician.

2.8 - Properties of the Control Room:

To obtain a flat response in the control room, the room shape and configuration must be carefully considered, as in the live room.

It is desired to have non repeating dimensions in the room; the room height, width, and length are not the same. This is because a room with repeated dimensions, like 10'*10' will allow waves of certain wavelengths to create standing waves of the same frequency in multiple dimensions. In a square room, waves of a certain frequency build across both the length and width of the room and will then add to each other, creating undesirable peaks and troughs and natural resonances in the room. This leads to the room having an uneven frequency response and unacceptable reverberation characteristics, including flutter echo. [31] A range of ideal room dimensions has been created mathematically. [32] There are three "Golden Ratios", shown in figure 2.8.1, which are related to but not equal to the Golden Ratio in mathematics and provide near optimal sound quality in a rectangular room. Another method of avoiding standing waves is to use non-rectangular dimensions in the room. This prevents waves from building between parallel surfaces. To create a reflection free zone, as mentioned previously, the side walls are angled such that the room is wider behind the listener. This is so that the early reflections, the first and strongest reflections, are reflected behind the listener. Having the sound reflected into the back of the room has the added benefit of concentrating it on one wall. Sound absorbing materials are often placed on the back wall in order to more effectively absorb these

Height	Width	Length
1.00	1.14	1.39
1.00	1.28	1.54
1.00	1.60	2.33

Figure 2.8.1: Golden room dimensions for rectangular rooms

reflections. This is cost effective because less absorbent material will be required than would be if all sides of a rectangular room were treated. Placing the listener in a room corner may reduce standing waves, but will also affect the sound's symmetry. One speaker may sound louder or be more or less reverberant than another. For this reason the control room is usually symmetric.

In a high budget scenario the room may be altered or built specially to the aforementioned dimensions or in a non-rectangular shape. However, it may be possible to alter the dimensions of a room on a low budget as well. To begin with, if multiple rooms are available it would be prudent to choose one with dimensions similar to the golden ratios mentioned before. Priority should be given to the live room when this selection is made. Angled walls or more desirable dimensions may be acquired simply by cutting part of the room off with wood or another cost effective material.

Having selected and possibly modified a room, it then becomes necessary to discuss room layout. Speaker and listener placement are vital to the quality of the control room or any acoustic space. As stated above, the speakers are usually placed symmetrically along a wall of the room in order to preserve the stereo field. It is desirable to place them by the short wall, limiting early reflection time. [33] It is also important that they be properly spaced away from the front wall (behind the speakers) and the side walls. They must be spaced from the wall so that the walls do not interfere with the near field of the speaker. The distances between the two walls and

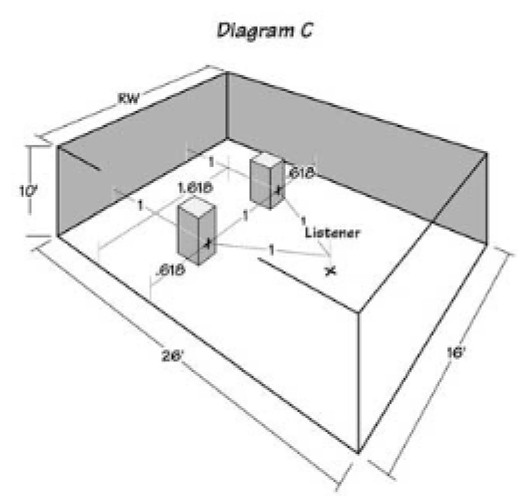

Figure 2.8.2 Ideal rectangular control room layout.

one of the speakers also should not be equal for similar reasons that the dimensions of the room should not be equal. A preferred method for determining the speaker positions in a rectangular room is the Cardas method. [34] This method employs the mathematical golden ratio in order to spread the room modes out more evenly, limiting standing wave effects. The Cardas method is simple to use, the length of the wall behind the speakers is measured. This is multiplied by .276 to find the distance from each side wall to the speakers. The same distance is then multiplied by .447 to obtain their distance from the backwall. The listener is placed equidistant from each speaker, so that an equilateral triangle is formed between the two speakers and the listener. This design is intended to limit detrimental standing wave effects, though it is not and cannot be perfect in it's own right. Further treatment and adjustment is necessary. Next the height and directionality of the speakers must be determined. Their height should be at ear level to the listener to provide the most direct sound without reflections from the ceiling or floor. The vertical angle should most times be level, for similar reasons. Horizontally, the speakers should be 'toed in' or angled towards the listener. In theory, in a room without reflections, they should be pointed straight towards the listener for the most direct sound. In practice, however, this is seldom the case. They should be toed in towards the listener, but the extent of which they are is variable. Usually, due to the uneven or unknown frequency response of the room, the amount of toe in is determined experimentally. The angle is varied until the listener notices the position of maximum clarity, or a frequency response measurement can also be used.

When we interviewed Mr. Chilorio, in order to learn more about the details of control room design, he showed us the specially designed listening and control space in Mechanics Hall. [35] The Mechanics hall control room was a high budget construction but some of the strategies it employed could be used in a low budget scenario. A Helmholtz resonator was employed to attenuate a particular problematic bass frequency. This is essentially an enclosed volume of air connected to the rest of the room via small holes or slatts. It resonates like a bottle when blown into. This is useful for eliminating specific frequencies because of it's high quality factor and because it is easily tunable. Chilorio also confirmed that the listener and the speakers should form an equilateral triangle in order to preserve the stereo field, as mentioned previously. He also agreed that in a low cost scenario, absorption should be employed more than diffusion.

In addition the Mechanics hall visit confirmed the validity of some of these methods. The speaker placement, for instance, improved their frequency response curve greatly. The frequency response curve was tested with the speakers against the wall and again when they were in the proper position mentioned before. It was found that the variance was about +/-7 dB across all frequencies with the speakers against the wall and only about +/-4 dB with the speakers positioned properly.

Lou Clark also discussed control room design. [36] He agreed that speaker placement is a major aspect of the sound of a control room or any room. His preference is to have the lower frequency speakers as far away from the walls as possible. He also stated that the vertical position of the speakers is very important. The medium and high range speakers should be at ear level, about four feet, while the low frequency bass can be placed lower as it is less directional.

2.8.1 - Dedicated Control Rooms:

Some may question the necessity for a dedicated control room given the rising technology in high-end headsets. There are many benefits to mixing and recording with headsets, not the least of which being that an entire room need not be treated. Other benefits include isolation from the live room and a listening experience similar to the listeners' as the current trend is towards portable audio. Some arguments against mixing with headsets are that the stereo field is not as well preserved and that no headset has a linear enough frequency response for mixing. The non-linearity of headphones vs studio monitors is shown in the following image where the frequency response of headsets ranging from $7 to $1950 are compared to the Yamaha MSP5 studio monitor. [37, 38]

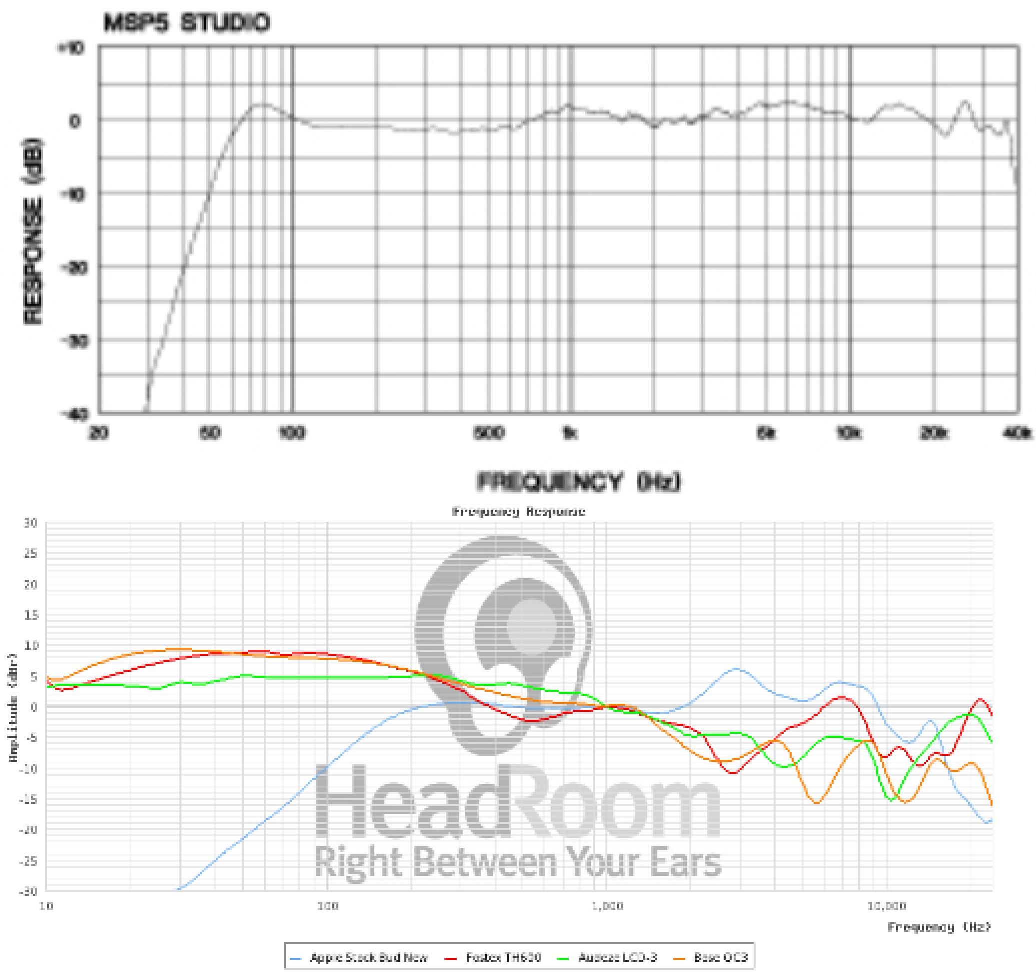

Figure 2.8.3 Frequency response of MSP5 studio monitor(top) and of various headphones (bottom).

It can be seen in figure 2.8.3 that the high end headsets perform well until about 2 kHz when they begin to break up, whereas the MSP5 has nearly no major variation until over 20 kHz. According to Lou Clark, a professional level control room usually has a frequency response with a variance of about +-6 dB. A control room of this quality with quality speakers can definitely outperform these headsets, but can a home recording studio match these response characteristics? Even if it could, is it more effective to spend money and time treating another room or to buy the headsets and accept a slightly uneven response? Even in high budget professional recording studios, headphones are often used due to the vast number of listeners using headphones. The decision is mainly that of the artist or engineer. Both budget and the environment can play significant roles in this decision.

2.8.2 - Properties of Our Model Control Room

Our control room is smaller than our live room discussed in section 2.7.1, but both are nearly rectangular. The walls and floors are gypsum board, wood, and concrete, with a thin, dense carpet on the floor. We expected some similarities to that of the live room in terms of acoustics but not completely. One exception to the similar materials this is the polyurethane drop ceiling fibers that will absorb mid-high frequency in the room. Also the size of the room will be the greatest contributor to bass frequency, the small size will result in a much greater bass response than the live room. With these two factor in mind we expect the absorption in the control room and the evenness of the frequency response to be quite adequate for a control room. Much of the alterations here will come from altering the orientation of the equipment used in the room.

2.9 - Existing Acoustic Testing Methods:

Currently there are several well known ways people test for the acoustic properties of rooms. These tests are done not only by professional companies for room modification, but also by many musicians who just want to understand the space they are in for recording or mixing purposes. Tests include simple hand claps, analysis of room modes as well as sophisticated auralization and real time analysis of waves.

Galen Carol is an acoustic consultant and salesman who recommends a simple quick test, "The *hand clap test* [which] is so named for obvious reasons. Simply sit in your normal listening position and clap your hands once, listening carefully to how the sound is affected." If the sound is prolonged and echoing then you have flutter echoes, " ...created when sound bounces back and forth between two reflective surfaces. Flutter echoes and strong distinct echoes that must be eliminated if optimum sound quality is to be expected." [39] Carol states the hand clap test however, "will not, unfortunately, expose another common acoustical anomaly - that of *standing waves*" For this other methods of testing must be used.

To determine the location and frequencies of standing waves in a room, Ethan Winer suggests calculating the room's modes, nodes and antinodes. "Room modes are natural resonances that occur in every enclosed space, and the frequency of each resonance is directly related to the room's dimensions." [40] Since the walls are large and generally reflective, They create standing waves that are prominent and impact the frequency response and reverberation characteristics greatly. The distance between the walls determines the wavelength and therefore frequency at which a standing wave will build. Whenever the distance between surfaces is a half wavelength or multiple thereof, a standing wave will be able to form. These distances are measured, their resonant frequency is calculated knowing the nearly constant speed of sound. These frequencies comprise the modes of the room. At each of these modal frequencies, antinodes are found at the walls and every half wavelength in between. Nodes exist a quarter wavelength from the walls and every half wavelength thereafter. This can be calculated in a room and used to determine what frequencies are going to naturally resonate, where to put material to counter these standing waves, and where to place recording equipment to avoid these peaks and nulls. [41]

Another method used at Torrence Sound Equipment Company is auralization, Torrence states, "Sometimes the changes that we recommend to resolve acoustic problems are structurally and financially significant. Auralization is an acoustic prediction technology… that may offer the customer additional affirmation of the effectiveness of a solution before investing in making the brick and mortar changes." [42] Auralization is a way to model a space in 3-D and make predictions on the way sound will react in a room, further explained in the next section..

Lastly a Real Time Analyzer or RTA is used to measure the reaction of of a room at various frequency projections. This information can be used to assess a number of different acoustic properties in a room. Winer states, "The two main things we measure are raw frequency response... and impulse response." and finally he also states, "...one important metric for room measurement is decay time versus frequency. The goal is for decay times to be more or less uniform over as wide a range as possible." [43] A smartphone may also be used as a simple RTA with one of several downloadable RTA applications, but this is not recommended also further explained in the next section..

From these various tests we have decided how we will conduct our own acoustic analysis. We will use a combination of mode calculation, and RTA testing to assess the sound characteristics of our control and live room as well as implement absorption material changes and test to achieve positive acoustic modification. Our methodology in section 3 explains these methods more thoroughly.

2.9.1 - Use of Software in Architectural Acoustics and Our Tests:

We first considered using auralization software to simulate a model for pre-test analysis, as is done in some professionally designed acoustic spaces. "Auralization is a term introduced to be used in analogy with visualization to describe rendering audible (imaginary) sound fields." [44] We believed for this project we would use use CATT-Acoustic, CATT being, "an acronym for Computer Aided Theater Technique... Since 1988, CATT has concentrated on software for acoustics prediction and auralization (CATT-Acoustic) and FIR reverberation tools." [45] We also researched other free or low cost methods for acoustic analysis and test them as CATT costs about $900 [46] but is free for students. Other software is available such as Odeon which costs about $5000 for a basic package [47] or adobe audition costing $20 a month [48] not including several required plugins, but the auralization function is limited on both these software and does not map as TUCT does. RAMSETE is a plugin collection package that requires a number of programs including Adobe and AutoCAD. [49]

The purpose of the software would have been to replace testing as we could not afford to buy various materials to test and did not have the time to constantly change the location of sound sources. We found, however, that even this software did not allow us to simulate room alterations of the architectural structure and design of the room. Also we could not simulate minor adjustments like material changes and source locations effectively in order to gather data that would be useful in the Real Time Analysis (RTA testing) of the room. Thus this software was not an effective way to look at multiple architectural acoustic scenarios and visualize theoretical sound responses and how they should affect recording as we had originally thought.

Real Time Analysis (RTA) is the use of software to visually observe acoustic properties of a room in real time. Our testing was conducted using an APx515 Real Time Analyzer connected to the ECM8000. The APx515 is a device used to test various acoustic and electroacoustic properties. The device allows a user to connect a speaker and a microphone to perform analysis of how a room sounds. It accomplishes this by generating either noise or a sine wave sweep through the speaker and listening to the response by way of the microphone. By using this device we are able to obtain accurate frequency and impulse response data on the room. These two data sets are important in the detection and correction of early reflection issues as well as sound absorption.

We use the APx515 RTA to test, but the device's starting price is $6200 [50], therefore we also explored other free RTA options. Handheld RTAs on a cell phone were the first option we explored. We tested RTA analyzer from the Google Play app store. This application only shows a live frequency spectrum, and does not provide any typical measurements. We also tested RTA Audio Free by AiNeuron s.r.o. in the Apple App Store. This one provides a better live frequency spectrum, but again does not provide a way to measure frequency or impulse response. The applications were all found to be poor with little options to export or even display Frequency response graphs. Also none of the RTAs tested gave impulse response feedback. We were so discouraged by the results that we did not test any purchasable handheld RTA applications.

However we did explore options in free laptop RTA software. These programs include RoomEQ Wizard and Speaker Workshop. These programs allow one to use their laptop as an room analysis tool providing measurements such as frequency and impulse response. We compared both of these softwares along with our APx515 in order to determine the differences between each. Out of all the laptop RTA software tested we found the Room EQ Wizard [51] to be the best performing.

Also to prepare for testing we compared three reference microphones of varying quality in the same configuration, we mounted the microphone within an inch of a linear studio monitor. The microphones tested included the Behringer ECM8000, Earthworks M23 and the G.R.A.S. 40PH. The higher quality microphones provided superior bass response, as was expected. The most pronounced difference between the less costly Behringer and the other two was from 10 to about 80 Hz. Other differences of less than 5 dB were seen but these were small relative to the 20 dB swings of the room's frequency response. Thus it was determined that for a home recording studio application, a high price and high quality reference microphone is not a necessity. For cost effectiveness it would be possible to use a relatively inexpensive reference microphone such as the ECM8000.

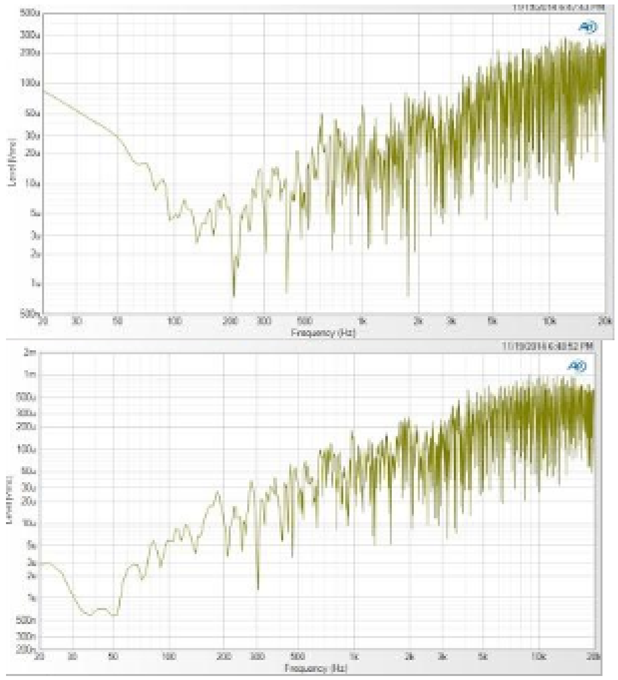

Figure 2.9.1 Frequency response(without smoothing) of M23 (top) and ECM8000(bottom). Logarithmic plot with y axis (amplitude) logarithmic and x axis(frequency) linear.

To aid us in locating problematic areas of the room in regards to modes, nodes, and antinodes as discussed in Section 2.2 we use "Mode Calc" a graphical low frequency mode calculator developed by Real Traps for modal bass frequency response. [40] The calculator shows the user exactly how important room dimensions as well as absorption is to bass frequency. It displays in both a graph and a table the modal properties of the room's dimensions (length, width, height) in respect to frequencies between 20Hz and 500Hz. This helps us understand what kind of bass trapping (high, mid, low) should be done based on the size of the room.

Specifically for analysis of nodes and antinodes we use a Microsoft Excel program designed by Dan Siefert and Allan Devantier of Harman International Industries. This program is available for free for anyone to use in their space. [52] This software not only reveals frequencies which will create standing waves, but also shows where those waves will be in the room. This program shows where the nodes and antinodes of these standing waves will occur in relation to the length, width and height of the room. Knowing these locations can be instrumental in placing recording devices. Placing a microphone near an antinode will cause an increased response and a longer reverb time at that antinode's frequency, while placing it at a node will have the opposite effect. In this way measuring a room's response characteristics can be based on a specific point where a reference for frequency power and reverb time is expected to behave in a certain fashion. Using the mode calculators to understand how best to use the RTA accurately leads to more scientific and ultimately more valid data that can be used to interpret the characteristics of the room.

Chapter 3 - Methodology:

In order to not only come to the proper conclusions and provide empirical evidence that our researched data was correct, the team needed to develop a strategy of tests and testing procedures to follow in order to be certain of the resulting data. This would mean utilizing our RTA and our reference microphone as well as software analysis in order to identify the inherent problems with the room. The testing methods and strategies employed in the our testing were derived from our background research and are described in detail in the subsequent sections. In the live room we first determined modal calculations based on the room's dimensions and then used an RTA device to physically test our space. Following that, acoustic modifications that were determined and then tested again until "ideal" treatment was added to the rooms. In the control room we used the Cardas method as well as acoustic absorption to treatment the room and again test with the RTA for quantitative data of the treatment's changes.

3.1 - Modal Information Calculation:

In order to best provide treatment to the live room we first addressed the acoustic characteristics of the room based on the room's size or its modal characteristics. A bass response modal calculator was used to determine what our bass response in the room should be based on the room dimensions. The reason a bass response calculator was used is because aside from absorption the modal properties of the room have a great effect on bass frequency because bass doesn't travel as straight line as a higher level frequency.

We used a room mode calculator in order to assess what our bass response in the room should be based on the room dimensions. We entered the dimensions in the calculator and the results of the graph are displayed in figure 3.1.1.

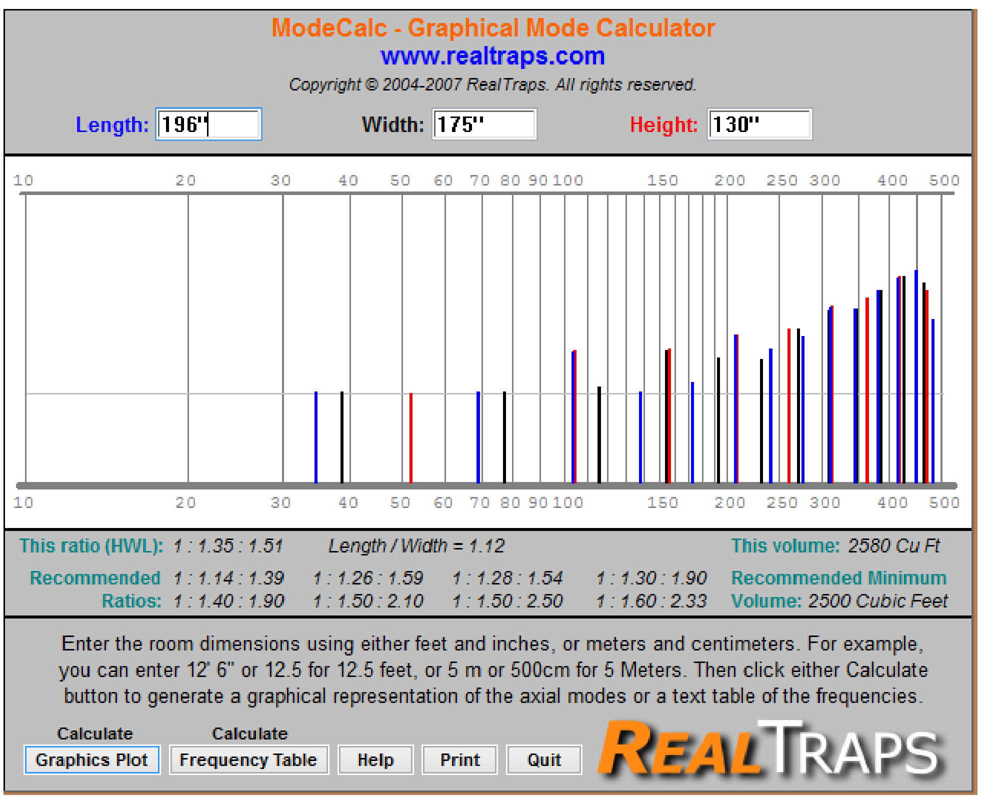

Figure 3.1.1 Displays the graphical results from the Real Traps Modes Calc, here the height and collection of colored bars indicate a problematic mode in the room thus here being problematic between 250-500Hz or "high bass response".

This figure displays how the 250-500 Hz region in the chart has the highest lines of length, width, and height respectively and are spaced close together. This is how the graph shows the user where the problematic bass response frequencies should be in the room. We addressed these problematic frequencies can be attenuated using bass traps.

The acoustic treatment we researched included the construction of bass traps to increase our space's bass response. According to GikAcoustics bass traps work by "... providing resistance, generally in the form of an insulation material with the right properties, specifically proper gas flow resistivity… which results in a loss of amplitude. That reduction in amplitude brings peaks down and valleys up by reducing the strength of one or more interfering waves." [53] Thus bass absorption is conducted by these traps by reduction of amplitude via the insulation material and air space within the traps. We can reduce the modal bass standing waves predicted using our room's dimensions by using this absorption to our advantage. Although this may seem counterintuitive, according to Ethan Winer it is a proven method. This is because it limits standing waves that decrease the bass response in some locations. It will lower the standing wave ratio, and allow for a more even bass response around the room. As the modal bass calculation information states we need to create high bass frequency (250-500Hz) absorbers. There are bass trap designs on Mr. Winer's website [54] for low, mid range, and high bass frequency absorption. Aside for the frequency specific quality of the bass traps we also use Mr. Winer's design due to the ease of construction and relatively low price.

We spent about $180 on materials for 64 square feet of bass trap, coming to a little below $3 per square foot to make high bass absorbing bass traps. This compares favorably to the Primacoustic London Bass trap which costs $250 for 16 square feet of trap, totaling about $16 per square foot. [55] We also purchased plywood sheets at $16.83 per 4x8 sheet for floorboards and fabric at $3 per yard to cover the walls. After construction we placed these traps in the corners of our room as GikAcoustics also states, "If you have pressure building along each wall and traveling to the outside ends, it stands to reason that it will pool in the corners since you're now where you're at 2 boundaries." [53] Therefore placing the traps in the corners will most effectively absorb the standing bass waves in the rooms that travel along the walls.

After determining the modal bass response we calculated the nodes and antinodes present in the room also based on the dimensions of the room to ensure appropriate mic placement. Figure 3.1.2 displays the graph of the node and antinode locations in the room.

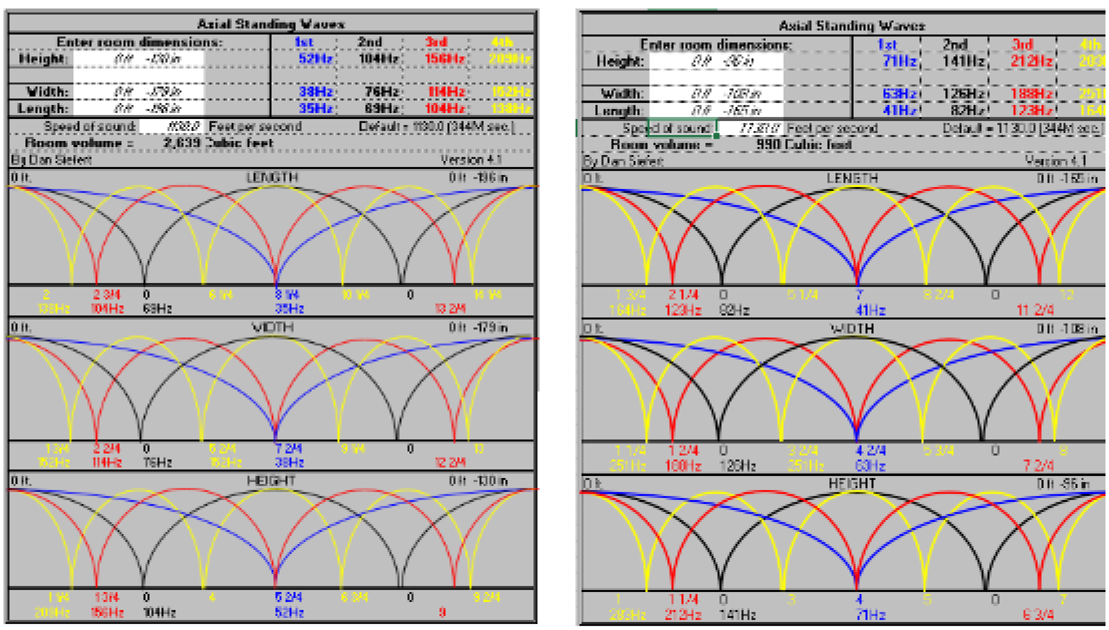

Figure 3.1.2 Calculation of modes in our live room(left) and our control room(right). Modes are calculated up to the fourth harmonic(at top). Below is a graphical display of the standing wave amplitudes. Nodes are located in the troughs and antinodes at the peaks.

This calculator is similar to the bass response modal calculator in that it uses the dimensions of the room to calculate probable acoustic characteristics in regards to nodes and antinodes. Using the information obtained we chose a location to place the mic where the parabolic waves were neither at a maximum or a minimum (nodes and antinodes) but about in between and choose that spot by length, width, and height respectfully, to place our microphone to be used with the RTA. In the analysis of this chart we found a point at 5’6” lengthwise, 4’6” width and 3’6” high that was not in either a node or an antinode, this is where we placed our microphone.

Finally with this information we began to test for real time acoustic response characteristics using the RTA. First we tested without acoustic treatment and then with bass traps in the corners of the room. After these tests we added floorboards, cloth, and mid to high range commercial absorbing equipment respectively.

3.2 - RTA Testing:

With the real time analyzer we conducted two main tests pertinent to a recording studio, frequency response and impulse response. According to our interview with Mr. Winer and our background research these are generally the most telling tests to perform when attempting to determine the acoustic quality of one's room, as they provide the best information regarding which frequencies have the most clarity with respect to reproducing the original sound. The impulse response test was conducted to determine how reflections will behave in the room in regards to sound pressure level and time. The frequency response test was conducted to determine what the relative sound pressure level of frequencies within the audible human range are in the room. These are a direct reflection of the absorption characteristics of the room's architecture as well as the rooms dimensions. The RTA and it's accompanying software is also capable of a wide range of testing signals and analysis but many are redundant and irrelevant to a small home recording studio. For this reason we chose to conduct only these two tests.

3.2.1 - Impulse Response Testing:

Our first test was the impulse response test. In this test, the RTA generates a sweep signal and digitally deconvolutes it with the microphone signal to find the impulse response characteristic. [56] From this we can see the early reflection behavior. The impulse response is defined as the ratio of the output to the input of a system over time after a single perturbation from the source. In an acoustic scenario this represents the reflection characteristics, spikes represent reflections off of surfaces in the room. It can be helpful in identifying large, undesired reflections. Once a reflection is identified, we can use its time after the impulse and the speed of sound to calculate the distance the wave traveled. For a first reflection the distance the wave traveled is twice the distance to the surface that it reflected off of, we can measure out this distance radially from the source and decide which surface to apply sound absorptive or diffusive material to. An example of the impulse response data is shown below in figure 3.2.1.

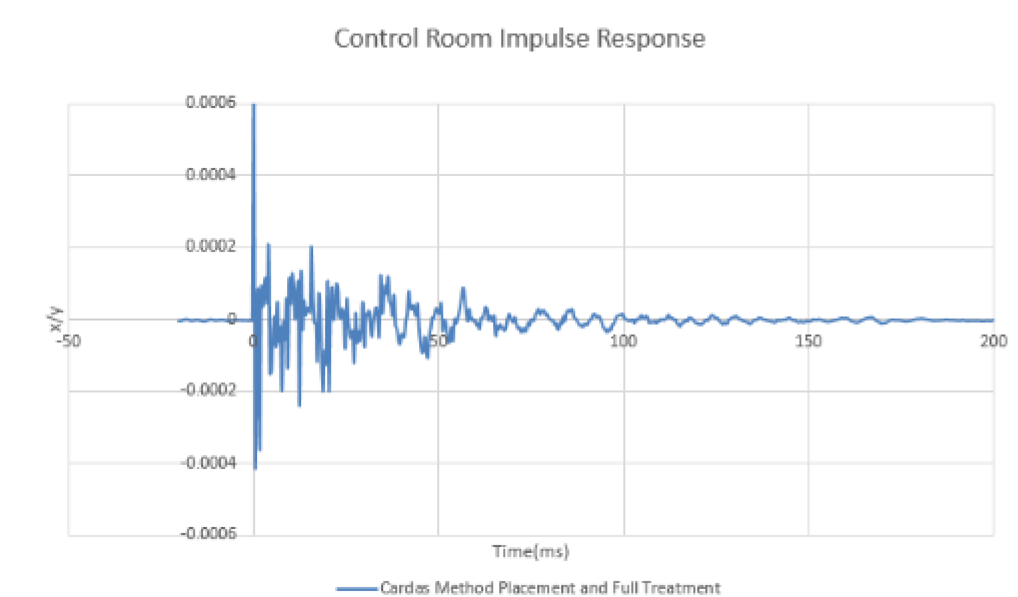

Figure 3.2.1 Impulse response graph in one of our live room tests. Time is on the x axis with the output to input ratio on the y. The large spike is the impulse itself. The much smaller ripples shortly after are reflections.

3.2.2 - Frequency Response Testing:

Our other test is the frequency response of the room. The frequency response test compares the amplitude of the recorded signal to that of the output signal throughout the frequency sweep range. This is usually recorded in a logarithmic expression of sound pressure called dB SPL. This tells us which frequencies are being absorbed and which are not and gives us insight into the standing wave characteristics of the room. The frequency response is a vital part of testing because it allows us to see which frequencies are problematic and need to be addressed. For example if high frequencies are higher in amplitude than lower frequencies, high frequency absorbers could be added to reduce the high frequency relative sound pressure level. Idealy this reduction would bring the relative SPL to that of the other frequencies, of course these modifications may have an effect on the frequencies not targeted as well. We can address these problems through proper material selection (see section 2.5). An example of the frequency response data is shown below in figure 3.2.2.

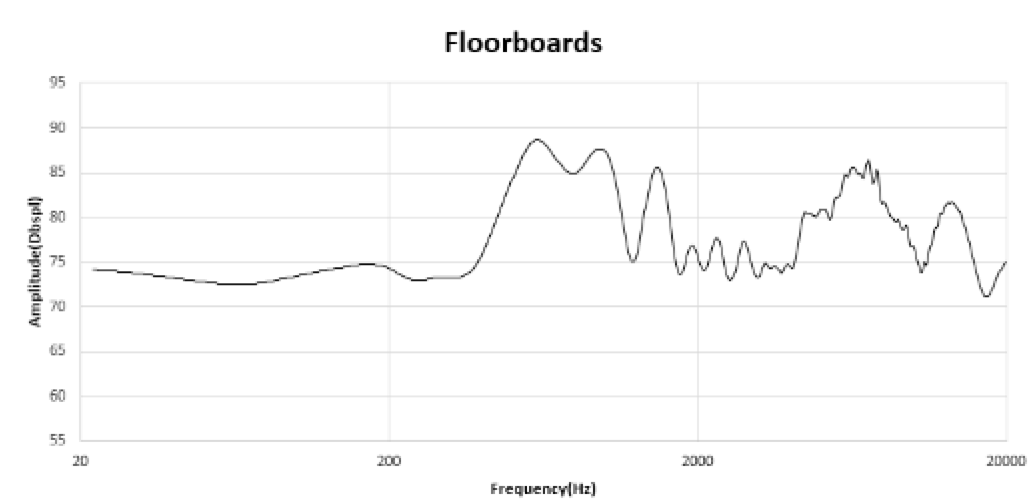

Figure 3.2.2 Sample frequency response curve of our live room with floor planks added to improve bass response. Frequency in Hertz is logarithmic on the x axis and amplitude in dB SPL is also logarithmic on the y axis.

3.3 - Acoustic Modification:

In order to alter the audio response of our room we needed constructed and placed acoustic modifiers such as bass traps, floor boards, fabric, and commercial absorption equipment. We chose to use these materials and modifiers based upon recommendations by Ethan Winer, Lou Clark, and other case studies and interviews. Typically bass traps are used to increase the SPL of lower frequency sounds by acting on waves that will destructively interfere with those that are desirable. Floorboards are used to allow low frequency waves to build without being absorbed by the carpet already in place in the room. Fabric is generally used to bring down and reduce some of the higher frequency flutter echoes and is a material that is generally easy to acquire in large quantities. These modifiers are to be used in combination to achieve an overall better, or flatter, frequency response as well as reducing early reflections.

3.4 Tests and Test Configuration Live Room

In order to accurately represent the best possible acoustic response of our room and to ensure our tests were repeatable and accurate we set up a standardized testing procedure and set up. First we cleared the room of all objects, save for those that would regularly be in the room. We wired the RTA to the output speakers and the microphone underneath the door. This way the user could operate the RTA from outside of the room so that his body is outside of the system. We used Yamaha HS-7 speakers coupled with a HS-10w subwoofer in a vertical arrangement for their flat frequency response.

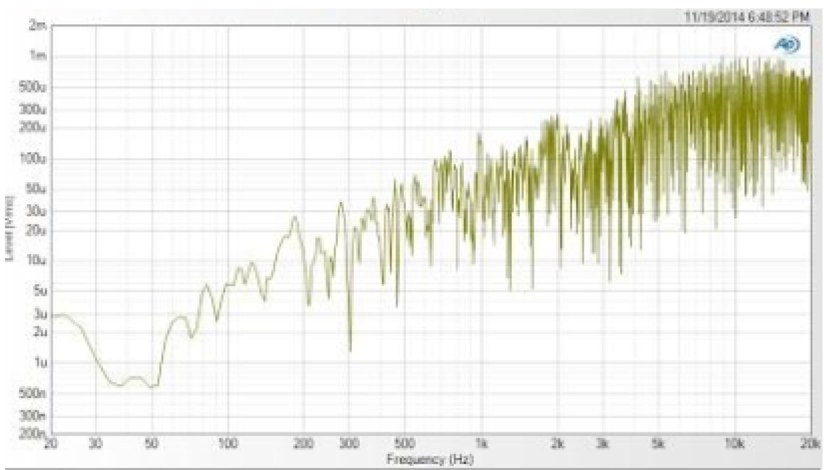

Figure 3.4.1 Frequency response of the Behringer ECM8000.

For the microphone we used the Behringer ECM8000 for its comparable frequency response, omni-directionality and its low cost of approximately $60. The signal path consisted of two outputs from the RTA into the left and right HS-7s which then both fed into the accompanying sub-woofer which summed their signals. Although there were two outputs from the RTA, the tests we ran were in mono, so both signals were identical. This system was left to its default settings which provide a nearly flat response.

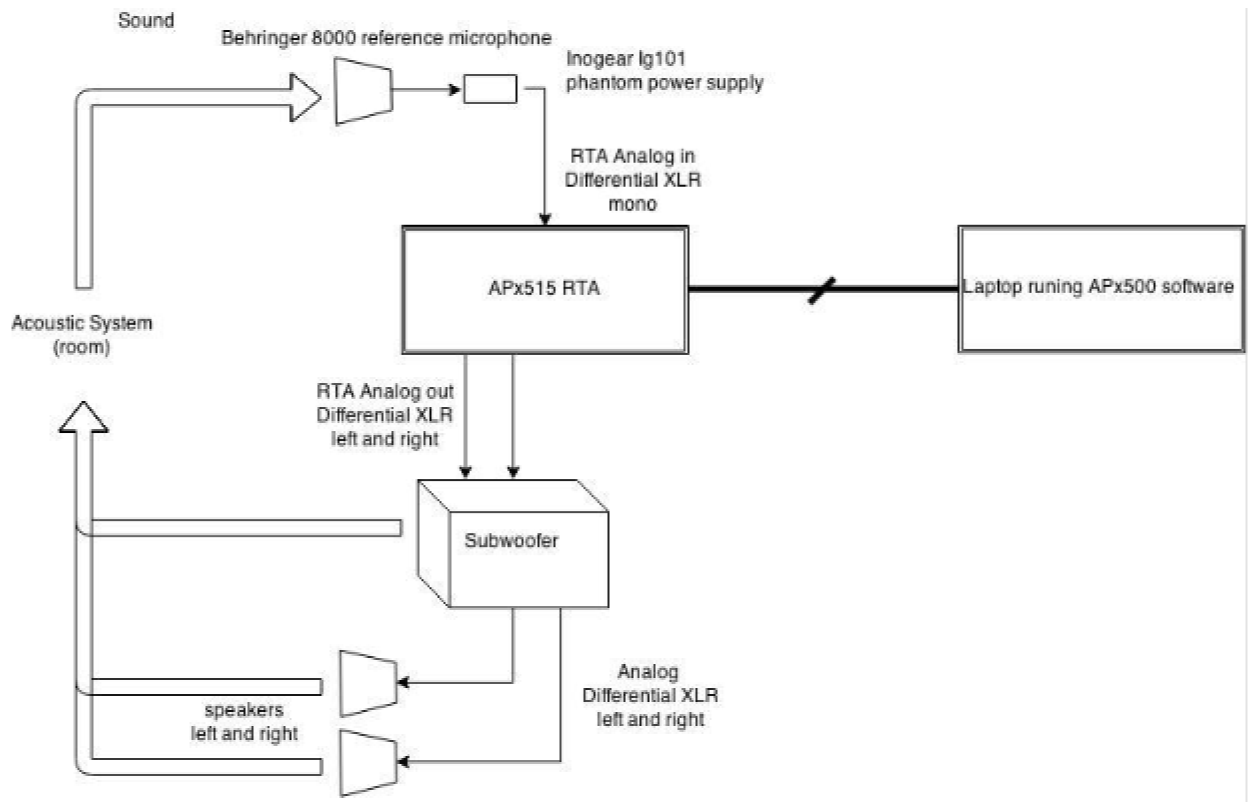

Figure 3.4.2. Signal path setup for all of our RTA testing. The computer running the included RTA software and drivers communicates serially to the APx515. The RTA creates an analog test signal and inputs it to the subwoofer which acts as a transducer and also passes the signal to the speakers. The sound is picked up by the microphone and fed back into the rta via a phantom power supply. The RTA uses digital signal processing to process the raw data and sends it serially back to the laptop.

The microphone signal path led from the RTA through an Innogear IG101 and then to the Beringer. The placement of the microphone was based upon our modal analysis of the room. The goal of this is to ensure that the microphone was not placed directly inside a node or antinode of one of the room's modes. We placed the speakers across the room such that the response of the room would have maximum impact on our signal.

3.5 Tests and Test Configuration Control Room

For our control room tests our signal path setup remained unchanged from that of the live room. The configuration of the room, however, was significantly different. For our first control test we used the room's original configuration where the sound sources were placed along the long wall, 4' from the wall at an elevation of 4' 6". This configuration was laid out by the previous users of the room. In order to properly place the speakers we used the Cardas method explained in section 2.8. We measured the short side of the rectangular room to be 9'6" in length. To find the distance from the source to this wall we multiplied this by .447, yielding 4'3". We multiplied this distance by .276, attaining a distance of 2'7", the distance from the long walls to each speaker. The microphone was placed equidistant from each speaker at average human ear level, seated (about 4').

We then added treatment according to placement techniques discussed in section 2.8. We added the bass traps in the corners and then the floorboards were then used to cover the entire floor of the room. Finally mid to high frequency absorbers were placed behind the listener position and we tested each respectively.

Chapter 4 - Results:

The results of our tests conducted in the live and control rooms are shown in this chapter. Impulse and frequency response data is shown for both rooms with different levels of acoustic modification. First the impulse response data for both the live room and the control room through the various testing iterations is shown. The frequency response data for the live room and the control room is shown second. This section provides a comprehensive look at the results and data our testing methodology produced. For recommendations and further analysis on this data, see chapter 5.

4.1 Impulse Response Live Room Data

We tested our live room in five configurations; without treatment, with our bass traps, with bass traps and floorboards, with bass traps floorboards and fabric material, and with bass traps and commercially available medium-high frequency absorbers. For simplicity, two of these are included in Figure 4.1.1, the untreated room and the fully treated room. All of our data sets were compiled by averaging the results of five identical tests.

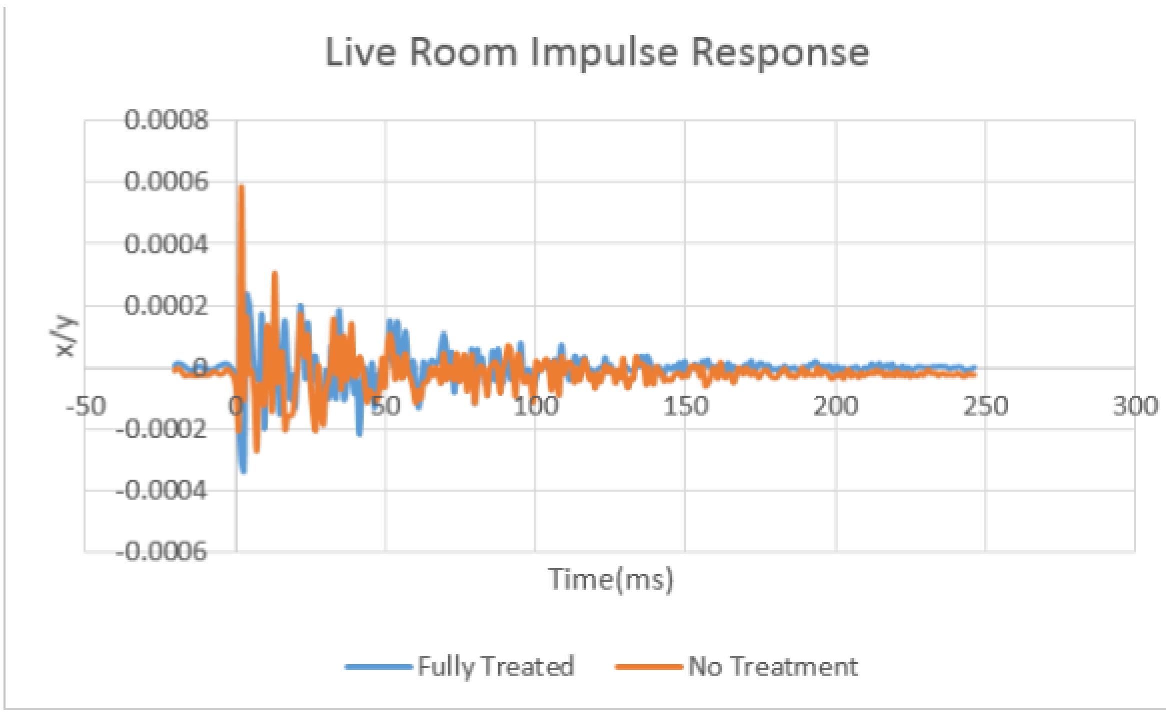

Figure 4.1.1. Impulse response tests of our live room. Two configurations are shown, with no treatment, and with full treatment, including bass traps, floorboards and mid frequency absorbers. The y axis variable is the input to output ratio of the signal displayed linearly.

The live room impulse response data in figure 4.1.1 shows a reduced first reflection in the treated room at about 2 ms. It also shows that the reflection at about 40 ms was slightly attenuated. Many areas, however, have higher reflections in the treated room than in the untreated room. With some of the early reflections reduced and some amplified, we are not confident that our acoustic treatment controlled or dissipated early reflections. As stated, other various treatment configurations were tested as well, these can be found in appendix 3. The results from each test shown in appendix 3 yield similar results to that of the fully treated and untreated room. Even the addition of flat floor boards, see appendix 3-2, does little to the arbitrary early reflection impulse response data we received from our tests. Although the reflections over the general reverberant time seem to be reduced with the carpeted floor, the first early reflections see no improvement by using a thin carpet floor versus floorboards. We concluded from this graph and those shown in appendix 3, that although the addition of treatment to the room did have some effect on the impulse response of the room, it did not improve or degrade it significantly. From our case studies we learned that a desirable impulse response is one which has no large noticeable early reflections, these types of reflections can cause undesirable effects like flutter echo or other non-logarithmic decay. Flutter echo however was not a noticeable or measurable problem in the live room. When comparing the tests from the full "treatment" of the room to the untreated room, the results presented simply reflect the ambiguity of our impulse data collectively for the live room impulse test.

4.2 Impulse Response Control Room Data

In order to isolate the effectiveness of the different acoustic methods utilized, the following impulse response characteristics are shown, first comparing the empty room in an incorrect configuration with the speakers along the longer wall and second with the room correctly configured with the Cardas method. This assesses the effectiveness of speaker placement on reflection characteristics. Next we compare the correctly configured empty room with the correctly configured room treated with our bass traps and wooden floorboards. Finally we added comercial mid range absorbers to the room and observe their effectiveness.

4.2.1 Impulse Response Control Room Cardas Method Effectiveness

Figure 4.2.1 assesses the effectiveness of speaker placement alone on the impulse response characteristics of the room. It can be seen that with the correct speaker placement the reflections from 0-50 ms are attenuated but are still irregular and generally are similar to that of the original configuration. After 50 ms, however, the impulse response is greatly improved in the correctly configured room, the amplitude of the reflections is approximately halved. This shows the effectiveness of the Cardas method in reducing the large uneven reflections. There is still no acoustic treatment in the room however, this is why the early reflections do not change in amplitude. Although the reflective characteristics are improved and standing waves are minimized, absorptive materials are necessary in order to absorb these reflections further.

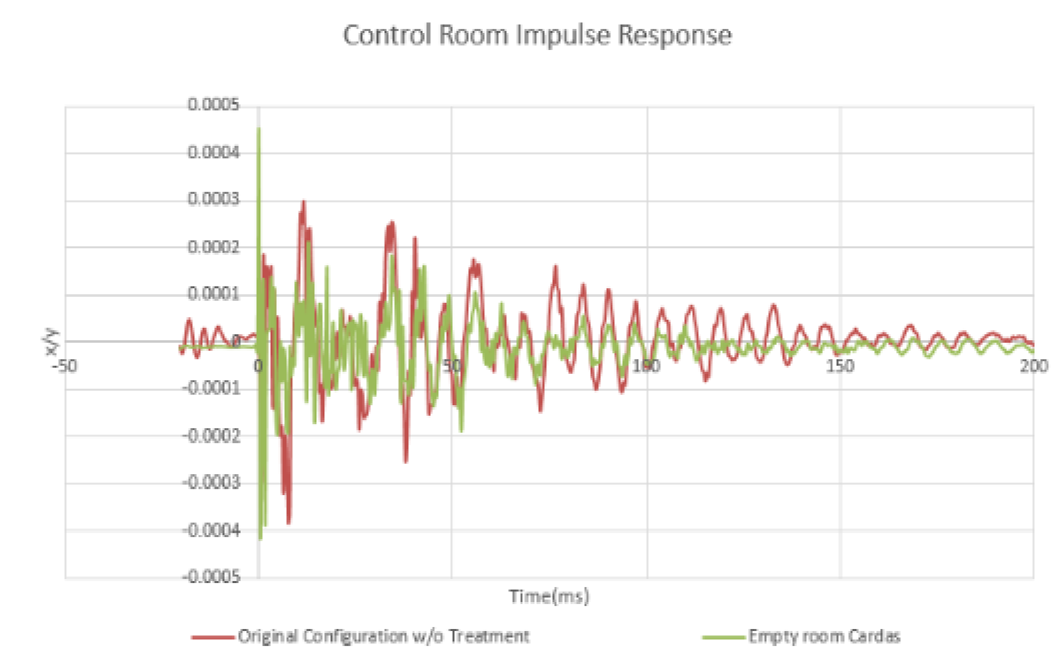

Figure 4.2.1. Impulse response curves of control room with speakers and microphone set up in suboptimal locations (red) and in the correct location according to the Cardas method (green). X axis represents time in milliseconds and y axis represents the input/output ratio.

4.2.2 Impulse Response Control Room Bass Traps and Floorboard Assessment

In figure 4.2.2, the effect of our bass traps and floorboards can be observed. These also improve the impulse response considerably, most notably before 50 ms. The amplitude of these early reflections is significantly attenuated. This could be due in part to the absorptive properties of the wooden bass traps and floorboards and in part to the altered geometry of the room due to the bass traps which were placed in four corners of the room per Ethan Winer's recommendation. This decreased the amount of parallel surfaces in the room, thus reducing the possibility of standing waves and flutter echo.

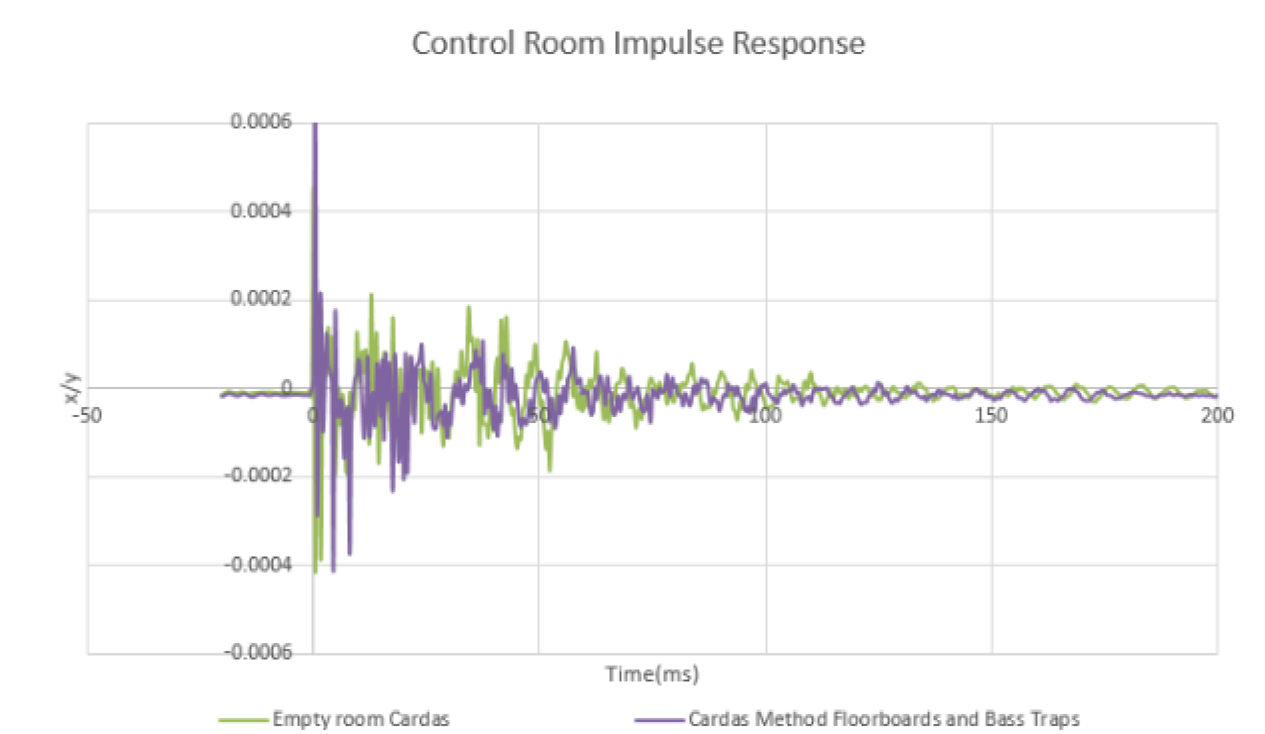

Figure 4.2.2. Comparison between impulse response of the control room properly configured with the Cardas method, both empty (green) and treated with bass traps and wooden floorboards (purple). Considerable improvement can be seen in the early reflection range below 50 ms.

4.2.3 Impulse Response Control Room Comercial Absorbers Assessment

In figure 4.2.3 the effect of the medium frequency commercial absorbers is assessed. The absorbers were placed behind the listener position so as to absorb the direct sound from the speakers and that reflected off of the sidewalls. There are minor differences, most noticeably the first reflections before about 10 ms are attenuated. Overall, however, there is little noticeable improvement from the addition of these absorbers.

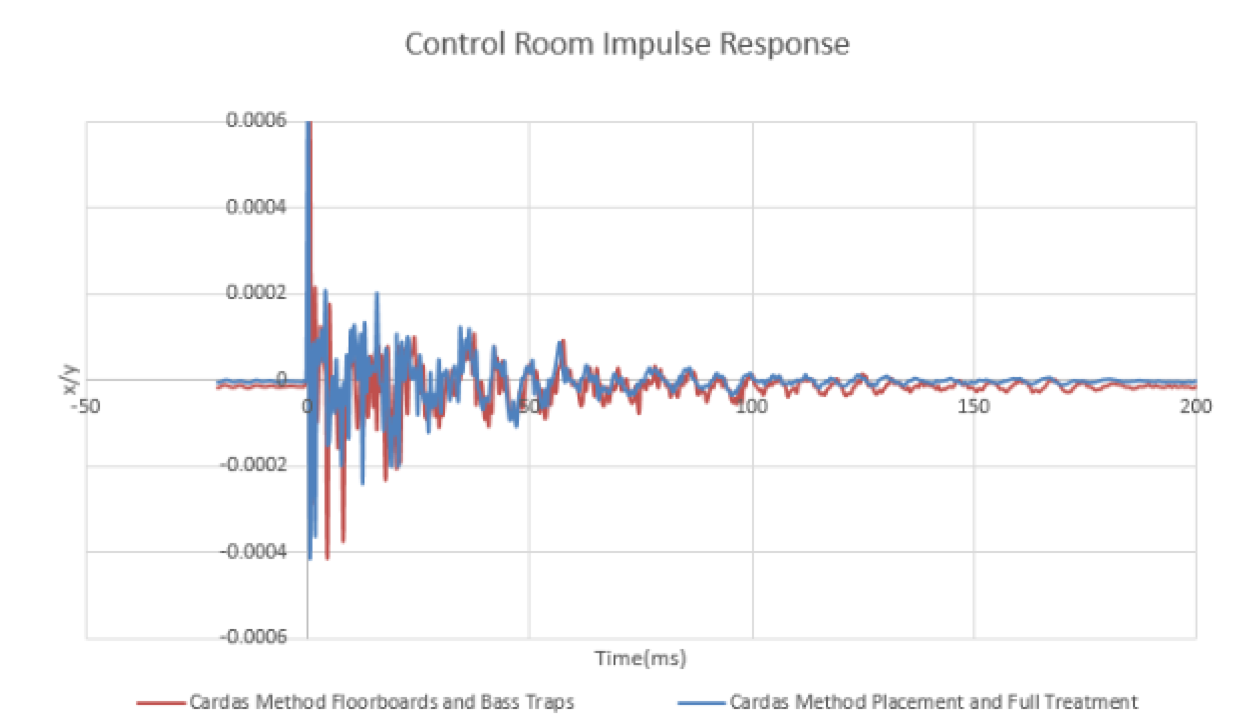

Figure 4.2.3. Impulse response comparison of room treated with our bass traps and floorboards against treatment with the bass traps and floorboards plus the commercial mid-range frequency absorbers. Both tests are configured with the correct Cardas method speaker and listener positioning.

4.2.4 Impulse Response Cumlative Results of Treatments

Figure 4.2.4 shows the impulse response data of the control room, both fully treated and correctly configured using the Cardas method and in the original untreated incorrectly positioned state. The correctly treated and configured room has significantly smaller reflections in both the early stages, 0-50 ms and later. The post modification response is both more consistent and smaller in amplitude than the pre modification response. The inconsistencies in the early reflection stages of the pre-modification response such as the large dropout between 20 and 30 ms are not present in the modified response. Instead, the modifications to the room allowed for more frequent reflections of lesser more consistent amplitude. The reflections also decay much more rapidly in the treated room. Although it is difficult to estimate the exact 60 dB point in order to determine the exact reverberation times of each, we can estimate their amplitudes at a given time relative to one another. The approximate amplitude of the reflections on the treated room impulse at 40 ms approximately equals that of the untreated room at 80 ms. Treating these curves as approximately logarithmic we can determine that the treated room has a reverberation time of approximately half that of the untreated room.

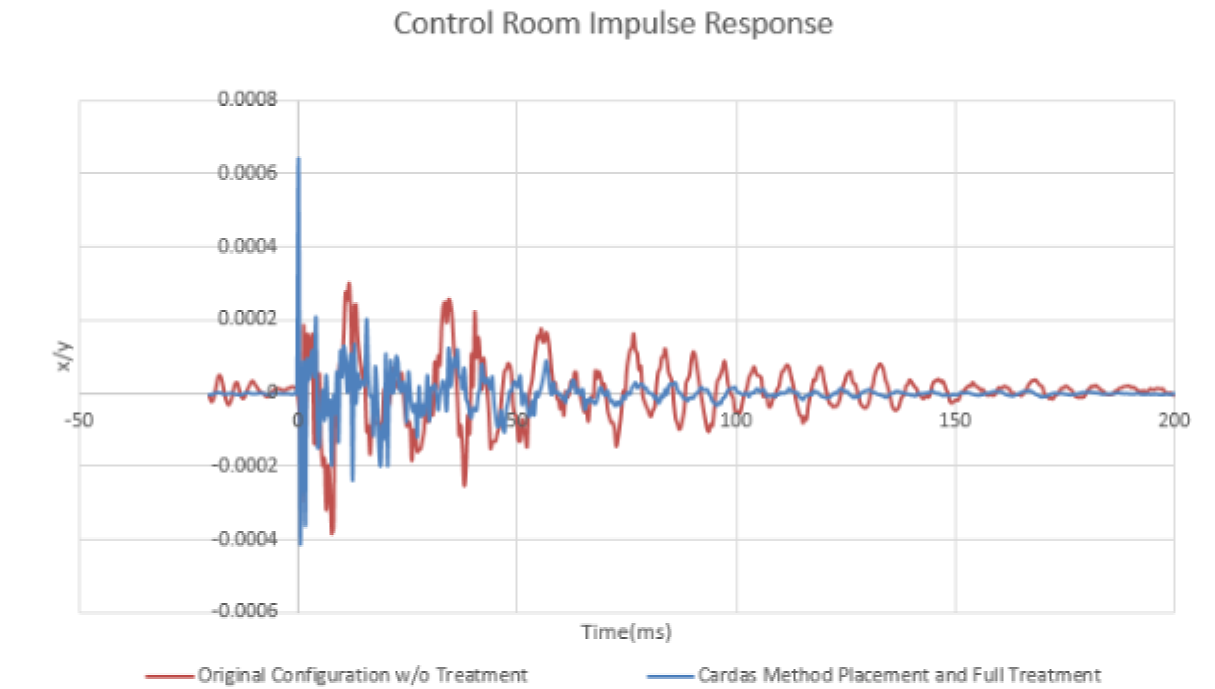

Figure 4.2.4. Impulse Response of control room. Red is pre-modified room and blue is the room configured with the Cardas method and treated with our Bass absorbers, floorboards and commercial mid range absorbers.

4.3 Frequency Response Live Room Data

Figure 4.3.1 displays the comparison of frequency response with the various treatment methods implemented in the room. It can be observed that the various levels of treatment did not greatly alter the sound pressure level response of the room. At some specific frequency ranges there are significant changes in SPL, however the change is so limited in range and the amplitude reduction so small that the results of these tests show that the absorptive materials did not create a significant impact on the frequency response of the live room. The greatest difference in SPL for any frequency given the the test was 4.5 dB SPL at 1300 Hz. This was the difference between the test with no treatment and the test with the bass traps and floorboards in the room. Also we expect the large difference in amplitude around 500 Hz, with all treatment models respectively, to be caused by an imbalance in our subwoofers dB SPL output to the mid and high range speakers. This change of source output would cause the dB SPL to rise significantly, as we see at the crossover frequency range (about 500 Hz). From these results, we cannot conclude that our treatment was effective in flattening the frequency response of the room.

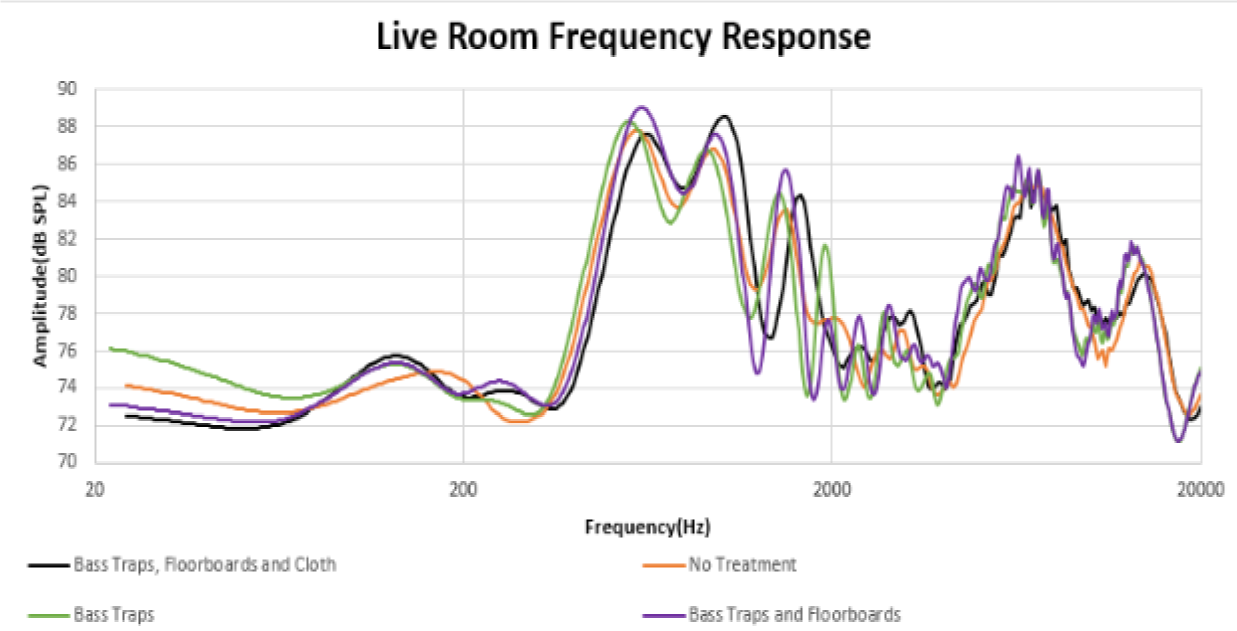

Figure 4.3.1. Frequency response chart of our live room with different levels of treatment. Results represent the average (mean) of five individual tests and are smoothed.

4.4 Frequency Response Control Room Data

The frequency response curves of our live room tests are shown in figure 4.4.1. The first test (in red) was conducted in the untreated control room with the speakers against the long wall, this was the original layout that the previous users of the room used. The next test, in which the Cardas method was implemented, shows great improvement over the first test. The large valleys at 1 kHz and 2 kHz are eliminated and the above 10 kHz response is more consistent. An undesirable consequence of this modification was the attenuation in the bass frequencies below about 500 Hz, at these frequencies the Cardas method response remains consistently 2-5 dB lower than that of the original configuration. The rest of our tests parallel each other closely, with one exception. While testing the bass traps independent of other treatment, the bass was attenuated greatly below 100 Hz. This shows the effectiveness of these absorbers. Once the floorboards were added in the next test, the bass was again amplified to a similar level as before. Little impact was observed when the commercial high and medium frequency absorbers were added in our last test(in blue). Lastly there is a dramatic valley for all tests in both the original configuration and the cardas method with various materials around 12000 Hz. We speculate that this is due to our microphone being placed in a node of modal room height for both tests. In both tests we placed the microphone at average listening height around 4 feet, and according to figure 3.1.2 in section 3.1, this is indeed a node. This offers even more support for the Cardas method in which without the node present the frequency response would be relatively flat throughout the mid and high range. These results demonstrate that the Cardas method is effective in flattening the frequency response of the control room and that adding absorptive material as in the live room, did very little.

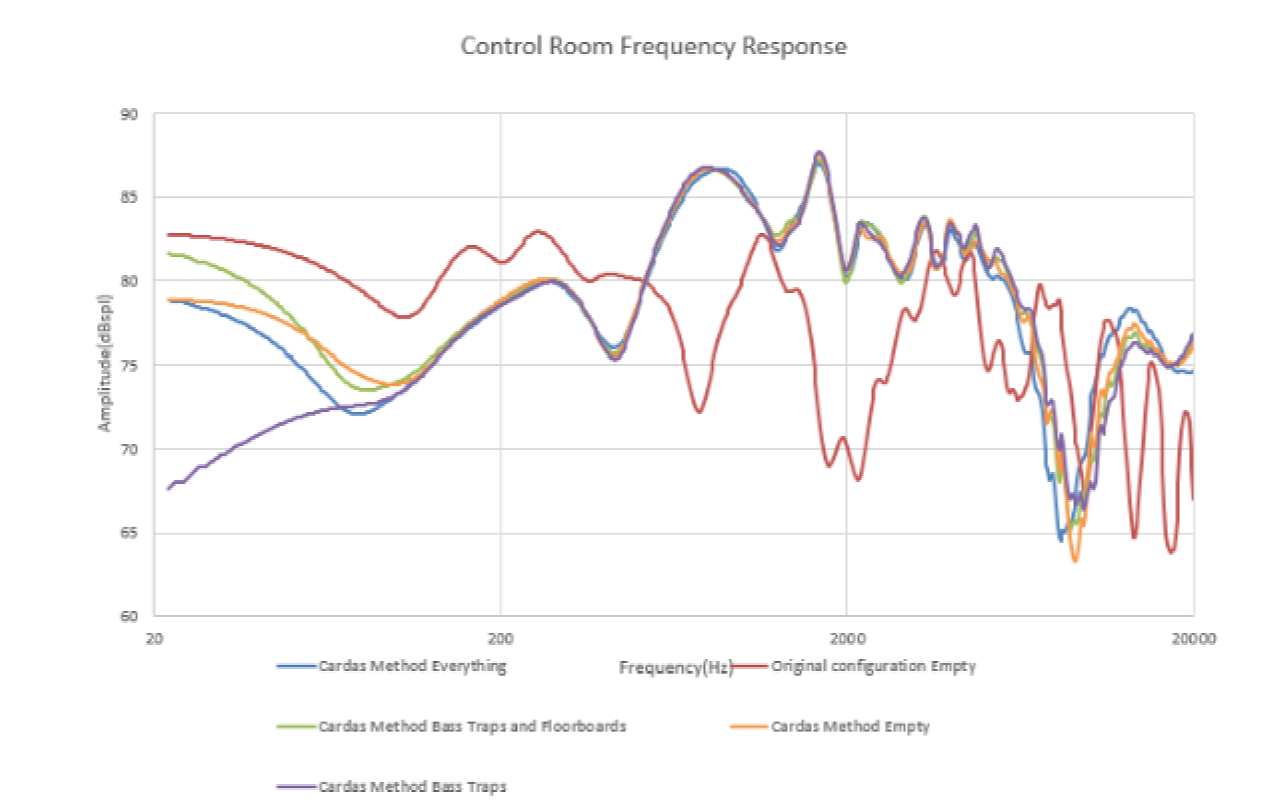

Figure 4.4.1. Frequency response curves of the control room in five different positioning and treatment configurations. Results represent the average (mean) of five individual tests and are smoothed.

Chapter 5 - Conclusion

This project started with the goals of determining a method for identifying common acoustic problems that home recording artists and musicians in general might encounter with the space that they are recording or performing in and finding cost effective methods that address and treat those common acoustic problems. Throughout three academic terms the project has tackled these two main points of identification and treatment. The final project offers identification information that is quite helpful in determining acoustic properties and problems, but falls somewhat short on the topic of providing cost effective treatments. The treatments that the project deemed most viable have subsequently been tested and at least in this application proven to be ineffective at treating the problems in the rooms we had. This is not to say that the project should be dismissed, but instead the contrary. This project has shown scientifically ways in which acoustic treatment will be uneffective and uses this to highlight a sort of 'methods not to try'.

We have now gone through the process of fully testing and analyzing the spaces available to us in Riley Commons and have displayed the results in the prior sections. We have shown the raw data and how it has influenced our choices in room treatment and acoustical modification. After analyzing both the impulse response and sound pressure level data from the live room tests conducted we can conclude that the modifications made were largely unsuccessful. The treatment applied did little to flatten or otherwise improve the frequency response of the room. Figure 4.3.1 displays our frequency response comparison graph of the untreated to fully treated room, it is observed as stated that the materials present had no positive impact on reducing or flattening the relative frequency response. With regards to the impulse response, Figure 4.1.1 displays our impulse response comparison graph of the untreated to fully treated live room. Again it can be observed as stated that adequate improvement to the sound space in regards to applicable quantitative data of early reflections was not obtained.

In the control room, an analysis of the data will reveal both what did and did not work to improve the acoustics of that space. The application of the Cardas method to position the equipment in the room appears to have the most influence out of all our applied treatments. Further observation of the frequency response data in the control room from figure 4.4.1 will indicate that our bass traps and other methods of acoustic modification had no large or viewable impact in regards to frequency specific absorption. This is either due to the fact that our bass traps and other materials and equipment used provided no modification, or if they do, then it is at a level undetectable to our testing methods.

The analysis of the impulse response test data for the control room in figures 4.2.1 through 4.2.4 show that the acoustical modifications and treatment have been largely successful in reducing early reflections in the room. This is most likely the result of adding the bass traps and other acoustic treatments such as fabric and commercial modifiers to the room. If the addition of these modifiers did not alter the absorption of frequencies in the room as discussed and displayed in figure 4.4.1 we speculate that at least they scattered the early reflections directly behind the sound source and microphone. This means that in this specific case our alterations to the room configuration had a positive effect on the sound of the space and home recording artists can follow similar steps in order to improve the sound of their control room.

5.1 Recommendations

We as a team can recommend to an an at-home musician or recording engineer which methods do and do not perform a few key things we found necessary to alter the sound of the recording and mixing space. We do recommend that the first thing home musicians and engineers do is utilize the Cardas method in their control room. The Cardas method will immediately generate positive acoustic characteristics in a listening space that was previously not following a designed layout. We also found that since none of our absorption materials made a great impact on the absorption properties of the rooms, using more expensive commercial equipment is not inherently better than less expensive fabric, plywood floorboards, etc. In fact neither the commercial material, fabric, floor boards, or our bass traps did anything to alter the frequency response of the room dramatically. Therefore the only recommendations the team can make to at-home musicians and engineers from this report is that the Cardas method is a very efficient and effect first step in improving the sound qualities of a listening space, and inferences can not be made about the effectiveness of absorptive materials in improving sound quality.

5.2 Future Studies:

While this project can not scientifically offer any recommendations other than to utilize the Cardas method, the team is still able to speculate as to where future improvements and studies can be made. Even without success, the team can still leave a place where future projects and investigations can pick up from without having to repeat our work. The team does ultimately feel that the project has a lot more area to investigate and that this project only illuminates part of a larger whole.

In large part, the team is of the understanding that more treatment than what we created would be necessary to see a demonstrable change in the live room's acoustics. With more treatment in general, a better idea can be gained about the effectiveness and actual impact of bass traps and other homemade acoustic treatments. From there even more research can be done to determine the optimal amount of treatment needed per unit of room volume.

There is also the matter of the Cardas method. In our tests, the Cardas method had the most acoustical impact on the control room and it is the opinion of the team that it be implemented as an easy, first step to improving the acoustics of one's control room. With that said, it could also be a point of future investigations into its effectiveness with respect to other setup configurations in multiple environments. Even more work could be done to determine the impact of more acoustic treatment in addition to the Cardas method in the control room.

Lastly we speculate that our graphic results do not entirely reflect the acoustic "quality" of a room. Throughout our testing despite what the quantitative data shows, we and others students with us in the space "heard" a difference in sound with the various levels of treatment. Specifically many, including our team, report that the live room sounded dramatically different when full treatment was added than originally with no treatment. Blind tests could be made with amateurs and professionals alike in determining whether changes that do not reflect graphs of impulse and frequency response may reflect how the sound is audibly projected in the room.

We these future tests in mind, perhaps another group may be able to discover more about the proper use of the many aspects of architectural acoustics, not just material properties, to increase the sound quality of a recording space. We as a team have thoroughly enjoyed working on this project despite our results being greatly different than what we originally expected. In addition, through our extensive case studies, interviews, and research we learned a great deal about the realm of studio acoustics and professional versus semi-professional recording through architecture, materials, and technique.

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Appendix 1 - Budget:

This project had only a small budget available to it, and as such the project included the use of funds provided by the team members. Small expenditures in any long term project are to be expected. Having a small pre-allocated budget is beneficial to the project in two ways. One way is that it induces an environment in which most of the target audience, namely home recording artists and hobbyists, will find themselves. The other way in which the project will benefit from the lack of a dedicated source of funding is that this will encourage a multifaceted approach to solving problems in that the project is not tethered to one product or method to solving an issue. This biasing of problem solving methods can be the result of becoming invested in one piece of technology or solution. Without a budget, the project will not be tempted to invest in something, and try to reuse its solution over and over again.

In the course of acquiring the materials needed in order to affect change to the room's acoustics, we have incurred the charges seen in Table A1.1.

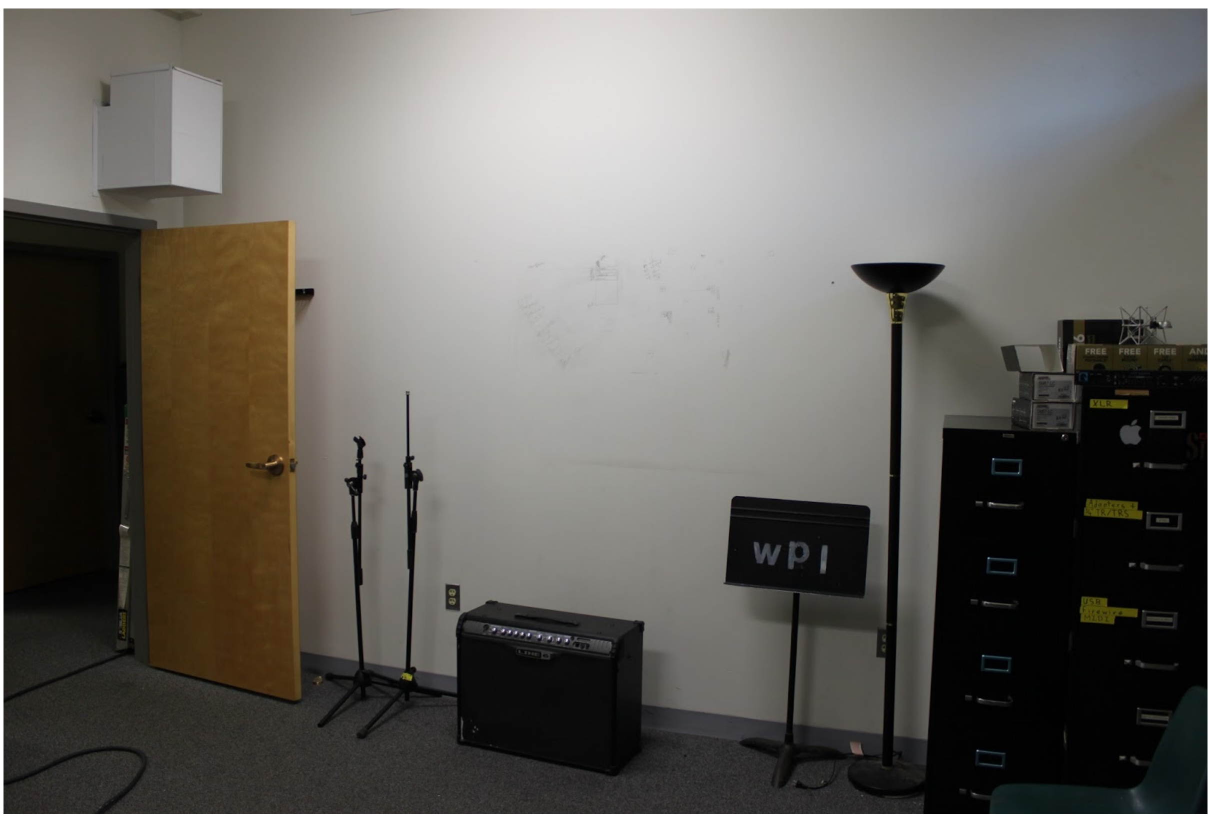
Item:	QTY:	Price:	Cost:	Store:		
2"X4X8' XPS	4	33.92	135.68	Home Depot	Subtotal 1:	150.1
Claw Hammer	1	6.97	6.97	Home Depot	Tax:	9.38125
Bright finish 1lb nails	1	3.47	3.47	Home Depot	Total 1:	159.48125
Dynaflex 230 Clear	1	3.98	3.98	Home Depot		
Lumber cutting	2	0.5	1	Home Depot	Discount:	21.19
11/32" 4'X8' Sheathing	7	16.83	117.81	Home Depot	Subtotal 2:	174.9
1x4-8 No.2 Premium Pine	8	5.98	47.84	Home Depot	Tax:	10.93125
1X2-8 No.2 Premium Pine	8	3.68	29.44	Home Depot	Total 2:	185.83125

Table A1.1: Current Expenditures

It is also worth noting that we have only currently spent about $350, which is within the realm of possibility with respect to a home-recorder's project budget. This fits our initial intentions of trying to provide cost effective methods to improving an acoustic space. Unfortunately, the project was unable to find methods that did affect change on the room, and therefore we are unable to declare that the methods used were effective.

Appendix 2 - Pictures:

A2.1 - Live Room:


wpi

A2.2 - Control Room:

Appendix 3 - Live Room Impulse Response:

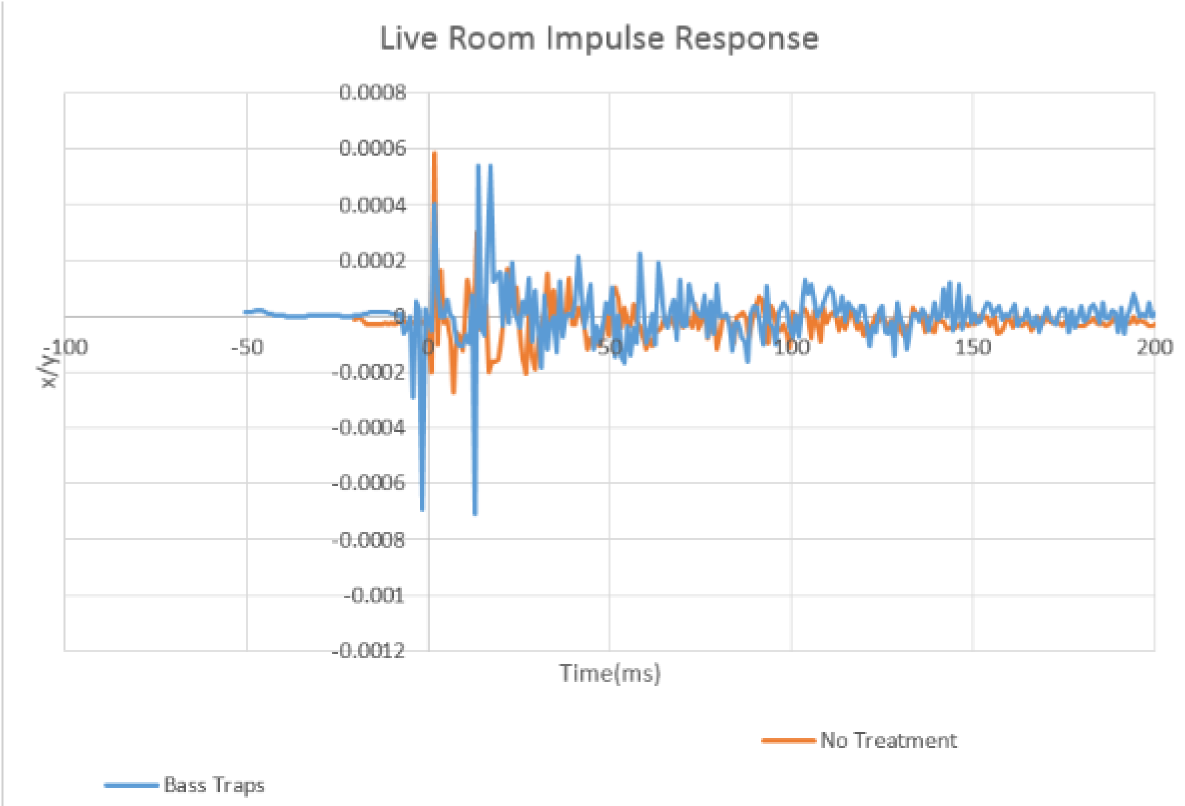


Figure appendix 3-1. Impulse response characteristic of untreated live room versus that treated with our bass traps in the four corners.

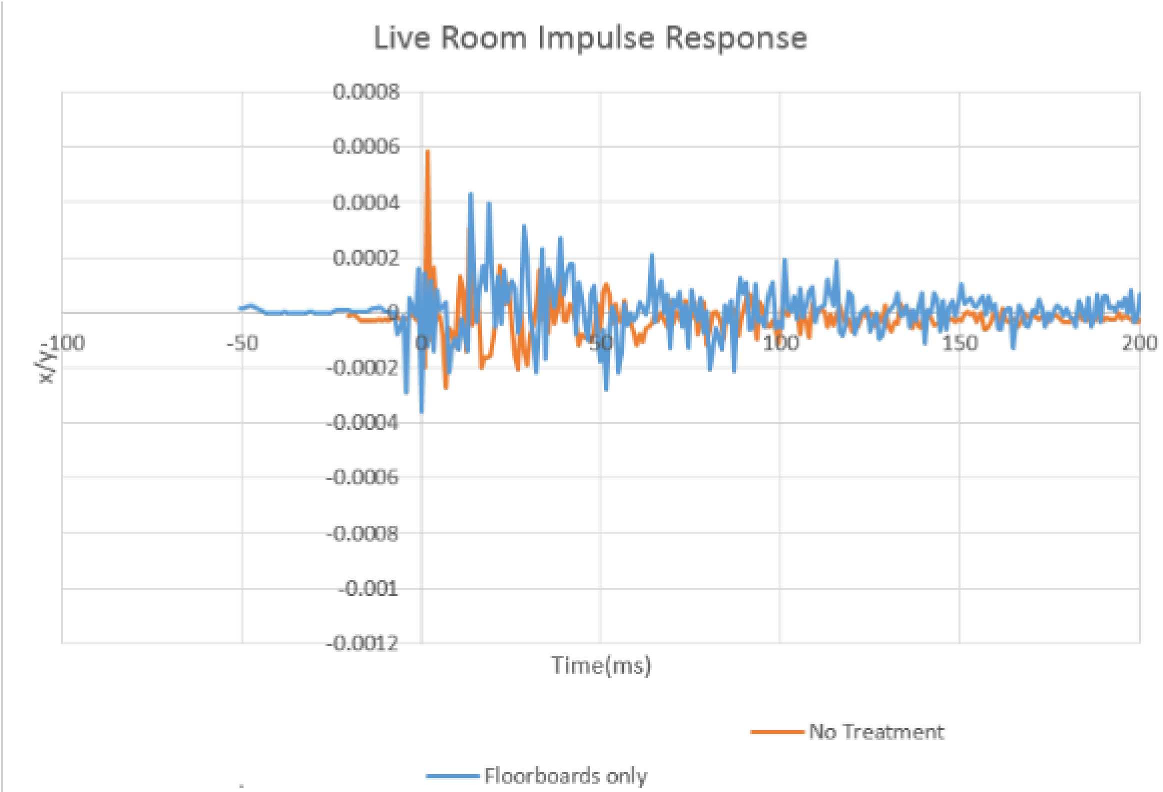


Figure appendix 3-2. Live room impulse response treated with floorboards only and untreated.

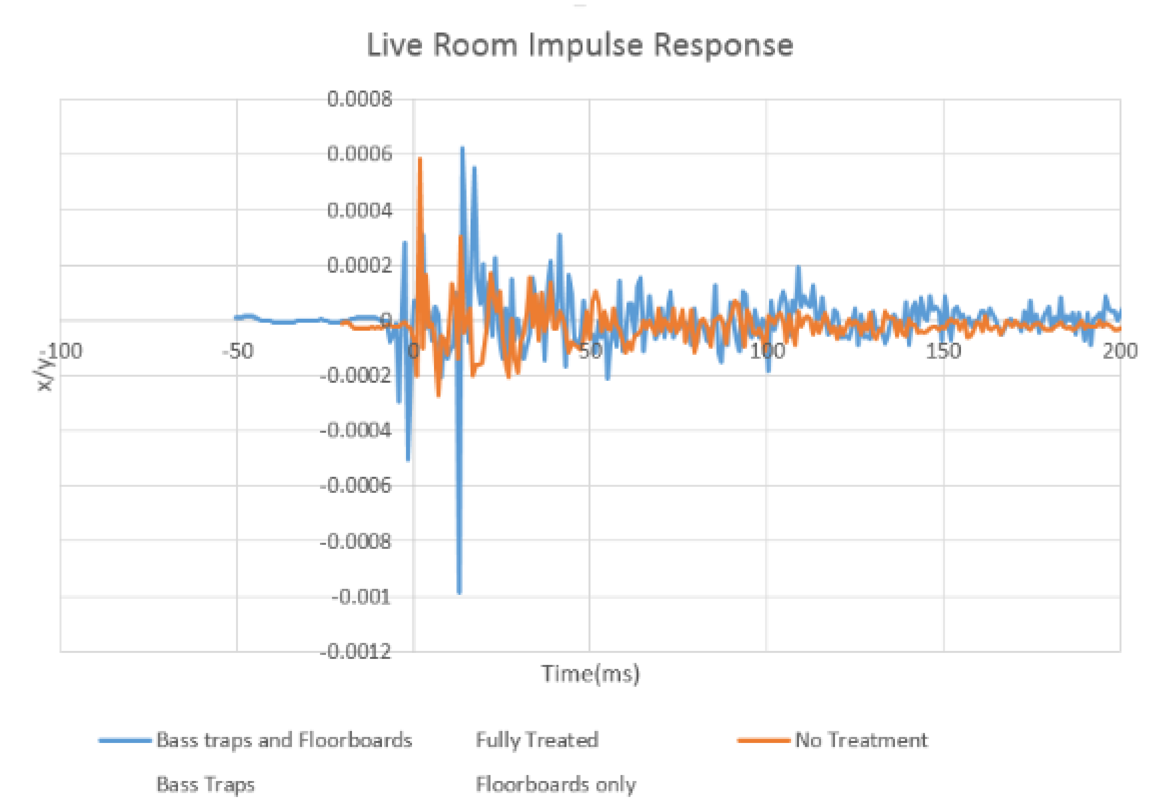


FIgure appendix 3-3. Live room impulse response with no treatment and with bass traps and floorboards but without commercial absorbers.

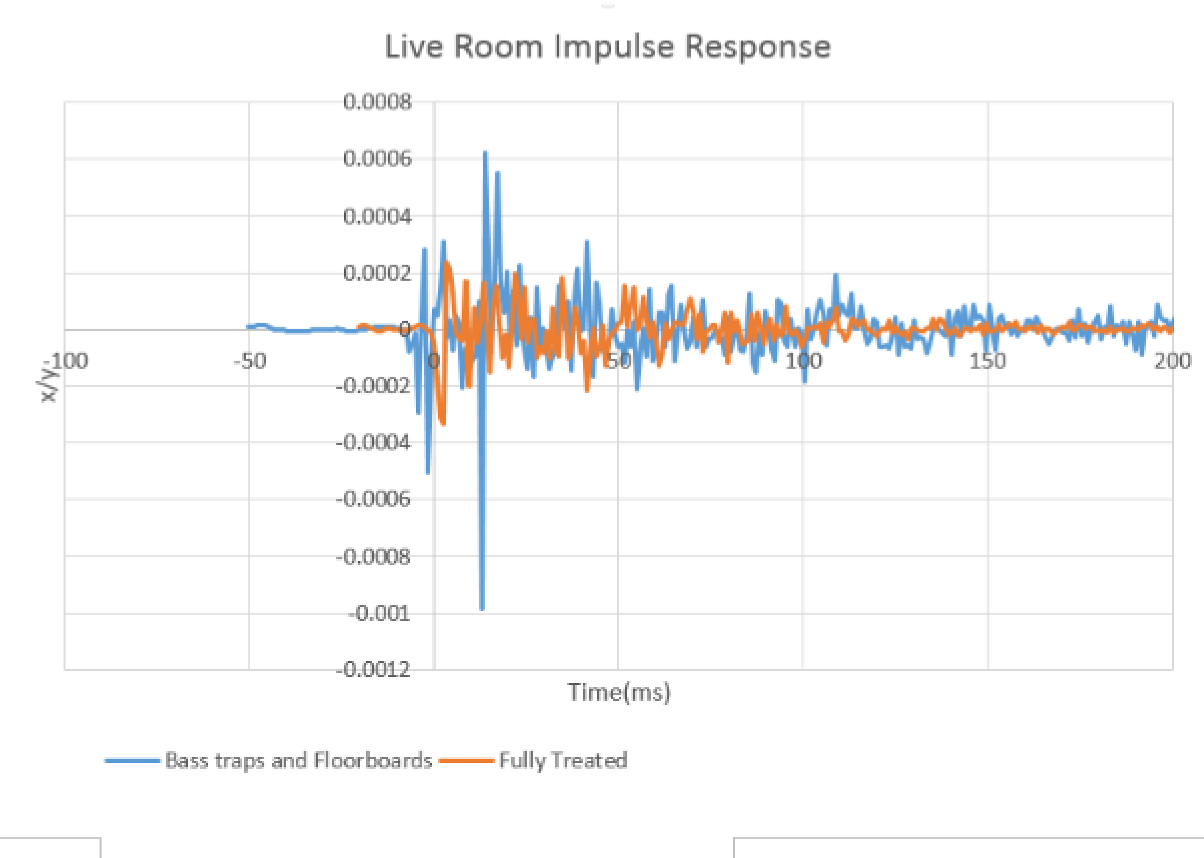


Figure appendix 3-4. Live room impulse response test treated with floorboards and bass traps and fully treated with the addition of commercial absorbers.

Appendix 4 - Glossary of Terms:

- Absorption
    - The tendency of a material to dampen sound waves. Expressed mathematically by the ratio of power lost per reflection.
- Absorption coefficient
    - In this case, the quantitative value representing the amount of sound at a certain frequency a material will capture when it is hit by that sound.
- Antinode
    - A location of constructive interference in free space which is dependent on frequency.
- Auralization
    - The computerized simulation of sound used to predict acoustic characteristics of a room
- Bass trap
    - A device that when placed in a room will capture and nullify the low frequency waves. These can be used as a method to decrease the standing waves in the bass response of a space.
- Control room
    - Room in which the engineer listens to and edits music, both during and after recording. The objective of the control room is to simulate the listener's scenario.
- Diffusion
    - A method of sound control where by the waves of certain frequency are scattered and spread out so that they never return to the listener. Related to absorption in that the sound is effectively canceled from the point of view of the listener.
- Flutter echo
    - An echo caused by two parallel reflective walls. This can be heard if one claps and the noise audibly echos repeated times as the sound bounces from one wall to the other. As a signal, it can be seen as a waveform which varies in amplitude as a damped sinusoid with time.
- Frequency response
    - The measured amplitude of a signal, either attenuated or amplified, dependent upon frequency.
- Linear or Flat response
    - a room or device in which sound of all frequencies is portrayed equally(either amplified or attenuated the same amount)
- Live room
    - Room in which artist(s) play and the sound is recorded through microphones.
- Node

    - A location of destructive interference in free space which is dependent on frequency.
- Reference microphone
    - Typically an omni-directional factory calibrated microphone. In this case omni-directional refers to a consistent gain or measured audio level in all directions around the microphone.
- Reflectivity
    - Tendency for a material to return energy after a reflection. This is typically frequency dependant and some materials will reflect at different rates based on the frequency imparted on it.
- RTA
    - Real Time Analyzer - A device capable of measuring and analyzing the audio in a room, typically by way of a reference microphone. This is then typically displayed in a measured amplitude over frequency graph.
- Room modes
    - Frequencies which resonate in a room due to it’s dimensions.
- Scattering Coefficient
    - In this case, the quantitative value representing the amount of sound at a certain frequency a material will reflect at an angle when it is hit by that sound.
- Sound Pressure Level (SPL)
    - A measure of the current air pressure taken in reference to the nominal ambient pressure of the surrounding area(gage or gauge pressure). This allows for a quantitative measurement of the loudness of a sound. Usually displayed logarithmically.
- Sound reduction index(R)
    - The attenuation of sound(in dB) passing through a barrier.
- Soundproofing
    - The act of limiting the sound transmitted in between rooms and spaces.
- Standing wave ratio
    - The ratio of the standing wave amplitude to that of the amplitude output from the source.