Lecture Hall Acoustics at the College of William & Mary

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Abstract

The desirable acoustical properties for any room are dictated by the way in which the room is intended to be used. For a room designed to be a lecture hall the most important consideration is that the lecturer can be clearly heard and understood throughout the entire seating area. This research project characterized the few large lecture halls on campus based upon that consideration by measuring their reverb time, decibel level changes within the seating area, ambient background noise, and room volume. This required the creation of a testing system that could be moved between the halls, which are scattered throughout campus. Once the measurements were taken, the rooms were given a quality ranking and if a room was found to have deficient qualities, suggestions for improvements were made. The acoustic rankings for the rooms were:

Ideal : None

Good + : Andrews 101, Morton 20

Good : Millington 150, Washington 201, Washington 301

Good - : Tyler 201

Mediocre + : McGlothlin-Street 20

Mediocre : Rogers 100

Mediocre - : Small 113, Tucker 120

Poor: Small 109, Wren Grammar School Room

1 Introduction

It has been clearly documented that an individual's learning ability is enhanced by a classroom with "ideal acoustics." The basics of classroom and lecture hall acoustics are summarized by Eggenschwiler, the Technical Committee on Speech Communication, and the Technical Committee on Architectural Acoustics of the Acoustical Society of America in Ref. [1], Ref. [3], and Ref. [5]. The experiments that are frequently used to test classroom acoustics focus on a Speech Intelligibility Index (SII) ranking system, which ranges from zero (the worst) to one (the best). A typical test for the SII is given by reading a list of prescribed words and having trained listeners scattered throughout the room see how many they can hear correctly. This method requires training for both the speaker and the listeners. The test yields a number that does not pinpoint any specific acoustical problems. For this research it will be crucial to understand how each component of the SII factors into the overall room quality so that each room can be classified by its components and improvements can be suggested for sufficiently poor components. The SII can be broken down into many components including reverb time (RT), decibel level (dB) changes throughout the seating area, ambient background noise, and the volume of the room. The dB is "the unit in which sound intensity is defined... which is the logarithm of the ratio of the sound intensity to an arbitrary intensity located below the threshold of hearing (10^{-16} watts per square centimeter)." Ref. [6] In equation form this looks like:

$$\text{dB Level } = 10\log_{10}\frac{I}{I_0} \tag{1}$$

Here I is the level of the sound and I_0 is that same sound reduced to the threshold of hearing. Since dBs are not measured in a linear fashion, an increase of 10 dB is a significant jump (an increase by a power of 10). This complicates the issue of how noise levels add together within a room. To add sounds together to obtain a new dB level, power combination is required.

$$\text{dB} \;=\; 10\log(10^{\frac{dB_1}{10}} + 10^{\frac{dB_2}{10}}) \tag{2}$$

If there is a difference of at least 10 dB, the louder signal will clearly overpower the softer signal. If a 100 dB signal is being played, then any signal below 90 dB will not have any noticeable affect on the noise level of the room. As the two levels get closer together they will combine into larger numbers. The greatest change is found when two equal in intensity signals are added together. In this situation, the resulting signal will be 3 dB louder than both of the other two signals. Creating experiments to test each component of the SII will reduce the error margin by removing the human element, which can be arbitrary at times and allow each component to be addressed in the proposed solutions.

Once the dB is defined, the RT can be defined using that unit of measure. The RT for an audio signal is defined as the time that the audio signal takes to decrease in intensity by 60 dB. The desirable level for a RT is logarithmically dependant upon the volume of the room.

The human vocal cords vary from person to person. The size and strength of the vocal cords determine what frequencies are prevalent in someone's voice and how loud he/she typically is. This variance makes it difficult to have strictly set guidelines to use when reproducing and analyzing the samples. I will be using general guidelines stated by Swenson in Ref. [8]. They show the human spoken frequency range to encompass 100 Hz to 5 kHz.

Most of the academic buildings at the College of William & Mary are well over twenty years old. Some have had renovations performed since they were built, but for the most part the classrooms have not been drastically changed in their architectural design. This means that while some of the lecture halls may have new seats or new electronic equipment, any acoustical problems in the design of the rooms are still problems. A unique feature of the campus of William & Mary is the Wren Building, the oldest academic building still in use in America. While it has burned down a few times, the rebuilding efforts have tried to keep the building architecture close to its original construction. This allows an opportunity to compare the modern classroom acoustics with the colonial classroom acoustics.

This research project has been influenced by the previous work done in Phi Beta Kappa Hall (PBK) by Yuki Ishibashi in 2003. Ishibashi's project focused on the concert acoustics of PBK. My project is unique in that the desirable acoustical properties for spoken voice are much different than those for a concert. Additionally, my project examined more data than the Ishibashi thesis. I also examined rooms as actual lecture halls, how they were designed to be used by the College, which makes the results more relevant for the College community. Providing feedback that will improve the intended usage of the rooms is a primary goal of this thesis.

2 Equipment

The first part of this project required the creation of an electronic system that could be transported easily between the lecture halls on campus. The ease of transportation and speed of set up and tear down of the system was crucial to be able to work around the busy scheduling of the lecture halls on campus. To accomplish this I wanted to utilize my laptop computer for software analysis of recordings after leaving the room, I also wanted to have a portable audio analyzer to carry around the room for quick and precise measurements. The following equipment was selected (reference names in parentheses):

- Apple Powerbook 12" - Portable laptop to record samples onto. (Laptop)
- M-Audio MobilePre USB - Digital preamp to connect a microphone signal to the laptop. (Preamp)
- 30 GB Video iPod - MP3 player to hold all of the test tones and signals that would be played through the speaker. (iPod)
- AKG C414B-ULS - Large diaphragm condenser microphone that would be used to record samples into the laptop. (AKG)
- Anchor Liberty 4500 - Powered speaker that would play the signals in the room and symbolize a human speaking. (Speaker)
- Phonic PAA2 Personal Audio Analyzer - Hand-held audio analyzer to measure dB levels in the room, check different frequency ranges, etc. (AA)
- 100' tape measure. (Tape Measure)

A typical setup of this system would have the middle speaker about head height off the floor with the iPod connected to its AUX Input. The AKG would be out in the seating area at a designated location with a long XLR cable connecting it to the preamp. The preamp connects via a USB cable to the laptop, which would be running the Audacity recording software version 1.3.3-Beta. The

AA was carried throughout the room to record various dB levels. Room dimensions were measured to a reasonable approximation ($\sim 10\ \mathrm{m}^3$) using the tape measure.

The AA has many different settings on it. It will be used to see what frequencies have a high dB level, what the overall dB levels are under various conditions, and calibrate the equipment. Since the electronics do not have the same frequency response as that of the human ear, the AA needs to be set up so that it will pick up the audio just as if it were a human ear. The AA comes with three pickup settings "Flat," "A-weighting," and "C-weighting." The C-weighting scale is outdated, but the A-weighting scale is the standard used by most audio engineers because it filters the frequencies based on how the average human being perceives them. All of this will be done under the "A-weighting" scale.

The AA contains a few different parts as well. The sound level is picked up by either the omni-directional microphone on the top, or by an XLR input on the bottom that would allow the user to check voltage levels coming through a wire. Once the sound level is picked up, it is transmitted through an electrical circuit that splits the signal into the multiple frequency components using filters. After the signal has been split up by frequency level, the user can select the weighting scale that best suits their purposes. These scaled amounts are compared with the meticulously calibrated standards the AA conforms to. The signals are then digitized and sent to the LCD that shows the various readouts for frequencies, maximum amounts, averages, etc.

The AKG comes with multiple settings as well. The calibration section covers how those settings are determined. The AKG can pick up noise from any type of cardioid or omni-directional pattern, select a 0 dB, -10 dB, or -20 dB pad on the signal, or roll off the low end noise. The pickup patterns simply refer to the area around the microphone that the microphone will pick up sound from. A cardioid pattern is a heart-shaped sphere that will pickup from all directions except one small area. An omni-directional pattern picks up audio signals from all directions around the microphone.

3 Experiments

1. **Background Noise** - The first experiment performed in each room is measuring the levels of ambient noise in the room at the designated recording points. Two measurements are recorded with the AA at each point. The first measurement is with all equipment in the room turned off except for the overhead lights. This is the baseline noise level in the room at that point symbolizing a basic lecture. The second reading is with as much equipment turned on as possible to denote the worst case scenario for a professor utilizing the classroom technology.

2. **dB Change** - The next experiment is to examine the change in dB level throughout the seating area. To do this the speaker is set up to project a constant noise/tone from the iPod in the front of the room to represent the professor's lecture. The dB level from the speaker is recorded at a point three feet away using the AA for reference. Then the dB level at various points in the room are measured using the AA and recorded to check for any major fluctuations.

3. **Reverb Time** - The most in-depth experiment required is a measurement of the reverb time. The speaker is once again set up to represent a professor. The iPod projects a constant tone/noise throughout the room. With the AKG placed at a measurement point in the room, the computer records what the AKG picks up. As the computer records the signal, the constant sound is cut off abruptly by pausing the iPod. The computer is allowed to keep recording for 10 more seconds and then the recording is stopped. This is repeated for every designated recording point in the room. The recordings are then shortened to just the period of time where the signal is falling off and that portion is processed by the computer to yield a fall off rate. The fall off rate can be used to calculate the RT.

4. **Room Volume** - The tape measure is used to measure the basic dimensions of the room to be able to estimate the room volume.

These experiments were being performed in lecture halls with varying capacities. However, I never performed the experiments with more than two or three people in the room. Experimenting under these conditions is justified because any class size can be scheduled in a room. If the attendance for a class is poor or a small class is scheduled for the room, the acoustics still need to be beneficial to the listeners. Washington 201, for example, has a few twenty person classes scheduled in it, but the room capacity is 170 people. While there will be a change in the room acoustics that is dependant upon how many people are in the room, we can reasonably say that a hall with few people in it could be a very small class and continue with the experiments. Adding more people to the room would decrease the RT a little (although never more than 0.2 seconds) but increase the background noise.

All of these experiments, besides measuring the room volume, have desired results. The background noise in each lecture hall is the acoustical property that I think will be the main problem in a lot of rooms. Ref. [3] specifically states that an empty classroom should have a background noise level at or below 35 dB. For a non-ideal room a signal-to-noise ratio of at least +10 dB is the goal according to Ref. [5]. Because dB levels are based on logarithms, instead of a linear system, 10 dB is actually a large difference in power. For a professor who talks at a 60 dB level, there should be less than 50 dB of background noise when he/she is talking. As you get further back in the room, his voice will decrease and less background noise is necessary. The dB level also needs to be fairly constant throughout the seating area. Ref. [1] states that a change of 6 dB at most in the seating area is ideal. Eiggenschwiler (Ref. [1]) states this in reference to audio systems installed within the room, but a major change with the normal voice would present the exact same issues as issues with the audio system. If the seating area has fluctuations that are very large some of the students will not be able to hear well. The goal is to have the entire seating area to hear a high, fairly constant level from the professor.

I am utilizing a graph that is presented by Eggenschwiler to determine the RTs desirable in each room. Figure 1 plots the ideal reverb time for each specific room volume in the top part and on the bottom it shows the bounds inside of which is an acceptable amount for the ratio between the measured RT and the ideal RT (RT_0). He specifies that for an unoccupied room the ideal RT value should not be exceeded by 0.2 seconds because adding people will not decrease that level more than 0.2 seconds. The lecture halls on campus will all fall onto the volume scale for the top graph. Only approximate values for the room volume will be needed since there is very little change in RT for a large change in room volume.

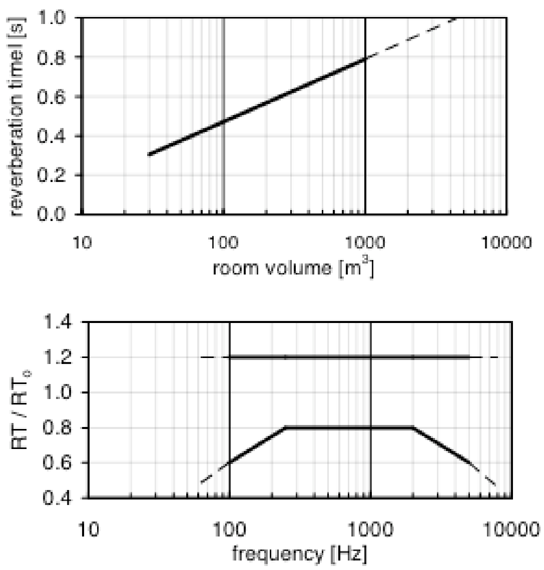

Figure 1: The top plot is the ideal reverb time plotted against the room volume. The bottom plot are the bounds placed on ratio between the experimentally determined reverb time (RT) and the ideal reverb time (RT_0). The target range is between the two lines. Taken from Ref. [1]

This means that we need to also set parameters for how far away from this is still acceptable (both above and below). Eggenschwiler also created the graph that shows the value of $\frac{RT}{RT_0}$ by frequency. The RT/RT0 value is a unitless number. On both the low end of the spectrum (below 200 Hz) and the upper end of the spectrum (above 1100 Hz) the ratio is allowed to be smaller. This indicates a smaller RT than expected which is allowed because these are more or less outside of the majority of the spectrum of the human voice. With this graph we can tell if the value that we record is within an acceptable tolerance of the optimal number. This graph takes into account the fact that the RT_0 factor keeps changing depending on the frequency, since it only checks the ratio of the two. I will rank the rooms based on how they fall on this scale.

The experiment to test the RT requires software analysis. After all of the recordings are made in room I turn to software for analysis. The software used to analyze the lecture halls initially is Audacity. Within this program there is a feature that allows the user to select a section of audio and have the computer perform a Fourier transform on the signal to obtain the frequency components. This feature is called the "Plot Spectrum" feature. While using this feature the user can select the function that is used (the default being a Hanning Window), the sample number (ranging from 128 to 16,384), the axis (linear or logarithmic), and what type of algorithm is desired (Spectrum, Autocorrelation, or Cepstrum). This feature will also allow the user to output a text file of every frequency that was computed and what the level is at that frequency. For my results I used a Hanning Window Spectrum at 2,048 samples with a linear frequency range. I selected 50 ms sections of audio and examined the frequency breakdown of them. These were exported to text files with 2048 entries in each. To whittle down the vast amount of data and be able to track specific frequency results, I turned to Jonathan Baumann with Three Planets Software to create a working program to parse all of the data. He created a website that allows me to upload all the text files for a single recording and outputs both text and excel files that contain a single frequency and all of its values over time on it. These changes over time were then opened with KaleidaGraph (version 3.6) to be able to chart them. They were plotted with a linear line of best fit and an R value. The line of best fit allowed me to compute the time it would take the signal to fall off by 60 dB. Figures 2 and 3 are two examples of the fitted data from Small 113.

On the graphs there is an "R" value associated with each line of best fit. This value is the correlation coefficient. it is calculated automatically by KaleidaGraph by dividing the covariance of the dB level and the time by the product of their standard deviations. To put it simply, it is a measure of how close to an exact linear fit the data is. The R value on figure 2 is very close to 1. This indicates a very close covariance (the variables change together) and a low standard deviation. Figure 3 shows a low R value, which indicates that the standard deviation is very high. Throughout my data collection the low frequencies typically had much worse R values than the higher frequencies. Many even showed no fall off at the very low end. This low end problem I believe is an indication of an issue that was not realized in the calibration tests. The calibration tests relied on playing back the signal through the speaker to pick up what is audibly happening in the room. This automatically decreases the low end frequencies as the speaker does not reproduce the low end frequencies very well. Since every recording I made had very significant low end noise, that appeared to never decay, I believe it may be an issue with the preamp. This will be corrected in future experiments by largely ignoring the RT of the low end frequencies. Once I had an equation

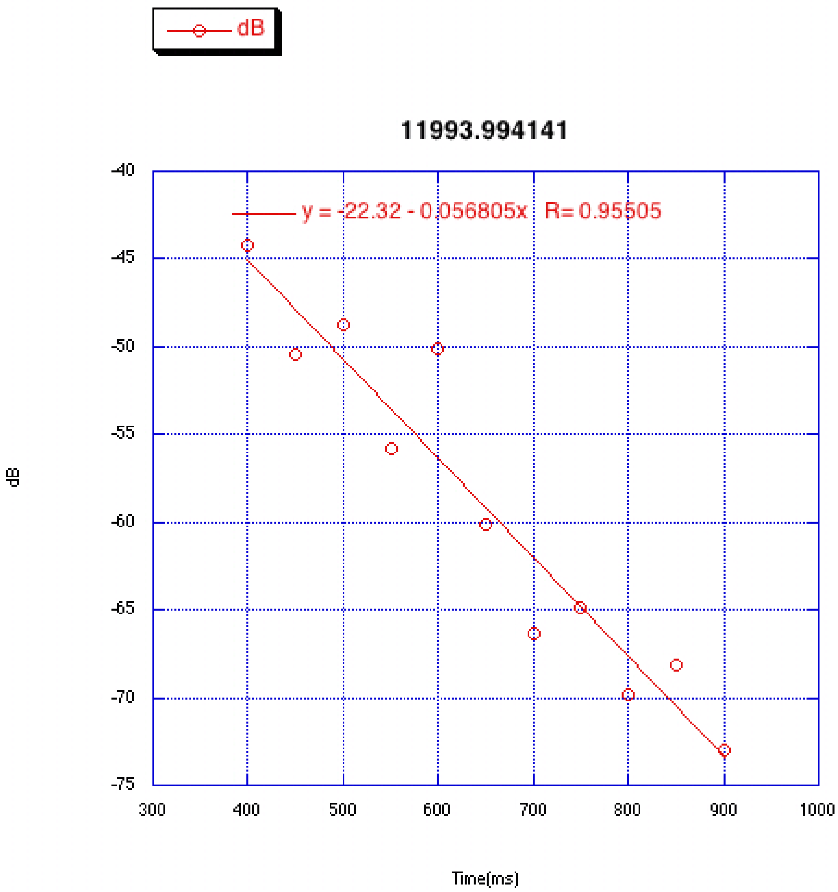

Figure 2: The plotted 12 kHz signal falloff using the data from point two in Small 113 demonstrating a good data fit. The plot is decibels vs. time in milliseconds.

of best fit I computed the time that it would take to fall off by 60 dB using:

$$\frac{-60}{\text{slope}} \times \frac{1}{1000} = T \qquad \frac{-60\ dB}{\text{dB/ms}} \times \frac{1\ \text{s}}{1000\ \text{ms}} = \text{seconds} \tag{3}$$

T is the time in seconds that the signal would take to fall off by 60 dB. The slope is the drop in dB over 1 ms intervals, so dividing by a factor of 1000 is crucial to obtain an answer in the right range.

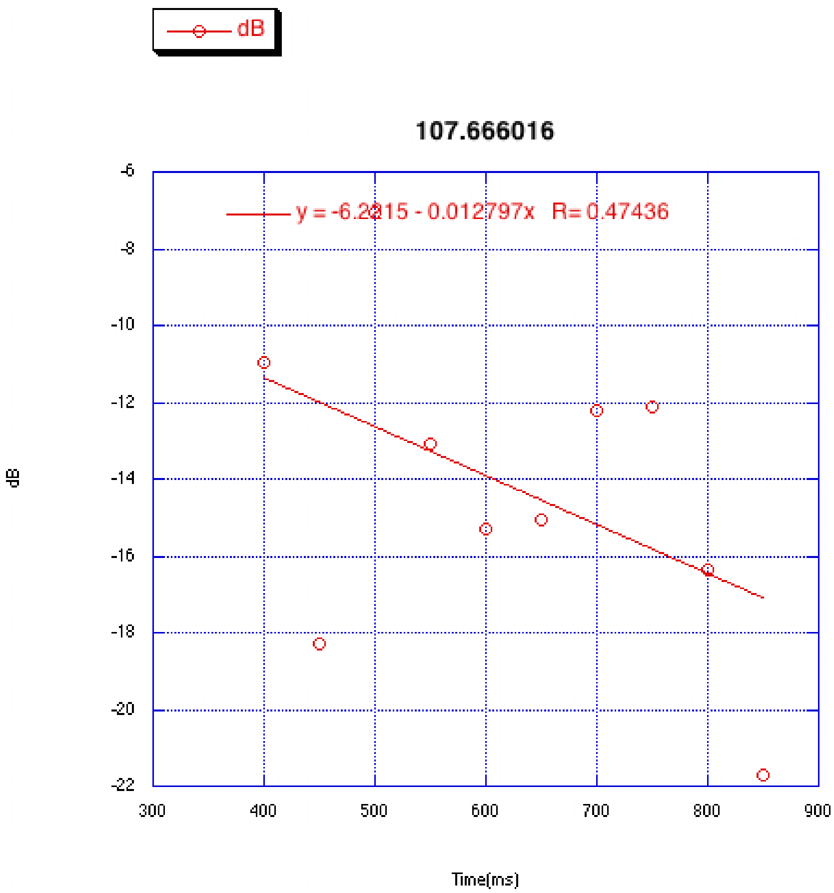

Figure 3: The plotted 100 Hz signal falloff using the data from point two in Small 113 demonstrating a poor data fit due to poor background noise. The plot is decibels vs. time in milliseconds.

4 Calibrating Equipment

Since I am working with these different pieces of equipment it is important that I know their responses to different frequencies and levels. If the equipment cannot reproduce any usable audio levels or record the samples with a high level of accuracy then there is no point in using it. In September 2007, I used room number four in the Swem Media Center as an isolated environment to calibrate the equipment in. The goal was to piece together the system adding one component at a time so that I could have an understanding of how they perform. To do this I utilized the EQ setting feature of the AA. In this mode the AA outputs a pink noise signal (which is just a white noise signal adjusted so that all frequencies are perceived at the same level) to a speaker and then reads back from its built in mic what it picks up in the room in the 20 Hz to 20 kHz range. The AA will then provide a digital readout of the changes to and external equalizer for each third of an octave on the spectrum. I first hooked the AA straight up to the speaker and read back the result. Then I fed it straight into the preamp on the computer, recorded that and then played it back on the same speaker. Finally I recorded into the computer via the AKG mic and the preamp, and played it all back on the speaker. Since I know every stage of that, I am able to figure out the final frequency responses for the system and can approximate each component's responses.

The proceeding table shows all the measurements for the various stages involved. These measurements are all in dB levels that you would use to set an external equalizer. A positive value indicates a need to boost the specific frequency, and a negative value indicates a need to cut the frequency to get all the levels to be perceived to evenly. Normally these measurements would be taken in the middle of concert venue and would include the room noise as well. For my needs I want to characterize just the equipment, so I was in a small sound isolated room. This means that any results should be mainly from the equipment. From the very first stage (i.e. just the speaker) we see very poor reproduction at the low and high ends of the frequency spectrum. Anything below 100 Hz and above 12.5 kHz needs a maximum boost. This indicates a problem with the speaker to handle those frequencies. The Anchor speaker is designed to provide amplification for human voice. The speaker does not have a subwoofer or large tweeter that would be found on a musically inclined speaker. The rest of the data shows that once the AKG is finally added to the mix there is still the fundamental lower issues, but the rest of the vocal range is very much intact. With these different levels being recorded, and without an external equalizer, it is important to keep this in mind when processing the data. If we deal with the individual frequencies then we will not need to worry about the relative levels between frequencies. Thus a slightly lower frequency would yield data that is just as usable as a high level frequency.

These values can be represented graphically in a way that is much easier to read. Figures 5 through 9 show each step in the process that I used broken down by the same designations that I used in table 1. From these plots it is clear that the low and high end are issues with the speaker since they are pervasive throughout and that is the only component in need of calibrating that was in every test. This is likely due to the size of the speaker not being adequate to fully reproduce the lower or higher frequencies.

Hz	dB 1	dB 2	dB 3	dB 4	dB 5
20	20	20	20	20	20
25	20	20	20	20	20
31.5	20	20	20	20	20
40	20	20	20	20	20
50	20	20	20	20	20
63	20	20	20	20	20
80	20	20	20	20	20
100	13.1	16.9	16.4	12.8	14.7
125	6.6	7.7	8.4	5.4	3.9
160	3.7	3.8	4.6	-3.9	-1.1
200	2.1	.3	.4	-1.5	-2.9
250	2.2	1.7	1.9	1.4	-1
315	2.8	1.3		2.6	4.5
400	4.2	2.7	1	.5	-2.4
500	4.4	4.5	1.2	5.3	5.4
630	2	2.1	-2.5	3.5	5.2
800	.8	3.1	-1.3	6.1	5.8
1,000	1.8	5.5	-1.2	12.6	8.1
1,250	1.8	6.2	-2.7	9	2.1
1,600	-4.8	-4.5	-4	.6	-1.2
2,000	-9.6	-9.8	-5	-12	-8.9
2,500	-10.8	-12.6	-6.2	-13.7	-11
3,150	-8	-11.2	-5.4	-10.3	-6.5
4,000		-13	-7.9	-13.4	-12.9
5,000	-2.3	-5	-1.5	-5	-1.8
6,300	.5	-1.9	2.5	4.1	4.8
8,000	2.3	.2	6.7	5.3	8
10,000	4	1.2	7.2	10.4	1
12,500	8.1	6.9	12	12.9	14.6
16,000	20	20	20	20	20
20,000	20	20	20	20	20

Table 1: Table of EQ settings for each preliminary calibration test (dB 1 - 5) showing the amount of boost or cut needed to equalize the signal at 31 distinct frequencies.
dB 1 = Just the speaker with Bass at 3:00 and Treble at 12:00 (actually my second attempt).
dB 2 = Just the speaker with both Bass and Treble at 12:00 (first attempt)
dB 3 = Pink Noise straight into computer and played back through speaker (3:00/12:00)
dB 4 = Pink Noise recorded in with AKG with normal settings
dB 5 = Pink Noise recorded in with AKG at -10 dB

Figure 4: dB1

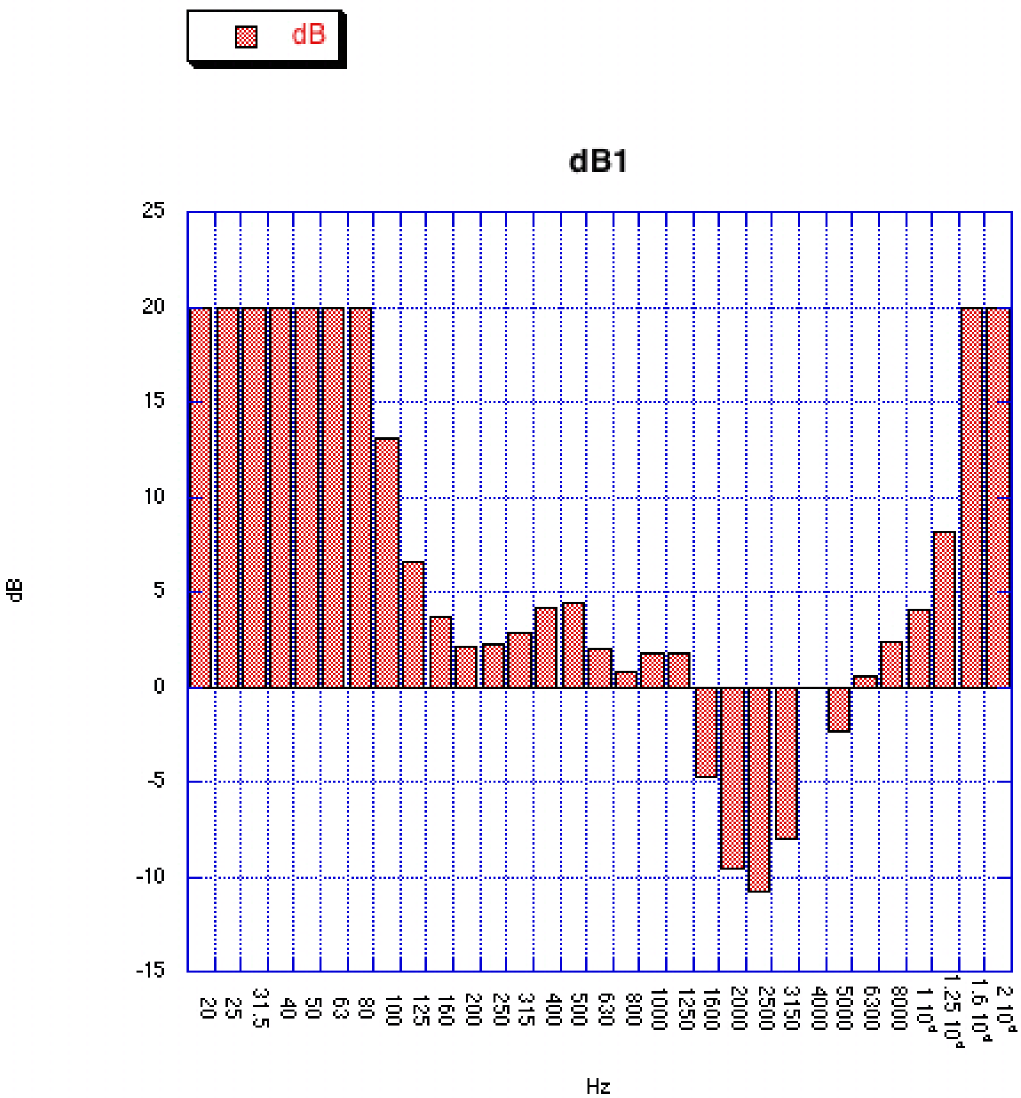

Figure 5: Graphical representation of the boost or cut amount for each frequency during the calibration test using just the speaker with boosted bass response.

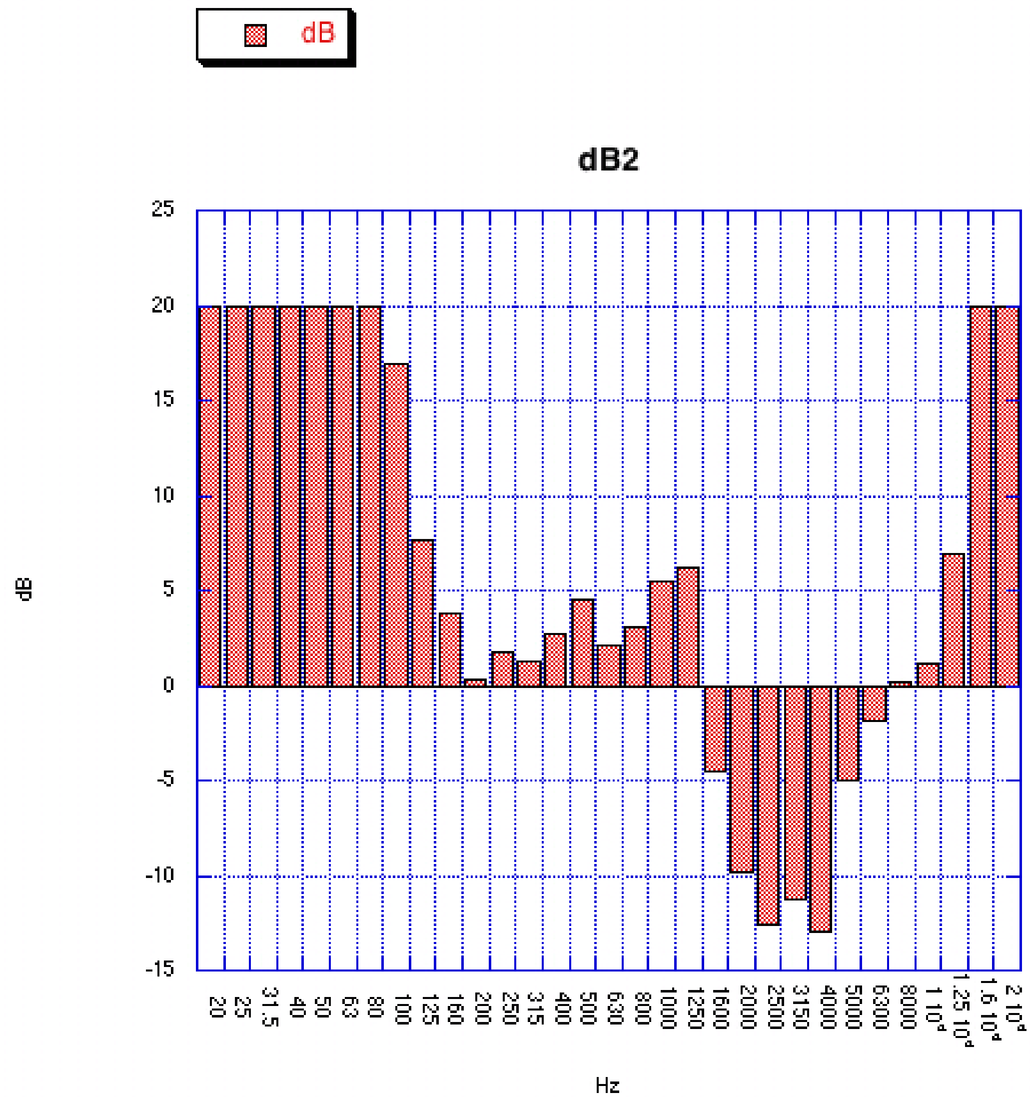

Figure 6: Graphical representation of the boost or cut amount for each frequency during the calibration test using just the speaker with standard response.

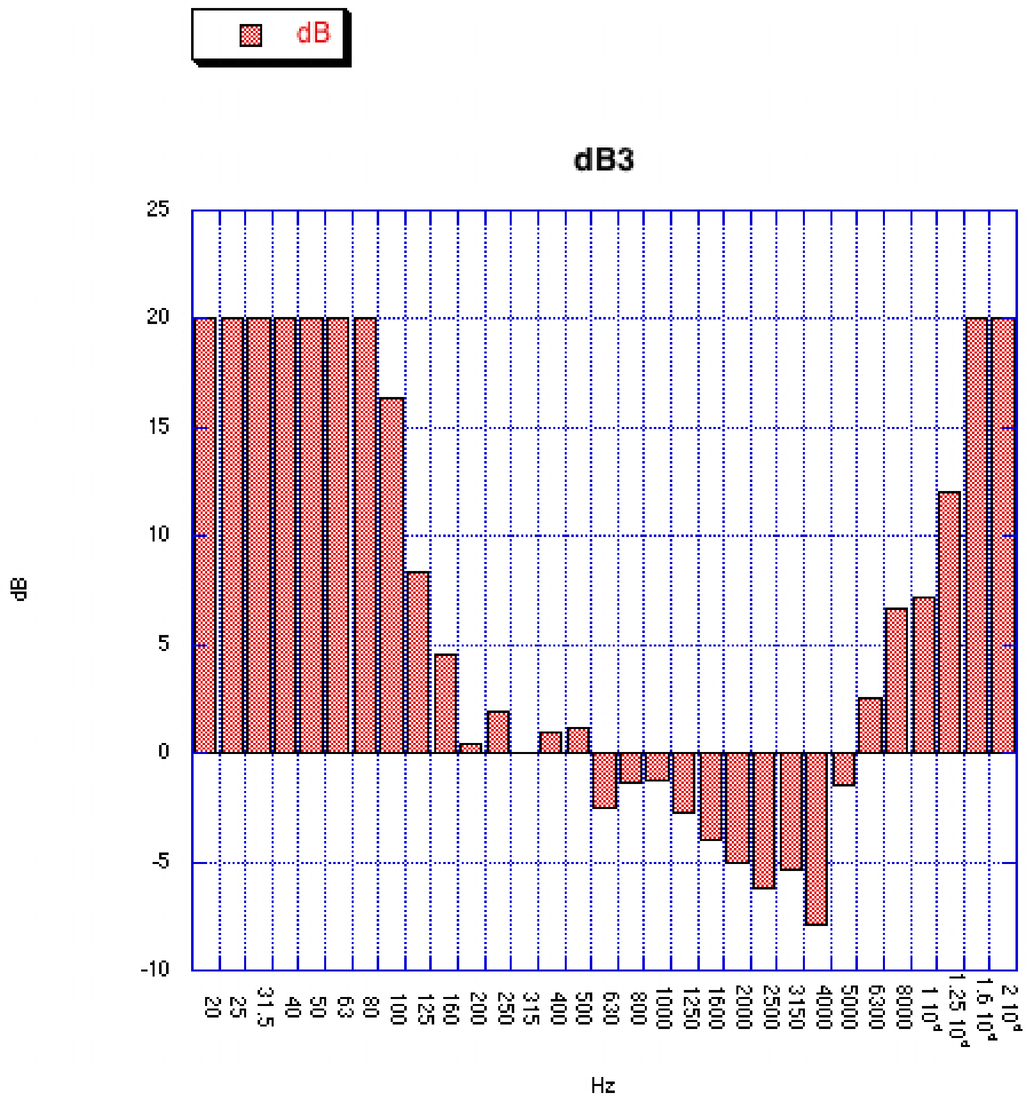

Figure 7: Graphical representation of the boost or cut amount for each frequency during the calibration test using the computer to play back pink noise with boosted bass response.

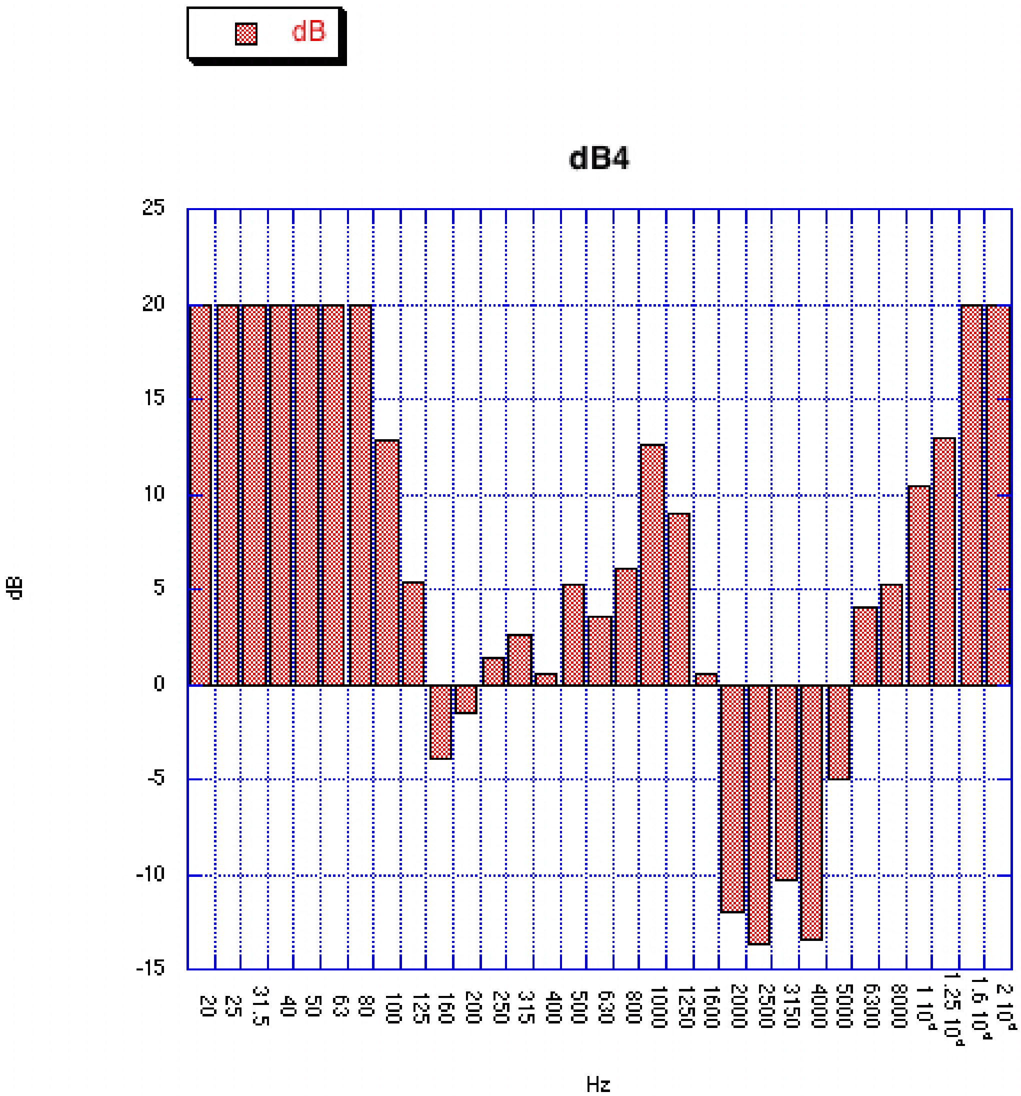

Figure 8: Graphical representation of the boost or cut amount for each frequency during the calibration test using the computer to play back pink noise recorded with a normal AKG with boosted speaker bass response.

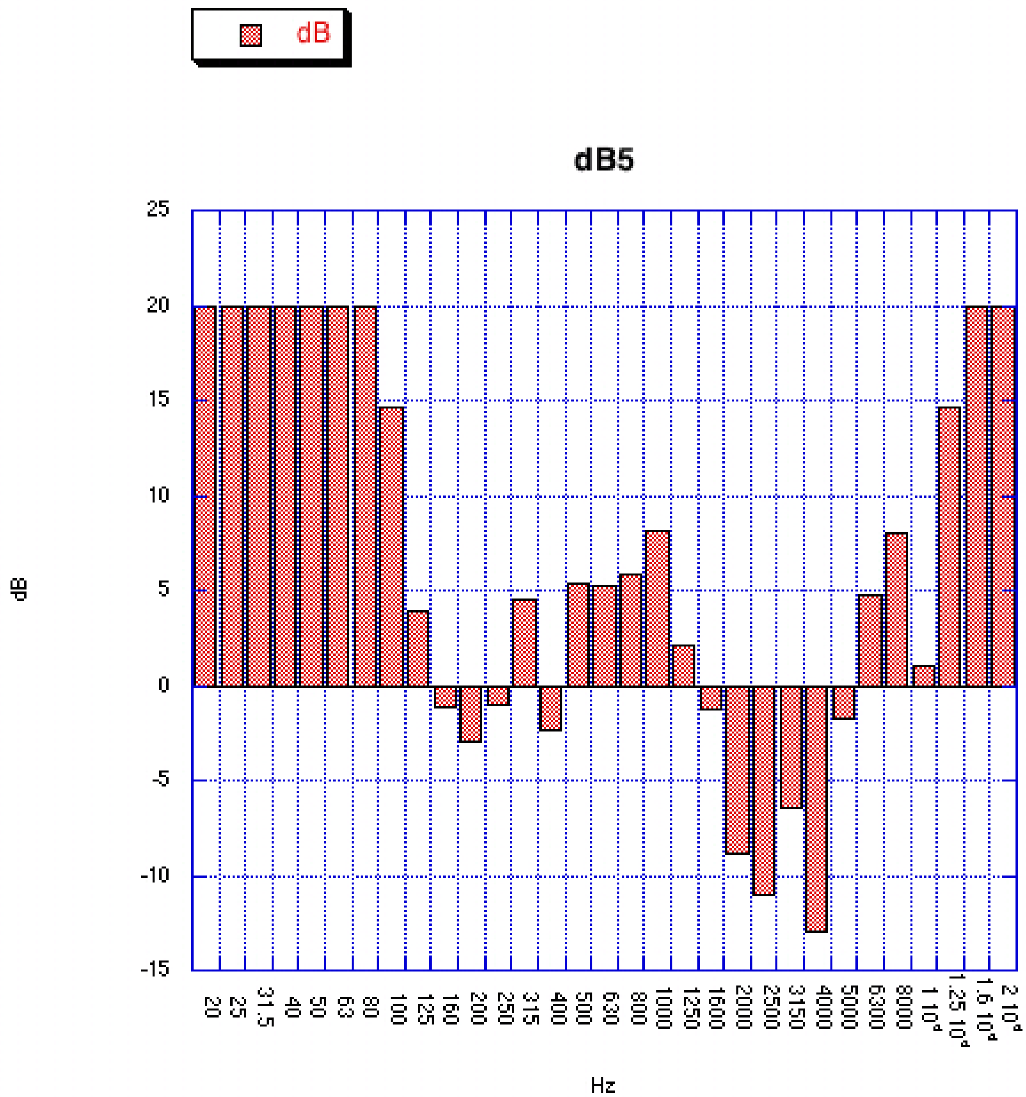

Figure 9: Graphical representation of the boost or cut amount for each frequency during the calibration test using the computer to play back pink noise recorded with a -10 dB AKG with boosted speaker bass response.

Another major concern was whether I could create useful tones that would not introduce extraneous noise to the experiment. I created a few test tones within Audacity to make sure that if I wanted a 1 kHz test tone I could create it cleanly, and also that I could record it. I created a 500 Hz tone with Audacity and played it back on the iPod. As I played it back I recorded it with the AKG set at −10 dB since the room was so small. I also created and played back a pink noise tone. For comparison I recorded just the room noise and kept the pure pink noise tone. All of these were then checked with the plot spectrum feature in Audacity. The results are what you can see in figures 10 through 13.

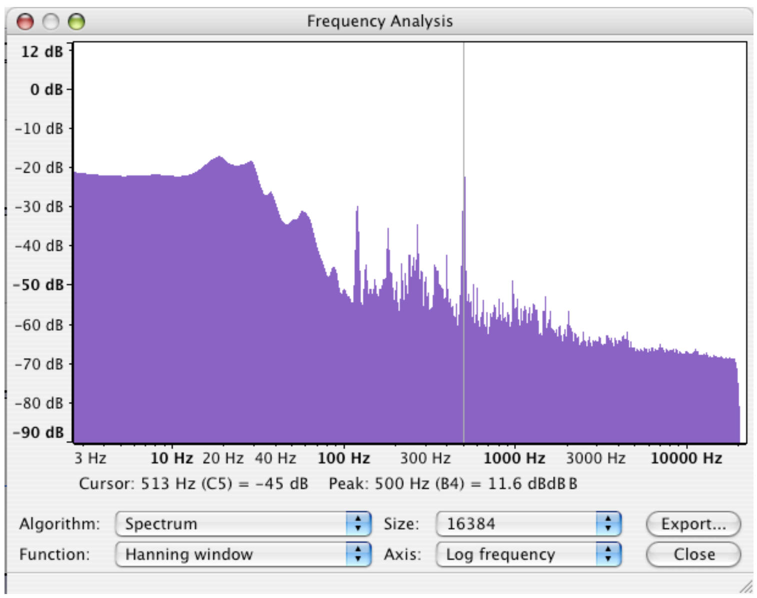

Figure 10: Frequency Spectrum for a pure 500 Hz tone recorded with an AKG broadcast by the speaker showing a peak at 500 Hz.

Figure 10 has a peak approximately at 500 Hz. If you compare it to the 11 you can see that no other noise is added except 500 Hz. It is a very clean signal since it registers about 30 dB above the room noise. This indicates that using Audacity to create the tones and the iPod to play them back will add very little extraneous noise. The pink noise before being played back appears to be a fairly constant level throughout the audible spectrum. There is a little fall off which is expected of pink noise so that every frequency can be heard at an even level, some of the upper frequencies are pulled back slightly. When the pink noise is played and recorded in the room, there are two very distinct dips in the sample. Just below 100 Hz has a linear fall off in the pure pink noise

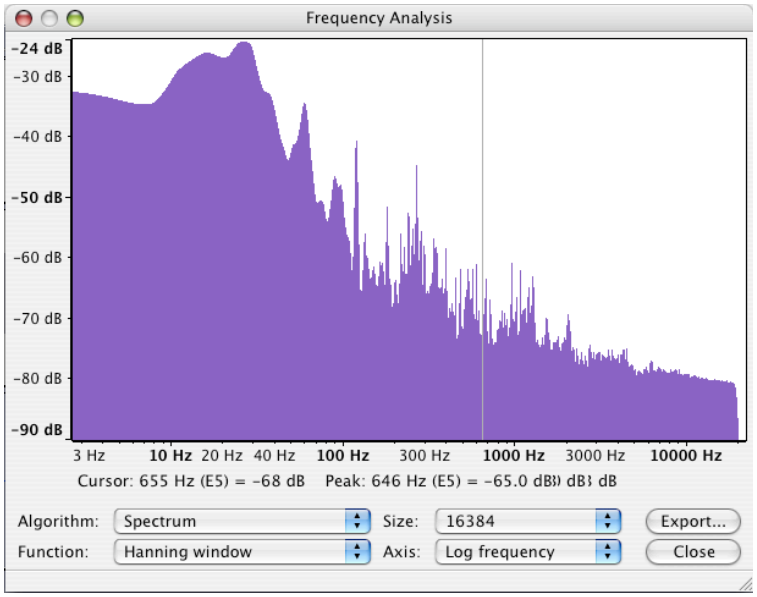

Figure 11: Frequency Spectrum for a recording of the room noise in Swem Studio 4 recorded with the AKG.

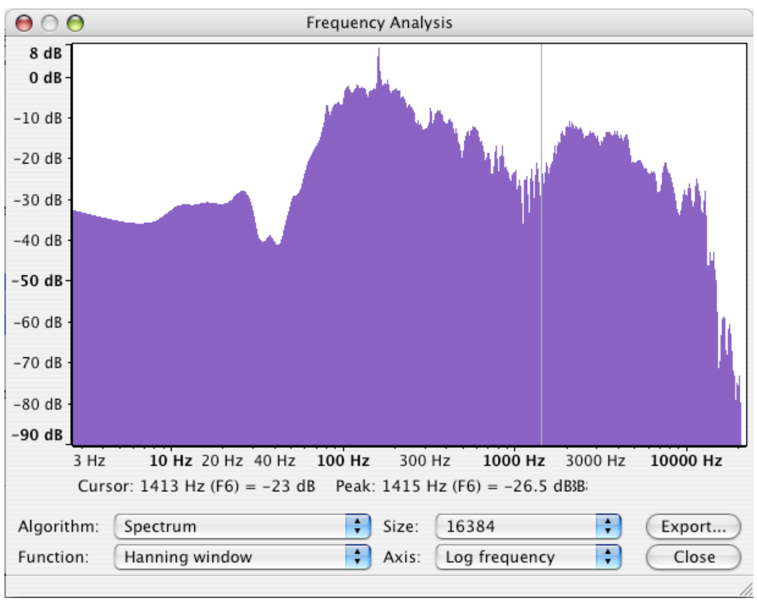

Figure 12: Frequency Spectrum for a recording of the pink noise in Swem Studio 4 recorded with the AKG and broadcast by the speaker.

plot, but has a much steeper drop in the recording. This is due to what we already know, that the speaker cannot reproduce the low end as well as we would like. The other dip is greatest around 1.25 kHz but exists between 500 and 1.25 kHz. We saw in the frequency analysis of the equipment that the system as a whole needs a boost within this frequency range so it is not a surprise that

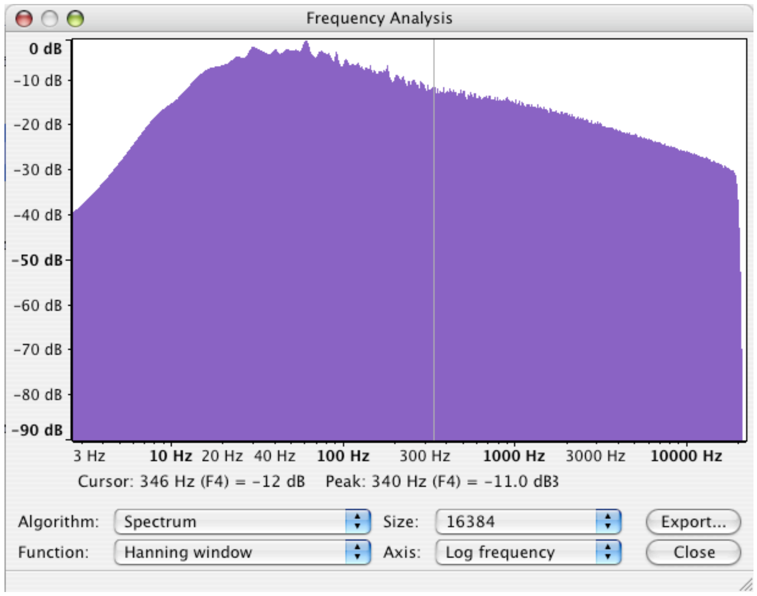

Figure 13: Frequency spectrum for the pure pink noise signal generated and and analyzed by the computer.

these would be at a lower level. The dip then would be created not because those frequencies are lacking, but because they are not quite being picked up as well or reproduced as well. This result is fine as long as we are willing to treat individual frequencies by themselves and not in relation to other frequencies which might be picked up better.

The method I will be using to check fall off slopes in Audacity (the plot spectrum function exported to the website) needs to be accurate as well. To check this I played back a 500 Hz tone in a room at a later date. I isolated the time during which the signal is decreasing, and then included 200 ms prior to the fall off. The desired result is a flat line indicating a constant 500 Hz signal, which then falls off linearly. In figure 14 it is evident that that is almost exactly what we get. There is a constant signal initially, which then decreases in a very linear fashion, even if it is not perfectly linear. The imperfections within the fall off are due to the room noise interfering with the signal and reflections off of walls boosting the signal. The 500 Hz are actually sampled and evaluated as 495.263672 Hz because of the sample size being used (2046 samples). This graph proves that this method is valid for basic data gathering and analysis. The sampling size divides total frequencies into equal portions. Since I do not wish to have to write out the long exact frequencies each time, I will be abbreviating them. The frequencies that I used, and their approximations for ease of writing and reading are shown in table 2. The chosen frequencies are those closest to some basic frequency values found on electronic equipment.

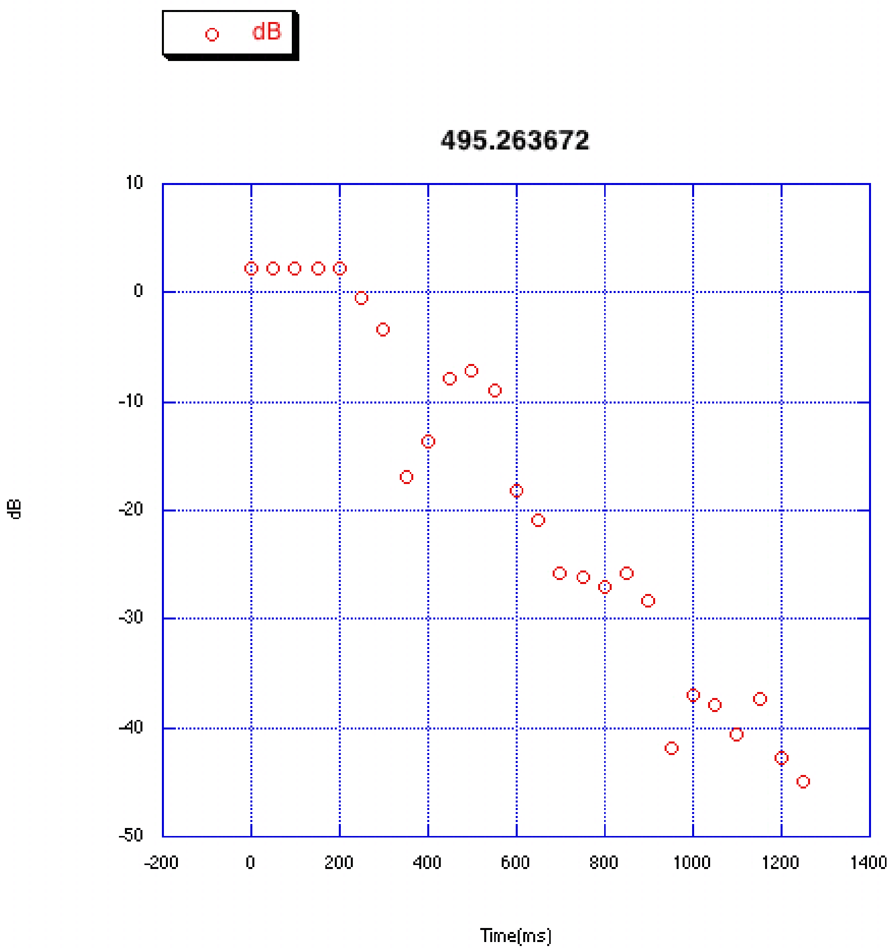

Figure 14: Graph of a 500 Hz signal showing dB vs. time in milliseconds, that was used to confirm that the FFT would show a constant level.

Actual (Hz)	Approximate (Hz)
43.066406	43
107.666016	107
495.263672	495
990.527344	990
2002.587891	2k
2993.115234	3k
4005.175781	4k
4995.703125	5k
8010.351562	8k
11993.994141	12k

Table 2: Table of the exact frequencies that were calculated by the FFT and the approximations used to simplify the writing.

5 Small 113

On October 31, 2007 I performed the experiments in Small 113 and 109, the two standard lecture halls within Small Hall. The rooms are used by many departments on campus and the Physics department is only a minor user. Small Hall has never been renovated since its creation in 1964 and the two lecture halls look very much as if they are 47 years old. Both have significant issues both aesthetically and audibly. First I will focus on Small 113 as it is the more used room of the two.

As I walked into Small 113 it was painstakingly obvious that there was a lot of ambient noise in the room. The room has a capacity of 225 people, which makes it the second largest lecture hall on campus behind Millington 150. The seating is slightly angled rows of hard plastic chairs on a hard linoleum floor. The walls and ceiling are also made of hard materials, cinderblock and plaster. I designated five points in the room to characterize it, which are listed in the next table. They were chosen to include the four corners of the seating area and the middle point, so that all of the extremes would be tested.

Point #	Location*
1	Front Left Seat.
2	Front Right Seat.
3	In between the Middle Seats in the Ninth Row.
4	Back Left Seat.
5	Back Right Seat.

Table 3: Small 113 Point Location
*All locations in reference to the professor's view.

The only equipment built into Small 113 that seemed to be able to produce significant sound levels was the LCD projector. Even so, the ambient background noise levels showed little variation after the LCD projector was turned on. The computer and other audio/visual equipment are built into the table at the front of the classroom, which both hides and severely limits the amount of noise they can produce. Only point two seemed to have any sort of noticeable increase when the projector was turned on. The rest of the values are all within .5 dB of each other, which is a barely perceptible amount. One explanation for this is that the point two data was taken before the point one data and as an LCD projector warms up it is louder while the fan gets going. This could represent a brief spike in the dB level that decreased before I made it to point one. This short lived sound has no impact on the room as a whole over the course of a lecture. The baseline average was 43.78 dB and the upper level average was 44 dB. Neither value is a good value.

Point #	Noise Before:	Noise After:
1	42.6 dB	42.9 dB
2	43.9 dB	44.7 dB
3	45.5 dB	45.1 dB
4	43.7 dB	43.6 dB
5	43.2 dB	43.7 dB

Table 4: Small 113 Background Noise

Small 113 is a very wide room with seats in angled lines terraced up to the back of the room. The rows are not curved, they are slightly angled from the middle, which puts the middle of any given row closer to the speaker's location than the seats on the aisle. In the first row it is 11' to the middle of the front row and 17' to the side of the row. This affects the experiment that looks for significant dB drops throughout a specific area that should be uniform. I could not simply walk along one row and consider it to be a "uniform" area since the dB level changes directly with a change in distance. However, since the room is so wide compared to where the speaker would stand, I decided to see how the levels changed on either side of the rows and in the middle. There is a distinct drop in the audio level as you walk to the outside of one row from the middle. The drop is larger than expected for a six foot increase in the distance from the speaker. The pink noise signal was output at 65 dB when measured 3' away from the speaker. I took measurements in the middle of the first, seventh, and sixteenth rows and recorded 56 dB, 52 dB, and 49 dB. The speaker was outputting pink noise at 65 dB three ft away from the speaker. I recorded 50 dB on both the left and right sides in both the first and seventh rows. By row sixteen, the level had dropped off to 48 dB. The edges of the first row have an issue here, the sound clearly has not simply decayed due to an increased distance from the middle of the row, although that is part of it. The middle of the seventh row, which is farther still from the speaker than the edges of the first row, is a full two dB louder. So what could be the issue? The main issue is the angle at which the seats fall away from the speaker's projection path. Much of the direct sound is taken away and a fainter signal is heard. The interesting fact is that the signal stays at 50 dB for a distance up the sides of the hall. The middle drops off as we would expect, but because the edges are getting indirect sound, they keep picking up relatively the same levels until the angle becomes shallow enough so that they are picking up mainly the direct sound. This presents an issue for the students who prefer to sit on the aisle, or who show up late and end up on the aisle. These students will get a lower sound level than those who sit in the middle if the professor lectures facing straight ahead.

Row #	Left*	Middle	Right
1	50 dB	56 dB	50 dB
7	50 dB	52 dB	50 dB
16	48 dB	49 dB	48 dB

Table 5: Small 113 dB Level Changes
*Positions relative to the professor's point of view

I then performed the first real run of the RT experiments. The speaker was set up 4' 7" from the back wall, centered behind the front counter. It was 4' 7" off the ground. The computed times for Small 113 are listed in the next table. Examining this data shows some large RTs. If we ignore the values above 8 kHz and below 495 Hz, the values which seem to have problems with the background noise, then the average RT for the room would be 1.439 seconds. This value is calculated by first getting the average reverb time for each point, and then averaging all of those together. The low and high values are omitted because these are either unnaturally high values or the signals are too low to have an effective drop off. The volume of Small 113 is approximately 955 m^3. According to the previously cited graph, we are looking for an RT value around 0.8 seconds. The computed average is 0.639 seconds above that number. To put this in terms of an RT/RT_0 we get 1.8, which is well above the scale that we want.

From this data Small 113 clearly has a poor background noise level, fairly standard dB levels throughout the seating area, and a high RT. Small 113 has a background noise level only about 10 dB above the desired background noise ideal level. If that is taken into account, along with the fact that someone speaking at 63 dB up front is percieved at 49 dB in the back row, shows only 5

Frequency (Hz)	Point 1	Point 2	Point 3	Point 4	Point 5
43	6.0883	N.S.F.*	N.S.F.	N.S.F.	N.S.F.
107	2.6193	4.6886	N.S.F.	N.S.F.	N.S.F.
495	2.6197	2.6001	1.226	2.0918	1.2670
990	1.1614	2.1973	1.3351	1.8800	1.3528
2k	1.2252	0.9245	1.3259	3.5394	0.9798
3k	1.2301	1.1295	0.8219	2.1297	0.8727
4k	1.2304	1.5499	0.8840	1.9593	0.7250
5k	0.9316	1.5260	0.9902	1.5628	1.3795
8k	1.0042	0.8779	0.7924	2.0919	0.9640
12k	1.3110	1.0563	1.4956	2.1715	1.3989
AVG†	1.344	1.544	1.054	2.179	1.077

Table 6: Small 113 Reverb Times
*N.S.F. - No Significant Fall off in signal.
† - AVG computed with 495 Hz - 8 kHz levels only.

dB of difference between the audio signal and the background noise. This will easily muddle the speech for anyone not in the front half of the room. The acceptable component of the room is that the seating area is fairly standard in dB levels. Ref. [1] calls for a dB change of 6 dB or less in any part of the seating area. Small 113 has a 6 dB change in any comparable seating location. The last factor of a high RT further garbles the intelligibility of the professor who is trying to lecture. As the sound reverberates within the room it mixes with the other sounds.

Unfortunately the dB change in the seating area is not a very major component to the overall quality of the room. To fix these two issues there are a few basic changes that could be made. Carpeting of some kind on the stairs would help the RT a little, as would cloth backed seats or seats with a cloth cushion on them. The air handling system is quite noisy in the room. There are a few large vents in the ceiling that produce low end noise and general degradation of the audibility of someone down front. Since they are spread out throughout the room and there is only one lecturer, their noise is constant whereas the lecturer's voice level falls off. These loud systems are unacceptable in a classroom environment. While they may be the most efficient for a large lecture hall, they certainly detract from the learning ability of the students in the room. This system should be investigated to find the differences between it and the air handling systems in lecture halls with low background noise.

6 Small 109

Small 109 was my next room visited. It is a smaller room compared to Small 113, but still has a sizable seating capacity of 95. It looks like a slightly scaled down version of 113 without an angle to the seating. The floor, seating, and wall construction materials are all the same as Small 113. The floor is at a much greater angle than 113. I selected five recording points again to characterize the seating area.

Point #	Location*
1	Front Left Seat.
2	Front Right Seat.
3	The Middle Seat in the Fifth Row.
4	Back Left Seat.
5	Back Right Seat.

Table 7: Small 109 Point Location
*All locations in reference to the professor's view.

Walking into the room I immediately noticed a loud hissing noise that sounded like dead noise from the speakers. Upon checking the small mixer located at the front of the room I found the speakers were turned up to a level that was quite high. I checked the LCD projector and found that it did not give any significant amount of background noise. I turned off the speakers and the projector to get my baseline readings. My next set of readings were with the speakers at the level I found them when I walked in (as the previous user had them that loud while lecturing) and the LCD projector turned on.

Point #	Noise Before:	Noise After:
1	46.8 dB	48.6 dB
2	46.1 dB	47.5 dB
3	48.4 dB	48.9 dB
4	47.1 dB	47.5 dB
5	46.2 dB	48.3 dB

Table 8: Small 109 Background Noise

These are horrible values for background noise. The average baseline level is 46.92 dB and the upper level average is 48.16 dB. This means that the background noise at any point in the room is within 4 dB of the low end of the human voice dB level range. Students or professors with hearing issues would have difficulty hearing and paying attention in this environment. Both the baseline and upper level average are over 10 dB above the ideal amount. Small 109 shares the same background noise issues that Small 113 had. The fact that both rooms share the showed problems that are not apparent in other rooms indicates a design flaw with the Small Hall lecture halls.

I next examined the dB level changes within the seating area. Small 109 has a much smaller seating area, so I am expecting that the dB changes will be similar to Small 113, but smaller. The data shows just this, with data being taken at the same three points in the rows as 113. The edges of the rows show little dropoff again. The middle of the rows shows a fairly standard dropoff in the noise level. The speaker was projecting at 65 dB when recorded 3' away. Since the background noise was so high, it would be hard for the sound to drop off much more than it has on the sides.

Row #	Left*	Middle	Right
1	50.5 dB	55 dB	50.5 dB
4	50 dB	52.5 dB	50 dB
8	50 dB	51 dB	50 dB

Table 9: Small 109 dB Level Changes
*Positions relative to the professor's point of view

My final experiments were to calculate the RT. The speaker was set up 5 feet from the back wall, centered behind the front table. The bottom of the speaker was 4' 8" off the ground. The recordings were processed and the following RTs were calculated. It is notable that the low end still has an issue with high levels. The NSL here indicates that the computer was not able to record a loud enough level in that frequency range. This is the opposite problem than NSF which indicates that the level never experienced decay. A probable cause of this is significant background noise within that frequency range.

The overall average reverb time for this room is 1.346 seconds. Given a room volume of approximately 414 m^3 the ideal RT for Small 109 is about 0.65 seconds. Our computed value is 0.696 seconds over this amount. The RT/RT_0 value is 2.07, a horrendous amount. This is another problem that is common between the large Small Hall lecture halls. Since Small 109 has the same issues as Small 113, the same improvements would help the room be a better acoustical environment for learning: carpeting the floor, installing upholstered chairs, investigating renovations or

Hz/Pt	1	2	3	4	5
43	NSF	NSF	NSF	NSF	NSF
107	NSF	NSF	NSF	2.398	NSF
495	1.921	1.771	2.283	2.937	3.591
990	1.387	1.104	1.303	1.925	2.232
2k	1.964	0.7546	1.086	1.749	1.77
3k	0.75	0.668	1.091	1.152	1.183
4k	0.9215	0.839	1.0326	0.739	0.808
5k	0.691	0.803	0.872	0.775	1.157
8k	0.905	0.735	0.712	1.038	1.252
12k	1.24	NSL*	1.198	1.472	2.247
AVG†	1.223	0.953	1.197	1.576	1.78

Table 10: Small 109 Reverb Times
*NSL - No Significant level in signal.
† AVG computed with all values available.

replacements to the air handling system, and adding acoustic material to the walls. Small 109 has a greater need of renovation than Small 113 since the room is smaller yet it has worse acoustics.

7 Andrews 101

Andrews 101 is one of the more recently renovated lecture halls on campus. It is a rectangular room with nicely upholstered seats, carpeted floors, a special room to house the projection equipment, and a special closet to contain the majority of the other technological equipment. There is a small stage up front that most professors lecture from. The walls are slightly angled up and down the hall to help diffuse the sound. This will stop any direct reflections from bouncing back together quickly. The seats are in 15 straight rows each containing 14 or 13 seats with a total seating capacity of 200 people. I again used 5 recording points to record audio in the corners and center of the seating area.

Point #	Location*
1	Front Left Seat.
2	Front Right Seat.
3	Between the Middle Seats in the Eighth Row.
4	Back Left Seat.
5	Back Right Seat.

Table 11: Andrews 101 Point Location
*All locations in reference to the professor's view.

Andrews 101 is a very quiet lecture hall. There are no major air handling duct vents throughout the room and the projectors, which could add some extraneous noise, are all housed in a small projector booth. The large windows that could reflect sound back into the room have heavy drapes, which absorb sound very well. These factors, plus little contact with mechanical rooms or the outside, yield an extraordinarily low background noise level. The average level is only 33.34 dB, just below that of the ideal level. The room is larger than Small 109 and almost as large as Small 113, yet the background noise level is over 10 dB quieter. The renovations and design of the room are much more acoustically sound than that of Small Hall.

I feel that it is necessary to point out that point two is the front right seat from the professor's view. In this corner there is a clock up on the wall. Andrews 101 is a quiet enough room that point two becomes the loudest point simply due to the clock on the wall. The airvents all sound quieter then the ticking noise, which bumped the background noise up to 34 dB. The room is extremely

Point #	Noise:
1	33.5 dB
2	34 dB
3	32.7 dB
4	33.1 dB
5	33.4 dB

Table 12: Andrews 101 Background Noise

uniform acoustically since it only has about a 1.3 dB change throughout the background noise levels. Because it has such a low background noise dB level, I expected that the seating area would be fairly uniform as well in the dB level change experiment. The speaker was set up 4' 8" off of the floor and 7' 10" from the back wall so that it was centered on the stage up front. When I examined the dB level changes, you can see that once I was measuring points that were similar in distance away from the speaker, starting about row seven when the side chairs received a direct signal, and the dB change is very small. The change is well within the tolerance that is desired as most small areas have a less than 6 dB change within them. The pink noise signal was broadcast at a 78 dB level when measured 3' away from the speaker.

Row # /Position*	Left	Middle	Right
1	60.5 dB	67 dB	60.5 dB
4	60.5 dB	65 dB	60.5 dB
7	60 dB	62.5 dB	60 dB
10	59 dB	60.5 dB	59 dB
13	58.5 dB	59.5 dB	58.5 dB
15	57.5 dB	58.5 dB	57.5 dB

Table 13: Andrews 101 dB level changes
* Positions relative to the professor's point of view

Because Andrews 101 appears to be one of the most recently renovated lecture halls on campus I expected a lower reverb time than the ones that I recorded in the Small lecture halls. The angled walls and ceiling, having the entire floor carpeted, and limiting the use of hard, parallel surfaces all appear to yield low reverb time results. I have dropped the results for the 43 Hz frequency for the remainder of the experiments since it never shows a valid drop off in the signal. I also wanted to try a signal that I could control better than pink noise because a pink noise tone is a varying mixture of all frequencies at an even level. If I added a pure tone that should give me a comparison. However the pink noise is still important because no human voice is composed of a single pure frequency. To this end I added a pure 500 Hz signal. The reverb times that I measured for the pure tone were very close to the 495 Hz levels from the pink noise.

Frequency/Pt #	1	2	3	4	5
107	0.717	1.125	0.980	1.009	1.077
495	0.718	0.753	0.769	0.923	1.059
990	0.936	0.511	1.148	1.007	1.013
2k	1.07	0.82	0.873	0.989	0.9
3k	0.804	0.629	0.992	0.974	0.755
4k	0.866	0.684	0.620	0.758	0.974
5k	0.766	0.747	0.527	0.611	0.98
8k	1.012	1.0457	0.647	0.926	0.871
12k	0.935	0.856	NSL‡	NSL	1.064
Tone*	0.527	0.726	0.736	0.715	0.927
AVG†	0.836	0.789	0.81	0.879	0.962

Table 14: Andrews 101 Reverb Times
*Tone - Values for the pure 500 Hz tone.
‡NSL - No Significant Level in Signal
†AVG computed with all values available.

The volume of Andrews 101 is approximately 970 m^3. This means that we want an ideal reverb time of 0.8 seconds. The average RT is 0.855 seconds, which is very close to what is desirable, even after being recorded in an empty room. The RT/RT_0 is 1.069, which is quite good for a lecture hall. The entire construction of Andrews 101 promotes a favorable reverb time.

8 McGlothlin-Street 20

In the basement of McGlothlin-Street Hall is the only real lecture hall in the building. It has a surprisingly low and long construction with four different terraced levels each containing two long tables with a bunch of movable chairs at each. The approximate seating capacity, since the room has movable chairs, is 110. The walls are all parallel and the room feels like a long box. Because the tables do not have fixed chairs, the recording points were chosen in reference to the tables only.

Recording Point	Location*
1	Far Left of the First Full Table.
2	Far Right of the First Full Table.
3	Middle of the Front Table on the Middle Tier of Tables.
4	Far Left of the Back Full Table.
5	Far Right of the Back Full Table.

Table 15: McGlothlin-Street 20 Recording Points
*All locations in reference to the professor's view.

In McGlothlin-Street 20 there are a lot of individual sets of lights. Those closest to the blackboards emit a buzz that is significant. Behind the main blackboards that are centered in the middle of the front wall, which are also motorized, there is an old rear projection screen leading into an office behind the wall. This room is also a source of background noise. To top it all off, the LCD projector creates its own level of audible background noise. To get my baseline reading, I turned the LCD projector and noisy lights off, and moved the blackboards to block the back screen. The baseline levels show an average of 41.9 dB. The higher levels average out to 44.9 dB. The upside of these numbers is that there is not a very large difference between the baseline and higher levels (only 3 dB).

Since the level of background noise is now known, I next measured how much the professor's voice will fall off from the front of the room. I checked the dB level changes in the room as before. The speaker was set up centered along the front wall 4' 6" from the wall and 4' 8" off the ground. The level that the pink noise was projected at was 76.2 dB 3' away from the speaker. As the following table shows, the seating area is very uniform. There is only a 4 dB change between the three terrace levels. However, the sound level drops off by about 13 dB in the middle of the back

Pt #	Baseline*	After
1	43.4 dB	46.4 dB
2	40.2 dB	45.3 dB
3	40.5 dB	44.2 dB
4	43.3 dB	45.3 dB
5	42.1 dB	43.3 dB

Table 16: McGlothlin-Street 20 Room Noise
*Before and after refers to when the data was taken in relation to the noisy lights and LCD Projector being turned on, as well as the blackboards being moved out of the way.

terrace. So if a professor talks at a 65 dB level, he/she would be heard at a level of 52 dB. The background noise averages to about 45 dB in the same location, showing a signal to noise ratio of less than 10 dB.

Terrace/Position*	Left	Middle	Right
1	64 dB	66.5 dB	64 dB
2	63 dB	65.5 dB	63 dB
3	62.5 dB	63 dB	62.5 dB

Table 17: McGlothlin-Street 20 dB Level Changes
* Position refers to the professor's point of view.
The pink noise was projected at 76.2 dB when recorded 3' away from the speaker.

The last test that I performed was the RT test. McGlothlin-Street 20 is a very simple room. It has no major ornaments that are designed to diffuse the sound. Due to the hard flat surfaces, I expected a higher RT. This would be due to the sound bouncing around more, instead of being absorbed quickly by the materials that the room was built with. The overall average RT for the room was 1.02 seconds. With a room volume of approximately 463 m^3 the desired RT is around 0.7 seconds. McGlothlin-Street 20 is over that number by 0.32 seconds. If we examine the RT/RT_0 value, we see that it is 1.46, which is clearly over the limit of 1.2.

McGlothlin-Street 20 is a mediocre room at best. The poor reverb time and background noise counter the ideal dB level change in the seating area. Since the room already has some carpeting, we will leave that potential improvement alone. Hanging some absorbent acoustic material on the walls or adding seats that are upholstered would decrease the reverb time. The construction materials made the room look nice, but were far from the ideal materials to promote an acoustically ideal learning environment. The background noise has multiple sources in this room. Having a noisy

Hz/Pt #	1	2	3	4	5
495	1.935	1.623	3.251	NSD*	1.061
990	0.744	1.038	1.374	NSD	1.187
2k	1.141	1.219	0.765	0.951	0.931
3k	1.102	0.824	0.834	1.111	1.064
4k	0.904	1.341	0.623	1.368	0.857
5k	0.859	0.883	0.904	0.853	0.899
8k	1.126	0.904	0.597	0.931	0.45
12k	NSL†	NSL	0.65	0.935	NSL
Tone‡	0.551	1.373	1.112	1.085	1.071
AVG⋆	1.046	1.212	1.123	1.032	0.94

Table 18: McGlothlin-Street 20 Reverb Times
* NSD - No Significant Drop in the signal.
† NSL - No Significant Level in the signal.
‡ Pure 500 Hz tone.
⋆ Avg computed with all available data.

set of lights is the easiest part to fix. The front set of lights should be looked at by an electrician to find the source of the buzz. This can be eliminated fairly quickly. Since the projector room is no longer used as a projector room, insulation could be added behind the movable chalkboards to help reduce the noise that bleeds through from that room. The final thing, as usual, would be to investigate the air handling system in the room to see if a quieter system is possible.

9 Reverb Time Math

Because McGlothlin-Street 20 has such a standard shape, it makes it the perfect candidate for presenting the math behind calculating a reverb time. The basics of the equation for RT is found in The Science of Sound Ref. [4]. Once the sound source has produced a signal, that noise bounces around the room. As long as the sound does not hit anything, it falls off at a rate of 6 dB each time the distance doubles. When the noise hits a surface, part of the signal is absorbed, while part is reflected. Since the RT is the amount of time that the signal takes to fall of by 60 dB, the equation needs to take into account both the volume of the room (since that determines how long the signal will be traveling as it drops off at a rate of 6 dB each time the distance is doubled) and the surface area of the walls (since that determines how much area there is to absorb the sound). It ends up being a directly proportional relationship.

$$RT = .161\frac{V}{A} \quad (V,\ \text{in m}^3;\ A \text{ in m}^2) \tag{4}$$

We need to figure out a way to relate surface areas of different materials in this equation because if the room is made out of different materials, each one will affect the sound diffusion differently. To do this we can scale each square meter or material by a factor where a factor of 1 would mean complete absorption, and a factor of 0 would mean complete reflection. These factors are determined experimentally in a controlled environment. For my purposes, I pulled them from Table 23.1 on page 466 in Ref. [4]. The relevant data that I will use, all of which is frequency dependant, is shown in the following table.

Material/Frequency	125	250	500	1k	2k	4k
Concrete Block, painted	0.10	0.05	0.06	0.07	0.09	0.08
Plaster on lath	0.14	0.10	0.06	0.05	0.04	0.03
Carpet, on concrete	0.02	0.06	0.14	0.37	0.60	0.65
Wood/Metal seats, unoccupied (m^2)	0.014	0.018	0.020	0.036	0.035	0.028
Air 20^{o}C, 30% Humidity	0	0	0	0	0.012	0.038

Table 19: Absorption Coefficients for Various Materials
Taken from The Science of Sound

The first step, since we already know the room volume, is to calculate how much surface area there is, and of which different materials. We will label each different material as A_1 through A_5. The ceiling is 40' x 50', as is the floor. This yields 186 square meters for each. The walls take a bit more math to calculate. Roughly they are: 40' x 10' + 40' x 7' + 2 x 11' x 10' + 2 x 13' x 9' + 2 x 15' x 8' + 2 x 11' x 7' = 1528 ft^2 or 142 m^2. There were approximately 100 chairs in the room as well on the day of my experiments. I could not find absorption coefficient data for the tables, so they have been left out of the equation.

$$A_1 = \text{The Ceiling} = (186)(\text{factors for plaster}) \tag{5}$$

$$A_2 = \text{The Floor} = (186)(\text{factors for carpet}) \tag{6}$$

$$A_3 = \text{The Walls} = (142)(\text{factors for concrete blocks}) \tag{7}$$

$$A_4 = \text{The Chairs} = (100)(\text{factors for chairs}) \tag{8}$$

$$A_5 = \text{The Air} = (463)(\text{factors for air}) \tag{9}$$

$$RT = 0.161 \frac{463}{A_1 + A_2 + A_3 + A_4 + A_5} \tag{10}$$

Once we take these numbers and plug in every factor from the table, we see a different RT for each frequency. Overall there is an inverse relationship between frequency and RT since the RT tends to drop as the frequency increases.

Frequency	125	250	500	1k	2k	4k
RT	1.643	1.928	1.562	.813	.529	.471

These values averaged together show an average RT for McGlothlin-Street 20 that is 1.157 seconds. The average that I calculated from my experiments was 1.02 seconds. These is a very small difference here (0.137 seconds) that could be attributed to not having the absorption coefficients for the tables. Given a perfect knowledge of the materials used in constructing a room, it is not hard to calculate the resulting RT with accuracy. However, once the rooms are no longer nice rectangles like McGlothlin-Street 20, the math can become slightly tedious.

10 Millington 150

Millington Hall is usually considered one of the worst academic buildings, acoustically and architecturally. Millington is not the eldest on "new campus" but it is still held in contempt by the students who take classes in it. Since I have heard people's views on Millington, I was prepared for a nasty acoustic environment. When I walked into the room I was surprised at how quiet the room actually was. A faint popping noise came from the air ducts, and a buzzing noise was heard coming from the clock at three minutes until the hour but otherwise the room was dead silent. Due to the size of the room, I used nine different recording points, three in each seating section. The room construction is a weird pentagram, with an enclosed projector room, and one door to the outside world. The seats are folding chairs that are upholstered on a terraced linoleum floor. The ceiling is slightly angled to dissipate sound.

Recording Point	Location*
1	Left Section, Front Left Seat
2	Middle Section, 3rd Row, 5th Seat
3	Right Section, Front Right Seat
4	Left Section, 6th Row, 4th Seat
5	Middle Section, 6th Row, Between 6th and 7th Seats
6	Right Section, 6th Row, 4th Seat
7	Left Section, Last Row, Between 6th and 7th Seats
8	Middle Section, Last Row, 9th Seat
9	Right Section, Last Row, Between 6th and 7th Seats

Table 20: Millington 150 Recording Points
*All locations in reference to the professor's view.

This room is the largest lecture hall on campus with a capacity of 290 people. After examining the horrendous background noise that plagues Small 109 and Small 113, looking at a larger lecture hall would demonstrate either a correction by the school on its design of large lecture halls, or another failure. I started with the normal background noise tests. After turning on the equipment in the room, I realized that it created no noticeable blip on the background noise test. The only noticeable issues were the air duct popping noises and the clock. In fact, the popping noises bumped up the level registering at points seven and eight by about 4 dB. Overall I was shocked to see background noise levels a full 5 to 15 dB below that of Small 109 and Small 113. This was achieved in a larger room with a less regular shape to it. These values are very good for a room of this size, and the average of 37.8 dB (including the popping in the ducts) is good by any standard.

Point	Background Noise
1	39.8 dB
2	35.9 dB
3	38.6 dB
4	37.5 dB
5	36.7 dB
6	35.7 dB
7	39.9 dB†
8	40.1 dB
9	36.2 dB

Table 21: Millington 150 Background Noise*
* No significant audio issues related to technology.
† Points 7 and 8 were picking up a maximum background noise of 36 dB without the popping in the ducts.

I then examined the dB levels throughout the room. The speaker was set up centered on the front wall 3' 2" away from the wall (just behind the front demonstration table), 5' 1" up from the ground. My comparison was a pink noise signal that was produced at a level so that it was picked up at 77 dB 3' away. I decided to use the nine recording points as my comparison points in this test because they were more uniform throughout the room than in past experiments. As usual the points in the middle have a standard falloff between them that corresponds roughly to the normal amount of halving the power every time the distance is doubled. The points on the side are still able to pick up direct sounds, and they also decay as expected. Point nine appears to be about half a dB below point seven, which would be the first time that the symmetry of a room has been broken in my experiments. However, I think that since the background noise was almost 40 dB with the popping noise at point seven, that the background noise was close enough in power level to the pink noise that they combined to show a slightly higher level. Even so, a half decibel difference is rather insignificant. Overall, the back rows might need the assistance of the built in room speakers if there is a soft spoken professor down front.

Since the lecture hall beat Small 109 and 113 in the background noise category, I was anticipating the RT tests. The room sounded rather dead when I walked in, and it also got some leeway in that it is a larger room so a longer RT is desired, so initially I expected Millington 150 to win this

Point	dB Level
1	60 dB
2	66 dB
3	60 dB
4	58 dB
5	62 dB
6	58 dB
7	56 dB
8	59 dB
9	55.5 dB

Table 22: Millington 150 dB Level Changes

category as well. The approximate room volume was just over 1000 m^3 so the target RT is 0.8 seconds. I found it hard to get usable data at the 100 Hz level and below. This was due to the background noise of the room being made up chiefly of these levels and therefore masking the RT data. Overall, some of the lowest RTs were computed for Millington 150. The longest single time was 1.338 seconds, which was about the average for Small 109. The average for Millington 150 was 0.706 seconds. Almost 0.1 seconds below the ideal level. Computing the RT/RT_0 level shows a 0.875 average. This is all well within the recommended guidelines, and also the best for a large lecture hall.

Hz / Point#	1	2	3	4	5	6	7	8	9
107	NSD*	NSD	0.732	1.338	1.336	1.163	NSD	NSD	NSD
495	1.15	1.026	1.061	1.132	0.896	0.845	0.914	0.688	0.535
990	1.005	0.794	0.964	0.683	0.849	0.875	0.812	0.594	1.537
2k	0.596	0.508	0.702	0.581	0.5	0.561	NSD	0.934	0.496
3k	0.584	0.578	0.731	0.592	0.581	0.646	0.914	0.772	0.51
4k	0.505	0.476	0.626	0.709	0.53	0.548	0.812	0.583	0.593
5k	0.56	0.411	0.645	0.631	0.625	0.667	0.372	0.664	0.554
8k	0.661	0.439	1.261	0.632	0.846	0.391	0.676	0.746	0.389
12k	NSL†	0.804	0.632	NSL	0.798	0.495	NSL	1.053	NSL
Tone‡	0.725	0.658	0.544	0.657	0.472	0.502	0.406	0.652	0.512
AVG⋆	0.723	0.633	0.79	0.773	0.743	0.671	0.637	0.743	0.641

Table 23: Millington 150 Reverb Times
* NSD - No Significant Drop in the signal.
† NSL - No Significant Level in the signal.
‡ Pure 500 Hz tone.
⋆ Avg computed with all available data.

11 Morton 20

Since Morton has the same reputation as Millington for being a horrendous building, I decided to look into a room that is also often criticized by students who have classes there, Morton 20. The room is criticized because it sounded hollow, looked dingy, and has windows to the outside world, creating a bleak environment to learn in. The school has recently attended to Morton 20 and renovated the room by adding new technology, seats, flooring, and wall panels. Now the room looks better, the floor is a rubberized material that is slightly more absorbent of sound, and the technology does not seem outdated. This room will be one of the smallest that I take data in since its capacity is only 70 people. While it is not a large lecture hall, it is a good example of the school putting effort into improving its classrooms and demonstrating some of the possible renovations. Morton 20 resembles a baseball field, with a flat front area and curved back wall. The front area has a small stage and the upholstered seats are in curved rows terraced up to the back wall in six rows. To start I designated only five recording points in the room, since it is so small.

Recording Point #	Location*
1	Front Left Seat
2	Front Right Seat
3	4th Row, Between 7th and 8th Seats
4	Back Left Seat
5	Back Right Seat

Table 24: Morton 20 Recording Points
*All locations in reference to the professor's view.

I set the speaker up on the front raised platform centered along the front wall. The speaker was 4' 2" from the wall and 4' 6" up from the floor. From this position it was only about 26' to the curved back wall. The room sounded very quiet, even with the technology turned on. The technology did in fact make a difference however. When I took the background baseline readings, the AA was barely picking up anything since it has a threshold of 30 dB. At the point in the middle of the room, the AA didn't pick up anything. Morton 20 averaged a baseline level of 31.15 dB. When the LCD Projector and the speakers were turned on, the average was bumped up to 34.44 dB, which is still an amazingly good background noise level. The electronic equipment has a larger effect in this room because it is so small. A larger room has more space for noise to fall off in before the signal hit a wall and bounced back. It is also small enough that the weak noise produced by the LCD projector fan does not die off completely before hitting a wall.

Pt #	No Technology	LCD Projector & Speakers
1	32 dB	35 dB
2	32 dB	35 dB
3	Below 30 dB	35.3 dB
4	30.6 dB	33.3 dB
5	30 dB	33.6 dB

Table 25: Morton 20 Background Noise

I did not do any dB level change tests in Morton 20 because of the size of the room. I want to see what effect the renovation have on the RT and background noise, the dB level changes will be negligible and also unaffected by the renovations. I set about with the RT tests and the resulting data has a few interesting points to it. I added an extra AVG column to the data table to show the average RT for each frequency, since this room shows the reverse relationship then what we expect. Usually the lower frequencies have the higher reverb times (which is only true here for the 107 Hz level). The rest of the frequencies tend to increase in RT as they go higher.

Hz / Point #	1	2	3	4	5	AVG
107	0.467	NSD*	1.246	1.201	1.095	1.002
495	0.46	0.428	0.572	0.839	0.616	0.583
990	0.657	0.399	0.47	0.525	0.701	0.55
2k	0.616	0.557	0.472	0.499	0.567	0.542
3k	0.59	0.754	0.751	0.799	0.598	0.698
4k	0.721	0.541	0.572	0.856	0.52	0.642
5k	1.094	0.654	0.631	0.903	0.601	0.777
8k	0.74	0.584	0.701	0.778	0.514	0.664
12k	NSL†	0.729	0.853	0.72	0.835	0.784
Pure 500 Hz	0.5	0.38	0.469	0.535	0.559	0.4887
AVG‡	0.649	0.559	0.674	0.766	0.661	0.662

Table 26: Morton 20 Reverb Times
* NSD - The signal never fell off.
† NSL - There was never a high enough level to obtain data.
‡ AVG - computed with all available data.

Morton 20 has an approximate volume of 226 m^3, so the desired RT is about 0.58 seconds. The computed RT is 0.662 seconds, which is quite close to the desired level. It is well within the 0.2 seconds for an unoccupied hall, and the RT/RT_0 number is 1.13, also within the requisite limits. Along with the floor plans for Morton 20, I found the renovation plans for the room as well. The sound deadening panels on the wall, the upholstered seats, acoustical paneling on the ceiling, and the rubberized flooring material are all improvements that helped to drop the RT from where it was before when the room had hard plastic seats, a hard linoleum floor, and solid cinderblock walls without any adornments. All of these are improvements that can be made in other rooms to help with the RT. The new equipment helped with the background noise levels.

12 Rogers 100

Rogers Hall was built seven years after Millington, but is still due for a major overhaul. It is part of the current joint renovation plan between Millington, Rogers, and the new Integrated Science Center. This means that any issues found with Rogers 100, could be fixed within the next year under the present renovation timeline. Rogers 100 has 180 permanent seats, as well as removable seats along the back wall. The seating area is slightly curved, possibly to try to compensate for the width of the room, with terraced seating for the hard plastic seats. There are two sets of doors to the outside, both of which were connected to construction areas when I was doing tests, and one set of doors back into the building. The back wall has some sound deadening material on it, and the walls and ceiling are angled to cut down on sounds bouncing around. Due to the size, I utilized seven recording points

Recording Point #	Location*
1	Front Left Seat in the Front Row
2	Between the Middle Seats in the First Row of the Middle Section
3	Front Right Seat in the Front Row
4	Between the Middle Seats in the 6th Row of the Middle Section
5	Back Left Seat in the Last Row
6	Between the Middle Seats in the Last Row of the Middle Section
7	Back Right Seat in the Last Row

Table 27: Rogers 100 Recording Points
*All locations in reference to the professor's view.

To setup for my experiments, I placed the speaker in between the middle seats in the front row 3' $5\frac{1}{2}$" from the back wall and 4' 7" up from the ground. This placed the speaker behind the front demonstration table. Most of the electronic equipment is housed within cabinets, and since the LCD Projector is a good deal up in the air, I did not find any significant increase from the baseline in my background noise tests. It is worth noting that recording points 1, 3, and 7 are all right next to doors, with 1 and 7 next to the outside doors. These doors allow more noise into the room, and the insulation on the back wall might help keep noise out of the room more than it helps the noise level inside the room. Within the room there is an average background noise level of 44.7 dB, which is not a very good number.

Point #	Background Noise*
1	44 dB
2	43.8 dB
3	44.7 dB
4	45.1 dB
5	45.3 dB
6	44.1 dB
7	46.1 dB

Table 28: Rogers 100 Background Noise
* No significant change in background noise was obtained by switching on equipment.

Due to the width of the room, I expected a wider range of dB levels across any single row. I performed this experiment using pink noise that registered at 72 dB 3' from the speaker. As usual, at the corners of the front row, I did not pick up a strong signal. Again, I was not picking up a direct sound from the speaker, instead I was picking up the sound from reflections throughout the room. As I moved back, it was not until I got about halfway back in the room that the sound started to decay. The noise down the middle of the room decayed from the start, dropping off a grand total of 5.5 dB over the ten rows. On the sides they actually increased by .5 dB between the first and last rows. A student who does not want to sit in the middle section in Rogers 100 would benefit highly from moving halfway back instead of sitting in the front row. The overall difference between comparable sections here is about 5.5 dB.

Row / Position	Left Side*	Left Middle	Middle	Right Middle	Right Side
1	55.5 dB	58 dB	63.5 dB	58 dB	55.5 dB
4	56.5 dB	58.5 dB	60.5 dB	58.5 dB	56.5 dB
7	56.5 dB	57.5 dB	58.5 dB	57.5 dB	56.5 dB
10	56 dB	56.5 dB	58 dB	56.5 dB	56 dB

Table 29: Rogers 100 dB Level Changes
* Positions relative to the professor's point of view.

The final test is the RT test, as usual. Given the angled walls and ceiling, as well as the sound deadening back wall, I expected a decent RT. The volume of the room is an approximate 675 m^3, so the ideal number is about 0.725 seconds. While I was doing the experiment I was able to audibly hear the decay in the room, an indication that it is longer than what is desired. There are individual reverb times for specific frequencies that meet the ideal number, or beat it. Yet once all the data was taken and averaged together, it is clear that Rogers 100 has a longer than ideal RT. In fact the number is 1.202 seconds, almost a full half second more than the desired amount. The RT/RT_0 number is 1.66, well over the allowable limit.

Hz / Point #	1	2	3	4	5	6	7
107	1.451	1.89	2.864	3.408	NSD*	1.296	NSD
495	1.614	1.307	2.557	1.558	1.657	2.073	0.965
990	1.24	0.903	1.238	0.927	1.729	1.501	0.935
2k	1.416	0.67	1.149	0.899	0.987	0.896	1.25
3k	1.0422	1.405	0.847	1.827	0.86	1.17	0.898
4k	1.257	0.843	0.919	0.816	0.74	0.681	1.321
5k	1.138	0.678	0.883	0.691	1.253	0.882	1.379
8k	1.055	0.63	0.808	0.604	0.774	0.458	0.801
12k	NSL†	0.586	NSL	NSL	NSL	1.125	1.336
Pure 500 Hz	1.308	1.01	1.035	1.363	1.313	1.142	1.952
AVG‡	1.28	0.923	1.367	1.345	1.164	1.325	1.204

Table 30: Rogers 100 Reverb Times
* NSD - No Significant Drop in the signal.
† NSL - No Significant Level in the signal.
‡ AVG computed with all available data.

To fix these inadequacies, a few basic changes could be made. The room design of Rogers 100 seems to be decent. It is the materials that are involved that need upgrading. Switching out the seats for upholstered ones would cut down on the RT as well as make the students slightly happier to sit in class. Switching the hard linoleum flooring for carpeting much like that in Andrews 101 would also have a drastic impact on the RT. More research into the source of the background noise issues is necessary to fix that problem completely, although more insulation on the outer doors would help keep out a lot of that noise, especially before they finish the construction.

13 Tucker 120

Inside the English building, Tucker 120 is a lecture hall that can double as a theater with nice wood paneling up front, nice carpet, 159 upholstered seats, and plenty of speakers around the room to enhance the movie experience. The drawbacks that I saw upon walking into the room were that there were a lot of windows and the ceiling had many air vents in it that were making a lot of noise. The seating area is 13 straight rows of either 12 or 13 chairs on a slope. At the front of the room there is a small wooden stage. Once again I used five recording points for the corners and center of the seating area.

Recording Point #	Location*
1	Front Left Seat
2	Front Right Seat
3	7th Seat in the 7th row
4	Back Left Seat
5	Back Right Seat

Table 31: Tucker 120 Recording Points
*All locations in reference to the professor's view.

I next set up the speaker on the floor in front of the stage. It was centered in front of the 7th chair in the front row, 7' 7" from the back wall and 4' 10" up from the ground. To examine the background noise I checked the AA and discovered that unlike most other rooms, which have mainly a low end background noise, Tucker 120 seems to have a full range background noise. It almost has a pink noise type background noise. The air handling system in the room is apparently quite noisy. Recording points 1 and 2 were directly under vents in the ceiling, which should explain why the background noise appears to be louder in the front of the room. As my recording points moved back, they were no longer directly situated below vents. Because I had some of my data taken under vents, and some more in the open, my average should be close to an average level throughout the room. The average background noise level is 49.32 dB. This average is at the lower level of the human vocal range meaning that someone speaking quietly up front is literally speaking at the same level that someone sitting under a vent would hear otherwise. This is a very poor value for the signal to noise ratio. Due to the large amount of background noise, no significant change was perceived when the electronic equipment was turned on. It was all swallowed up by the air handling system.

Point #	Background Noise*
1	50.9 dB
2	51 dB
3	48.8 dB
4	48.3 dB
5	47.6 dB

Table 32: Tucker 120 Background Noise
* No significant change in background noise was obtained by switching on equipment.

The dB level change experiments again showed a slightly skewed picture. I was projecting at a 78 dB level when picked up 3' away from the speaker. The right side of the first and fourth rows were half a decibel higher once more. I would attribute this to the background noise level in the room being slightly skewed in reference to the seating positions. However, since the difference is only half a decibel, and you would have to walk all the way across the row to try to perceive it, the change is negligible. As usual, the first few rows do not obtain a direct sound from the source, instead they work with the reflections from other parts of the room. The difference between seats at the back of the room is very small as well. Since the room is so long from front to back, there is a larger drop off in the signal between the first and last rows. Within a small area we see about a 7 dB difference. I am using half of the seating area as a definition for a small area. In the back half there is about a 5.5 dB difference. These values are not very bad. Although with a drop off about 19 dB overall, if a professor is speaking below 70 dB, their vocal level will reach the background noise level by the back row of the room. This can be distracting and make it hard to learn.

Row # / Position*	Left	Middle	Right
1	63 dB	70 dB	63.5 dB
4	63 dB	66 dB	63.5 dB
7	61.5 dB	64 dB	61.5 dB
10	60.5 dB	62 dB	60.5 dB
13	58.5 dB	59 dB	58.5 dB

Table 33: Tucker 120 dB Level Changes
* All positions relative to the professor's point of view.

Due to the architecture of the room, I was curious about the reverb time values. When I started taking data I found that the background noise was impeding my results by quite a bit. The 2 kHz frequency especially was clouded by the background noise. Below 1 kHz there were very large reverb times, except with the pure 500 Hz tone. The pure tone came across with low reverb time, indicating that given a pure tone that can cut through the background noise, the RT would be low, while if we examine the pink noise, there are a lot more frequencies interacting. This means that my RT data should be at an upper level on the average. The room volume is an approximate 445 m^3 so we desire an RT of about 0.675 seconds. The average for my data was 0.987 seconds, an RT/RT_0 value of 1.46, just above the level we consider acceptable.

Hz / Point #	1	2	3	4	5
107	1.674	NSD*	0.895	1.623	NSD
495	1.321	NSD	1.202	1.236	NSD
990	1.153	2.056	1.819	0.829	NSD
2k	1.512	NSD	NSD	NSD	NSD
3k	0.836	1.285	1.102	0.809	2.006
4k	0.516	0.837	0.885	0.969	0.909
5k	0.496	0.874	0.885	0.892	0.909
8k	1.347	0.831	0.665	0.892	1.301
12k	1.552	0.923	0.7	0.451	1.122
Tone†	0.442	0.43	0.445	0.73	0.57
AVG‡	1.085	1.034	0.942	0.906	1.186

Table 34: Tucker 120 Reverb Times
* NSD - No Significant Drop in the signal.
† Tone - Pure 500 Hz tone.
‡ Avg computed using all available data.

The problems with this room are the severe background noise level, and the RT. To fix the background noise problem, the air handling system should be looked into. It appears to possess the same problem as the lecture halls in Small. Diffusing the vents or spacing them out more should both help. The RT values could be decreased by minimizing the amount of hard wood paneling in the room, even though it looks nice. Sound absorbing materials along some of the walls or ceiling would also help.

14 Tyler 201

Tyler 201 has a configuration that is very much like McGlothlin-Street 20. It has a terraced floor where each level has a long table with office chairs behind the table. The seating capacity is only 60, but the large open area at the back would allow for many more chairs to be brought in. At the top terrace there is a wall dividing off a small area with smaller round tables. This back area has a lot of windows all around it that look out on a street. The floor is carpeted inside the room, but just outside this room there are marble floors which contribute a lot of noise when people walk on them. I noticed a significant fan noise from the air handling system at the front of the room when I came in. The walls are slightly angled and the ceiling is terraced as well. Because of the shape of the room, I decided to use six recording points - the standard five in the seating area, plus a sixth in the extra area in back. Because the room does not have permanently installed chairs, I used positions at the tables for reference, as I did in McGlothlin-Street 20.

Recording Point #	Location*
1	Front Left Corner in First Row
2	Front Right Corner in First Row
3	Middle of the Aisle Along 3rd Row
4	Back Left Corner in 5th Row
5	Back Right Corner in 5th Row
6	Centered Behind the Back Wall

Table 35: Tyler 201 Recording Points
*All locations in reference to the professor's view.

To set up the speaker, I centered it on the middle aisle, 4' 7" from the back wall, 4' 8" up from the ground. Turning on the built in classroom equipment showed me that the LCD Projector in this room was surprisingly quiet and also was a different model from most of the other rooms. Because of this I was not able to generate any significant difference in the background noise levels from the baseline. This room had an interesting frequency profile for the background noise as well. Here the background was made up of the frequencies from 100 Hz to 2 kHz, as well as the 20 kHz level. Most of the other rooms have background noise that is made up of primarily low end frequencies (the frequencies that show up in mechanical equipment like air handling systems and mechanical rooms). This means that the background noise is specifically within the human vocal spectrum, rather than below it as is expected. The average background noise level is 45.6 dB. The front row is louder than the middle of the room because of how the air handling system appears to be set up at the front of the room. If it were more spread out, the levels should flatten out more.

Point #	Background Noise*
1	47.1 dB
2	46.2 dB
3	45.6 dB
4	44.3 dB
5	44.1 dB
6	46.2 dB

Table 36: Tyler 201 Background Noise
* No significant change in background noise was obtained by switching on equipment.

The dB level change experiment showed the same things as most of the rooms with a wide seating area. For my experiments I took data at the ends of the rows, and then in the middle on either side of the aisle. I was projecting pink noise that was perceived at 77 dB 3' away from the speaker. The first row did not get direct sound at the ends of the row, so the sides did not decay the same way that the middle did. The drop off within the room appears to be quite standard. Overall there is a 10 dB drop from the front to the back wall, but if we examine just the usual seating area it is only 8 dB.

Row # / Position*	Left	Left Middle	Right Middle	Right
1	64 dB	71 dB	71 dB	64 dB
2	64 dB	68.5 dB	68.5 dB	64 dB
4	63 dB	65 dB	65 dB	63 dB
Back Wall	61.5 dB	63 dB	63.5 dB	61.5 dB

Table 37: Tyler 201 dB Level Changes
* All positions relative to the professor's point of view

The reverb time tests were conducted as usual. Because of the higher background noise levels at point 1, I had trouble getting good data from that point, so I dropped this point from my overall average calculations. For all of my points I could not get good data for the 100 Hz level because of the dominant background noise, so I dropped this frequency from my calculations. The room volume is about 645 m^3 so a RT about 0.725 seconds is desired. My calculated RT average for Tyler 201 is 0.836 seconds, within the 0.2 second limit and also with an RT/RT_0 value of 1.15. If I include the point 1 data, then the RT becomes 0.908 seconds with an RT/RT_0 value of 1.25. The first value is a better approximation, and a better RT for the room to have since it is less influenced by noise that I did not introduce to the room.

Hz / Point #	1	2	3	4	5	6
495	NSD*	1.367	0.859	0.825	NSD	1.757
990	2.384	1.439	0.714	0.818	NSD	1.092
2k	2.088	0.712	0.643	0.685	0.548	0.856
3k	0.969	0.608	0.413	0.768	0.709	0.59
4k	0.843	1.139	0.594	0.498	0.96	0.38
5k	0.982	1.138	0.634	0.642	0.972	0.406
8k	0.972	0.555	0.64	0.912	0.678	0.7
12k	NSL†	0.687	0.501	NSL	1.628	0.524
Tone‡	0.659	0.382	0.4613	0.667	0.662	0.342
Avg⋆	1.271	0.892	0.839	0.831	0.879	0.739

Table 38: Tyler 201 Reverb Times
* NSD - No Significant Drop in the signal.
† NSL - No Significant Level in the signal.
‡ Pure 500 Hz tone.
⋆ Avg computed with all available data.

The main problem with Tyler 201 is the background noise. The air handling system should be investigated for upgrades. Adding more vents to the room, and more evenly spacing them should cut down on the noise at any one point in the room. The RT is good, and the room does not have many potential improvements that could be made to fix the RT. It already has the angled walls, ceiling, carpeted floor, and upholstered chairs. Some sound absorbing panels on the walls might be helpful, if anything.

15 Washington 201

Washington 201 is a rather newly renovated large lecture hall featuring all the latest amenities. The walls have sound absorbing panels, the floor is carpeted, the seats are upholstered, and the ceiling is terraced. The seating area is broken up by a middle aisle with both sides containing an even number of seats. The overall seating capacity is 170. Each row has its own terrace. There are many light switches so the right lighting environment can be created, or specific lights can be turned off if necessary. Because of the depth of the seating area, I used six recording points along the room.

Recording Point #	Location*
1	Leftmost Seat in the Front Row
2	Rightmost Seat in the Front Row
3	4th Row in the Middle of the Aisle
4	9th Row in the Middle of the Aisle
5	Leftmost Seat in the Last Row
6	Rightmost Seat in the Last Row

Table 39: Washington 201 Recording Points
*All locations in reference to the professor's view.

I centered the speaker aligned with the middle of the aisle 5' 4" from the back wall and 5' up from the floor. When I turned on the lights in the room I noticed that the frontmost set of fluorescent lights was creating an audible buzzing sound. The LCD Projector also contributed some noise, so I recorded both the baseline level (without the equipment and front lights) and the level with all the lights and equipment on. Point three was more or less right under the LCD projector and showed a 2.7 dB increase in sound level by turning on the LCD projector. Point five was right next to an air vent, and the single loudest place in the room for background noise. The baseline average was 38 dB and the upper level average was 39.2 dB. Both levels are below 40 dB, so this room is quite good in terms of background noise.

For the dB level change experiment I again used the four recording points across the row, with the middle two on either side of the aisle. I was projecting the pink noise at 76 dB when recorded 3' away from the speaker. The edges of the front row do not show a difference between there and the fourth row, so they are not quite receiving a direct sound from the source. The decay along

Row #	Minimal Lights	All Lights and LCD Projector
1	37.1 dB	38 dB
2	35.9 dB	37 dB
3	38 dB	40.7 dB
4	39.2 dB	39.5 dB
5	42 dB	43.1 dB
6	36.3 dB	36.8 dB

Table 40: Washington 201 Background Noise

the sides is quite reduced when compared to the middle. There is about a 10 dB difference overall in a seating area, if we look at only half the seating area (rows 1 through 6 vs. 7 through 12) there is about a 5 dB change in each. The background noise is quiet enough that the decay, even along the sides, is not enough to drop a normal voice level to the same level as the background noise.

Row # / Position*	Left	Left Middle	Right Middle	Right
1	64 dB	71.5 dB	71.5 dB	64 dB
4	64 dB	68.5 dB	68.5 dB	64 dB
7	62 dB	65.5 dB	65.5 dB	62 dB
10	61.2 dB	63 dB	63 dB	61.2 dB
12	60.5 dB	62 dB	62 dB	60.5 dB

Table 41: Washington 201 dB Level Changes
* All positions relative to the professor's point of view

Because of the construction of this room, I expected a very low RT. The carpeting, upholstered seats, and acoustical paneling are usually good indicators of a room that will have a lower reverb time. Because Washington 201 has low background noise levels I was able to record very clean data. There was a large threshold between the level I was outputting and the background noise level in the room Only the 12 kHz level showed issues with interference between my signal and the background noise in the recordings. All of the frequencies have individual RTs about at the same average. The RT that I calculated from my data was 0.59 seconds. Since the volume was approximately 535 m^3 the desired reverb time is about 0.7 seconds. Our value is actually below this, and would only decrease with more students in the room. The RT/RT_0 level is 0.84, just within the acceptable level for the lecture halls. This room is borderline too dead acoustically, meaning that there is a slight chance that a lot of students in the room could help the vocal sound level die off a little too quickly. However it is easier to compensate for being in a room that is more dead than it is to compensate for being in a room that is equally too live. This is due to the fact that speaking slightly louder to overcome the drop off is easier to do than to deal with a lot of echos and reverb. Despite all of this, overall there are no major problems with Washington 201 that need improvement.

Hz / Point #	1	2	3	4	5	6
107	0.71	0.879	0.633	0.896	0.591	0.888
495	0.469	0.566	0.479	0.479	0.814	NSD*
990	0.775	0.334	0.614	0.556	0.833	0.434
2k	0.512	0.799	0.489	0.483	0.816	0.546
3k	0.497	0.505	0.509	0.426	0.836	0.679
4k	0.799	0.458	0.437	0.419	0.451	0.402
5k	0.858	0.454	0.537	0.513	0.84	0.506
8k	0.907	0.762	0.494	0.491	0.37	0.499
12k	NSL†	NSL	0.501	0.44	0.812	0.785
Tone‡	0.402	0.354	0.503	0.4	0.434	0.571
Avg⋆	0.667	0.569	0.52	0.51	0.68	0.59

Table 42: Washington 201 Reverb Times
* NSD - No Significant Drop in the signal.
† NSL - No Significant Level in the signal.
‡ Pure 500 Hz tone.
⋆ Avg computed with all available data.

16 Washington 301

I selected the rather small Washington 301 to provide a comparison to the larger rooms in construction materials and noise levels. Washington 301 is listed as a "film viewing room" so the acoustics should have been deadened to a more extreme end than with normal vocals. The construction is similar to Washington 201 with the same carpeting and wall material. It has a drop ceiling with many lights and speakers built into it. The seating is composed of office chairs behind slightly curved tables, much like Tyler 201. The seating area is quite small, as is the room since it only holds 40 people, but I still used five recording points. Since the chairs are not permanent, I used location at the tables, not in reference to the chairs.

Recording Point #	Location*
1	Front Left Corner
2	Front Right Corner
3	The Middle of the 3rd Row
4	Back Left Corner
5	Back Right Corner

Table 43: Washington 301 Recording Points
*All locations in reference to the professor's view.

The speaker was not set up in the middle of the room for these experiments. Instead, I set up the speaker right behind the podium, centered behind the touchscreen, about 1' back from the podium, 4' 10" up from the floor. I selected this location because it is more likely to be used by a professor, and in a room of this size being slightly off center will not create a large difference. Since the room is so small, I found that turning on the LCD projector actually created a lot of ambient noise, so I used both the baseline and the increased levels for my background noise test. The room averaged a baseline level of 34.2 dB. The upper level averaged 38.8 dB. Both of these numbers are relatively good for any room. Point 1 is the closest point to the door into the hallway and also the highest background noise level in the baseline test. This indicates that there is quite a bit of outside noise entering the room which a sturdier door could eliminate. Point 3 became the highest once the LCD projector was turned on, since it is right below the LCD projector.

Point #	Baseline	With Technology
1	36.4 dB	40 dB
2	34.6 dB	37.9 dB
3	34.9 dB	41.5 dB
4	33.5 dB	37.8 dB
5	31.5 dB	36.7 dB

Table 44: Washington 301 Background Noise

Due to the size of the room I decreased the scope of the dB level experiment to simply see how much the sound died off throughout the room. I projected the pink noise at a level of 76 dB at 3' away from the speaker. As expected, since point 1 was right in front of the speaker, it was quite loud there. The back row was uniformly at 61 dB indicating that a small section of the room would be basically uniform in the level. The overall change was about 10 dB in a small room, this is about the same as the change in Washington 201, which had 7 more rows to decay over. This means that the constant level is being absorbed by the room more quickly, which could potentially mean a very low reverb time, although there is not a direct correlation between the level when the noise is being projected by a speaker and how the noise decays once the source is turned off.

Point #	dB Level
1	70.5 dB
2	65.5 dB
3	64 dB
4	61 dB
5	61 dB

Table 45: Washington 301 dB Level Changes

I expected to see very similar results to the ones from Washington 201 in the RT experiments due to the similar construction. The only major difference, besides the size, is the ceiling construction. As before, most of the data for each frequency shows a rather uniform distribution. Each frequency averages out to almost the same RT as the overall level. The room volume is approximately 230 m^3 so an RT of 0.58 seconds is desired. The average RT for Washington 301 is calculated at 0.644 seconds, a difference of 0.064, very close for our purposes. This yields an RT/RT_0 value of 1.11, well within the tolerance level seen in figure 1. The drop ceiling should be more absorbent of sound than the hard ceiling found in Washington 201, but Washington 301 does not have the same sound absorbing panels on the walls that were found in the classroom downstairs. Washington 301 is also a proportionally longer and lower room than Washington 201, which yields a higher volume to surface area ratio by minimizing the surface area used to create a volume. As with Washington 201, there is not much need to improve this room.

Hz / Point #	1	2	3	4	5
107	0.857	1.0	0.577	1.292	0.846
495	0.461	0.528	0.54	0.72	0.576
990	0.441	0.365	0.616	0.443	0.477
2k	0.581	0.819	0.662	0.598	0.612
3k	0.665	0.759	0.547	0.622	0.7
4k	0.837	0.621	0.663	0.663	0.7
5k	0.581	0.779	0.577	0.692	0.937
8k	0.669	0.742	0.454	0.54	0.689
12k	0.67	NSL*	0.503	0.796	0.977
Tone†	0.459	0.396	0.434	0.449	0.473
Avg‡	0.622	0.668	0.557	0.682	0.691

Table 46: Washington 301 Reverb Times
* NSL - No Significant Level in the signal.
† Pure 500 Hz tone.
‡ Avg computed with all available data.

17 Wren Grammar School Room

Within the Wren building there are quite a few classrooms. There is only one that is based on the historical plans for the building, the Grammar School Room. This room is no longer used for actual classes, functioning instead as a stop for the tours that pass through the Wren Building. It is heralded as the room that George Washington and Thomas Jefferson took classes in. Care has been taken during restorations and renovations to keep it as close to the original room as possible. When the room is being worked on they go so far as to recondition the floors, then put the same ones back in. This all enables a chance to get a glimpse of what the colonial acoustics of the College sounded like.

The Grammar School Room is a rectangle with a lecturer's box along one long wall facing two rows of benches with tables along the opposite wall. Off to the right of the room is another double row of benches with tables. The ceiling is a lofty fifteen feet in the air. The floors, benches, tables, and lecturer's box are all made of hard wood.This creates an environment that is quite noisy acoustically. The capacity is approximately 40 as well.

Point #	Location*
1	Front Bench Far Left
2	Front Bench Far Right
3	Side Bench Far Back
4	Side Bench Up Front

Table 47: Wren Grammar School Room Recording Points
*All locations in reference to the professor's view.

I established four different recording points. They were all along the back row moving from left to right and the ends of each row. Since there were only two rows I could easily cover the entire seating area with just microphones in the back row.The background noise tests proved the room was very uniform. When I closed the outer doors to the room a lot of the background noise died off, leaving just what is recorded in the table following. The average background noise is 42.5 dB, which is not the worst that I have seen in my research. Most of this noise seemed to come from the vents. While my experiments hope to explore some of the similarities and differences between the colonial acoustics and the modern acoustics, the background noise would not be one of the factors that is comparable. There were no air handling systems or light fixtures to add noise to a room in the colonial era. The colonial acoustics would probably be much quieter in the rooms themselves since the builders would not have been able to place a lot of noise producing equipment in the building.

Point #	Noise Level
1	43 dB
2	42 dB
3	43 dB
4	42 dB

Table 48: Wren Grammar School Room Background Noise

Unlike the background noise, I expect that the dB level changes should be about the same as in the colonial times. This is because the dB changes are largely dependant on the RT of the room and the shape of the room. Both of these should be approximate to colonial times because the construction has been preserved to the best of our knowledge. The speaker was set up centered in the lecturer's box, 4' 10" off the ground. The entire seating area was uniform at a 70 dB level when the pink noise was broadcast at a level of 76 dB when measured 3' away from the speaker. This is an ideal situation for all the students in the room.

Point #	dB Level
1	70 dB
2	70 dB
3	70 dB
4	70 dB

Table 49: Wren Grammar School Room dB Level Changes

As soon as I walked into the room, I was sure that the RT would be poor for the Grammar School Room. People can hear a very audible decay in the sound as it dies off. This creates a very live room that can muddle speech between individuals or a lecturer and the people in the class. The data shows a clear decrease in RT as the frequency increases. This is exactly what we expect to see. The averages for all of the data, and each frequency level by itself, are all quite uniform. The downside is that all of the hard and dense materials used in the construction of the building create an environment that bounces sound all over the room. The average RT for the Grammar

School Room is 1.765 seconds. The room volume is approximately 311 m^3, so the target RT is 0.61 seconds. The RT/RT_0 number is 2.893, a very high number. When the Wren building was built, not much was known about acoustics from a mathematical point of view, nor were there very many choices for construction materials, so the poor RT is not the fault of negligence on the part of the builders. The RT/RT_0 number is the worst in my research, so the College is at least doing an increasingly better job with their acoustics planning.

Hz/Point #	1	2	3	4
495	NSD*	1.56	1.565	NSD
990	2.396	2.941	2.291	2.924
2k	2.445	1.988	2.193	2.522
3k	1.846	1.966	2.166	1.724
4k	2.122	1.982	1.79	2.24
5k	1.064	1.472	1.249	1.408
8k	1.104	1.218	1.278	0.807
12k	0.696	0.635	NSL†	2.2243
Tone‡	2.129	1.763	1.496	0.982
AVG*	1.725	1.725	1.754	1.856

Table 50: Wren Grammar School Room Reverb Times
* NSD - No Significant Drop in the signal.
† NSL - No Significant Level in the signal.
‡ Pure 500 Hz tone.
* Avg computed with all available data.

No improvements can be made to the Grammar School Room to improve the acoustics that would still preserve the historic nature of the room. However, if improvements were to be discussed, then acoustical paneling on the walls and ceiling, along with a carpeted floor would help the RT immensely. The background noise would need to be addressed through the HVAC system.

18 Improvements

I have already highlighted some potential improvements in the previous sections. Here I will present the improvements organized by the problem that they help alleviate. The most common issue appears to be the reverb time, so I will address that first.

Reverb Time: The reverb time issues are caused by the sounds in the room not dying off as quickly, or as slowly as the case may be, as they need in order to enhance the intelligibility of the professor. Every material used in the construction of the room absorbs a specific amount of the sound at every frequency level. Harder, denser materials tend to bounce sounds around the room, while materials that are less dense tend to absorb more sound. The other consideration is the room volume to surface area ratio that was examined in the Reverb Time Math section. If we increase the volume to surface area ratio, then the RT will increase as well since the sound will travel more distance before it hits a wall. However, since we are not working with any rooms pre-construction, we can focus solely on the materials that can be added to a room to correct the issue.

- **Floor Covering** - Lining the floor with a carpet is one of the quickest ways to decrease the RT. An absorbent carpet or thiner carpet on a pad will severely decrease the RT, even if it is only to line the aisles and front podium area. The difference between the carpet on pad absorption coefficient and the linoleum coefficient is on average 0.28, which represents 28% more absorption of the sound waves. Conversely, if the room is too dead acoustically, switching to a thinner, or no, carpet will increase the RT.

- **Upholstered Chairs** - Just like lining the floor with a carpet creates a significant decrease in the RT, covering the chairs has a similar effect. The thicker the padding is, the more that the reverb time will be reduced in empty chairs. If a chair is occupied, the difference will be smaller, but still there.

- **Wall Panels** - Since it is time consuming and rather expensive to cover the entire wall area in a new material, the quickest solution for the walls is to put up panels. This has already been done in the Washington rooms and Morton 20. These sound absorbent panels have almost perfect absorption of sound, which means that you can cover only a quarter or less of the walls to have a dramatic decrease in the RT.

Background Noise: The background noise issue is the issue that requires the most intensive changes to the room itself. Only a small number of the issues can be solved by installing a new piece of equipment. Most of the changes will require large scale renovations to the room.

- **Electronics** - The electronic equipment in the classrooms is designed to enhance the professor's lecturing, not detract from it. For the few rooms where the equipment gives off excess noise, either new equipment or better instruction on how to use the equipment will somewhat decrease the background noise levels. Speaker systems that are utilized improperly will generate background noise of their own. Simple instruction to professors can decrease this problem. Installing quieter LCD projectors will decrease the rest of the background noise issues.

- **Noisy Electrical Systems** - This is slightly different than electronic components. Instead of having the issue be an LCD projector, for example, this problem is the one that causes the noisy lighting fixtures. In some rooms I heard a buzzing noise that came from the lights. Turning off one set of lights, but not every set, fixed the problem. These systems should be investigated to discover the source of the buzz, whether it's a specific light that can be replaced, or if it is the entire set of lights that needs to have some part of its wiring replaced. If this buzz is corrected, the area around it will have a lower background noise level in the classroom.

- **Air Handling Systems** - The source of most of the background noise levels comes from the air handling system. These systems might need to be completely redesigned. Large overhead vents, like those found in the lecture halls in Small, enable more noise to enter the room. Having smaller vents, more spread out around the room, keeps more of the background noise contained inside of the ductwork. Building the mechanical rooms that power the air handling system in another part of the building away from the major lecture halls will also allow more of the background noise to dissipate before it reaches the room.

- **Outside Noises** - A few rooms experienced noise bleeding in from an outside source. This can be fixed by putting more insulation on walls, which could also help the RT issues, or making the doorways thicker. Windows allow light into the classroom, so they should not be done away with, however, double paned glass windows, or putting drapes along the sides of the windows, will help curtail the influx of outside noise.

dB Level Changes: My experiments did not determine that any room was severely deficient in the seating area in terms of dB level changes. However, there are some improvements that can be made should it be a problem in the future.

- **Structural Considerations** - Having a low ceiling in one area of the room, or sharp corners on the walls, restricts the movement of the sound waves. When the lecture halls are being designed, these oddly shaped sections of room should be avoided at all costs. While walls should not be strictly parallel, having huge angles in them would create weird reflection patterns and force the sound coverage to not be uniform. Also, creating rooms that are very wide creates a difficult environment for a single voice that does not have amplification to distinguish itself.

- **Audio Amplification** - If a room is found to have a dead area where it is hard to get adequate sound coverage, installing a sound system for the professors to use is very helpful. The speakers can be placed to create a uniform coverage pattern around the room. Care needs to be taken to ensure that professors know how to use the equipment correctly, and that the amplification would not overpower students in a discussion based class.

19 Final Results

In this section I will present the final rankings for each room. To do this I first need to define how I will rank each experiment.

1. Background Noise: Based on the background noise in the room, considering both max and baseline levels with priority given to the level that is more stable throughout the recording points.
   - Ideal: Max and baseline below 35 dB
   - Good: Max or baseline between 35 dB and 40 dB.
   - Mediocre: Max or baseline between 40 dB and 45 dB.
   - Poor: Max and baseline above 45 dB.
2. dB Change: Based on the largest change in dB levels within a row or area.
   - Ideal: $\pm$ 6 dB or less change within an area.
   - Good: $\pm$ 10 dB within an area.
   - Poor: Above $\pm$ 10 dB within an area.
3. RT: Based on the average RT for rooms ignoring values which are poor fits.
   - Ideal: Approximately at the RT value proposed by Eggenschwiler.
   - Good: Within the RT/RT_0 values proposed by Eggenschwiler.
   - Poor: Above the RT/RT_0 values proposed by Eggenschwiler.
4. Room Volume: Based on the m^3 room volume.
   - Large: $\geq$800 m^3
   - Medium: $\leq$700 m^3 or $\geq$500 m^3
   - Small: $\leq$500 m^3

Room Name	Room Volume (m^3)	Background Noise	Reverb Time	dB Change	Overall
Andrews 101	970	Ideal	Good	Good	Good +
McGlothlin-Street 20	463	Mediocre	Poor	Ideal	Mediocre +
Millington 150	1033	Good	Good	Good	Good
Morton 20	225	Ideal	Good	N/A	Good +
Rogers 100	673	Mediocre	Poor	Good	Mediocre
Small 109	414	Poor	Poor	Good	Poor
Small 113	955	Mediocre	Poor	Good	Mediocre -
Tucker 120	442	Poor	Poor	Good	Mediocre -
Tyler 201	645	Poor	Good	Good	Good -
Washington 201	535	Good	Good	Good	Good
Washington 301	227	Good	Good	Good	Good
Wren School Room	311	Mediocre	Poor	Ideal	Poor

Table 51: Final Results and Overall Rankings For Each Lecture Hall

Table 51 shows the final rankings of each lecture halls and the overall ranking that I assigned each room. The reverb time and background noise results carried a greater weight in my overall rank than the dB change since they create larger problems for the students. The absolute worst rooms were Small 109 and the Wren Grammar School Room mainly because of the background noise levels. McGlothlin-Street 20, Rogers 100, Small 113, and Tucker 120 are all also unacceptable acoustically. These rooms do not need large structural overhauls, but would benefit greatly from carpeting, upholstered seats, sound deadening material on the walls, or air handling system improvements. Both the largest and smallest rooms are acoustically acceptable. While no room achieved ideal results in all categories, clearly the school has already put some effort into fixing lecture halls both large and small.

20 Floor Plans

This section contains floor plans for each lecture hall. Each floor plan contains basic room dimensions, as well as a speaker logo where the speaker was placed and which direction it was facing, and finally each specific numbered location for each recording point.

Andrews 101

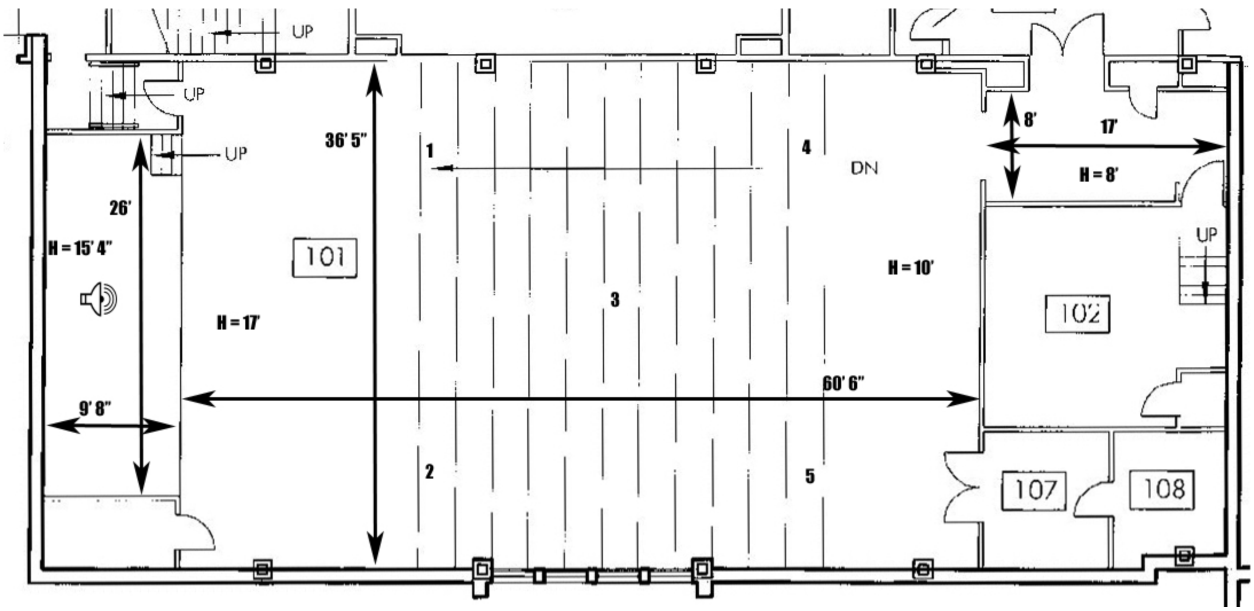

Figure 15: Andrews 101 Floor Plan, Speaker Location, and Recording Points

McGlothlin-Street 20

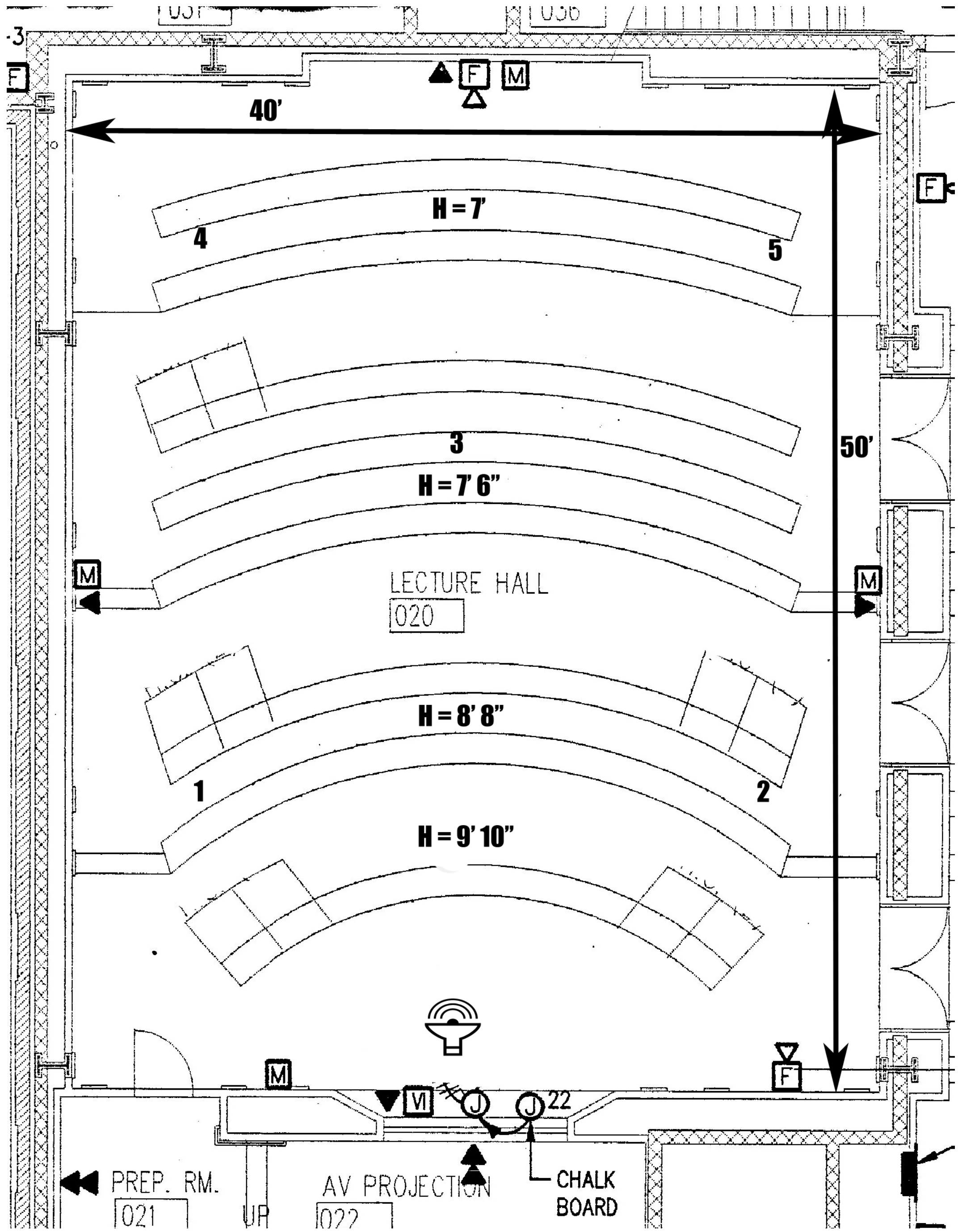

Figure 16: McGlothlin-Street 20 Floor Plan, Speaker Location, and Recording Points

Millington 150

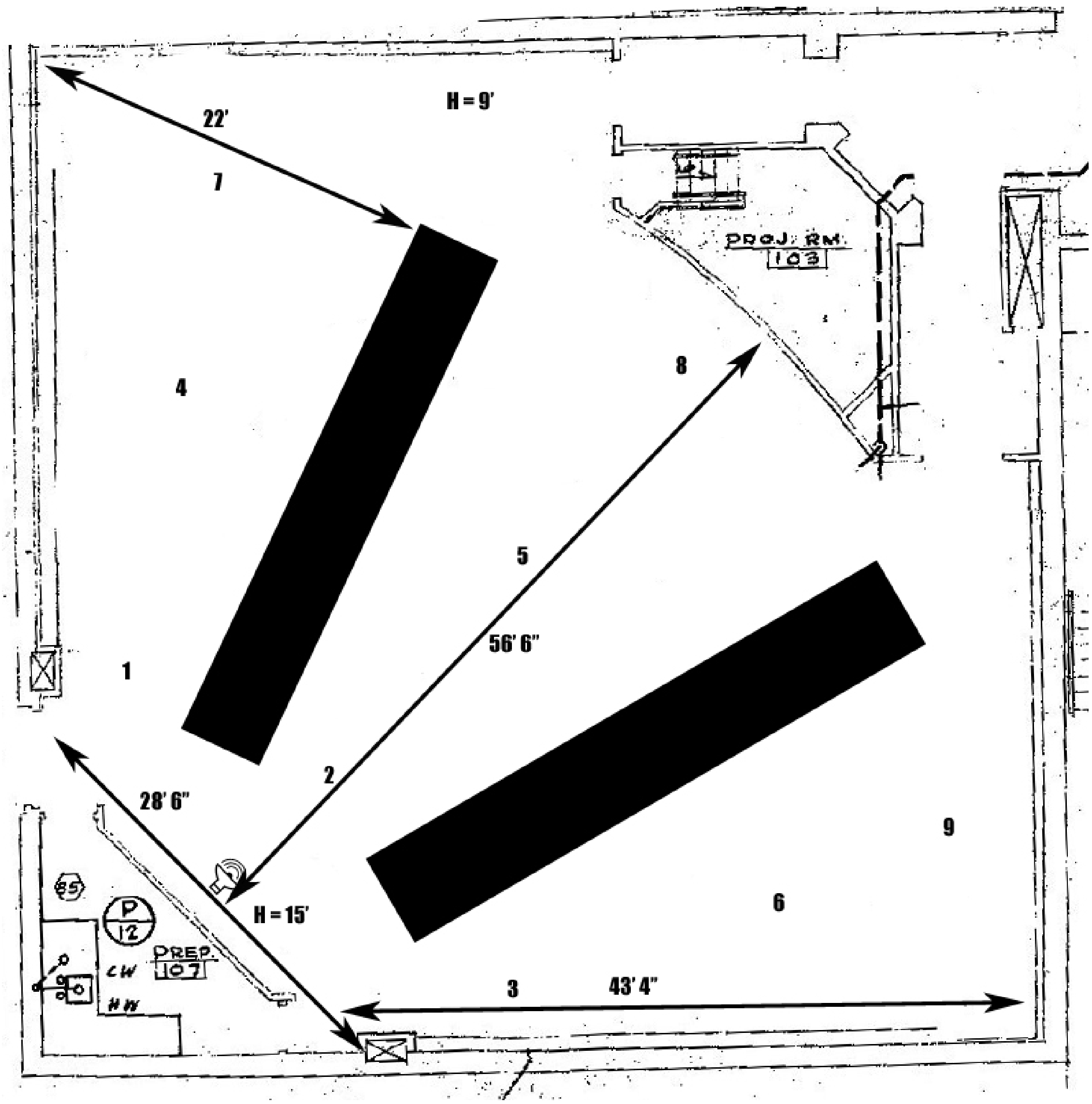

Figure 17: Millington 150 Floor Plan, Speaker Location, and Recording Points

Morton 20

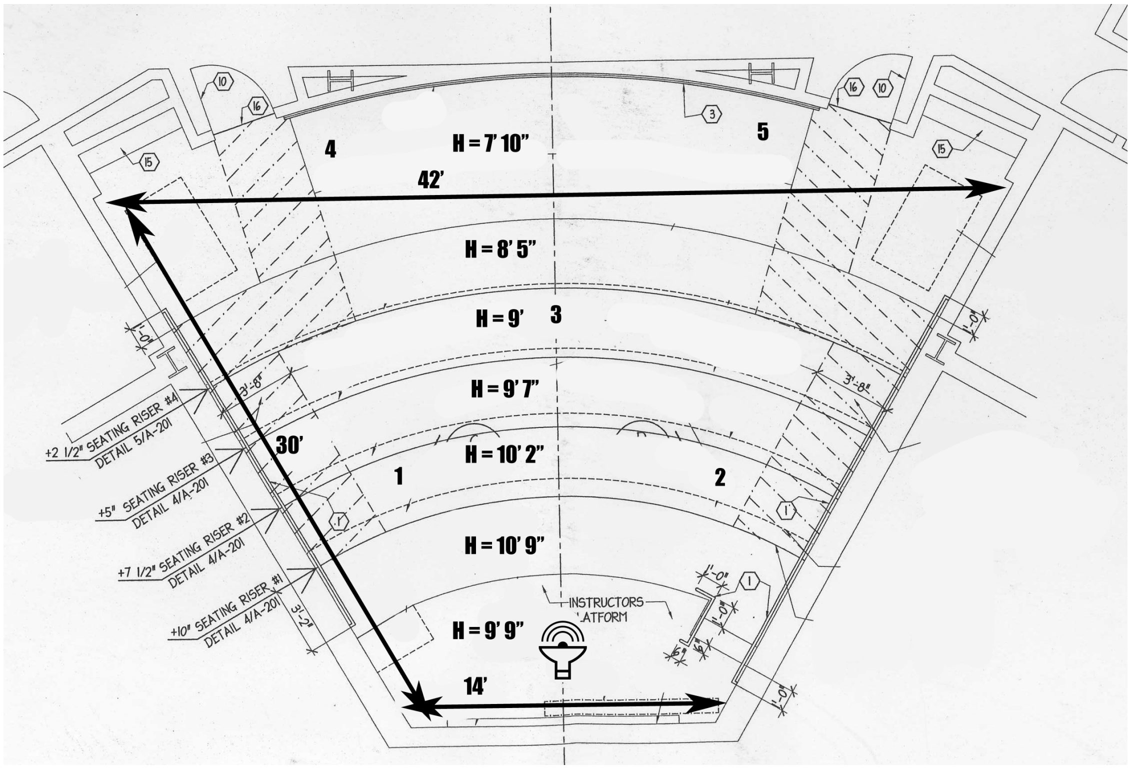

Figure 18: Morton 20 Floor Plan, Speaker Location, and Recording Points

Rogers 100

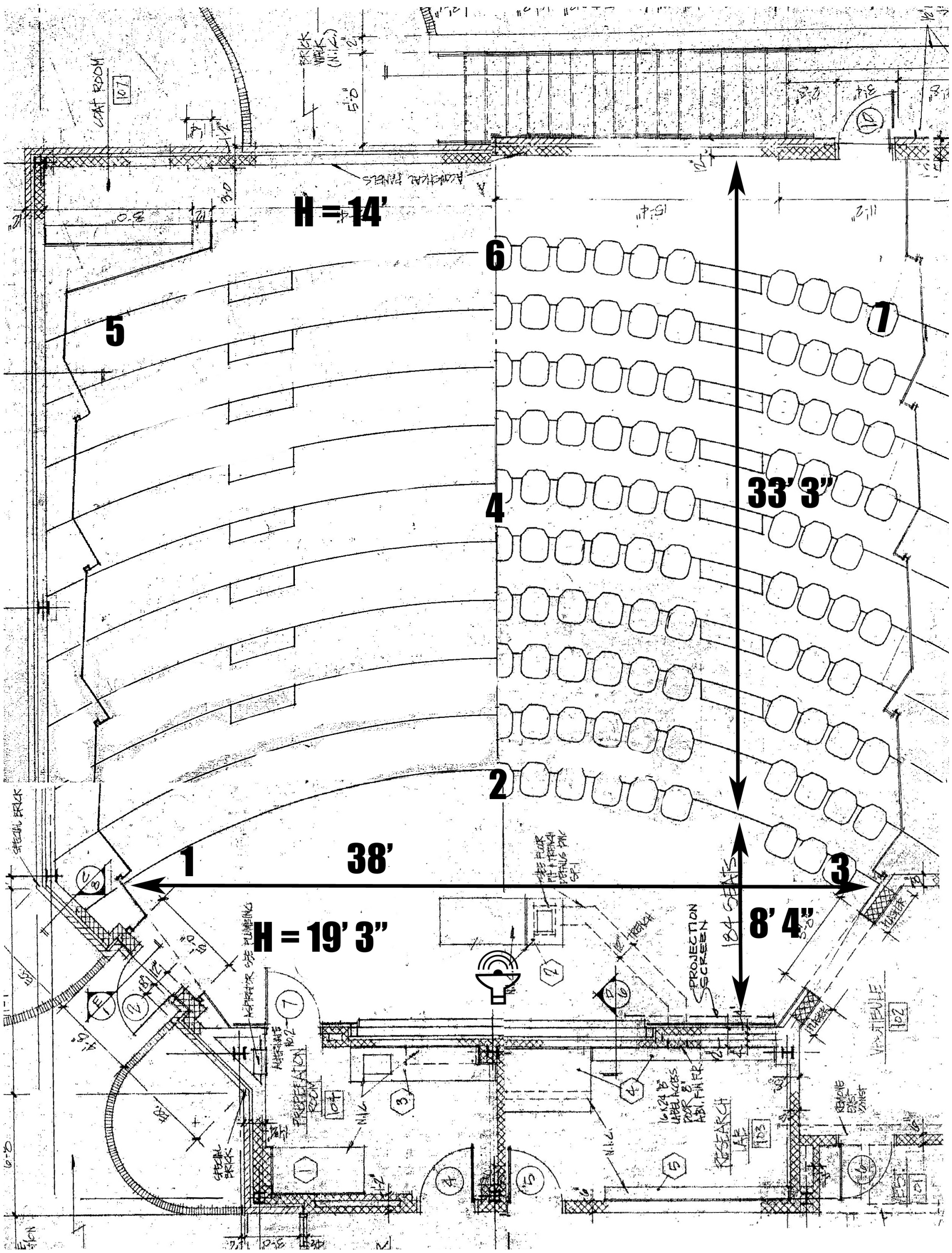

Figure 19: Rogers 100 Floor Plan, Speaker Location, and Recording Points

Small 109

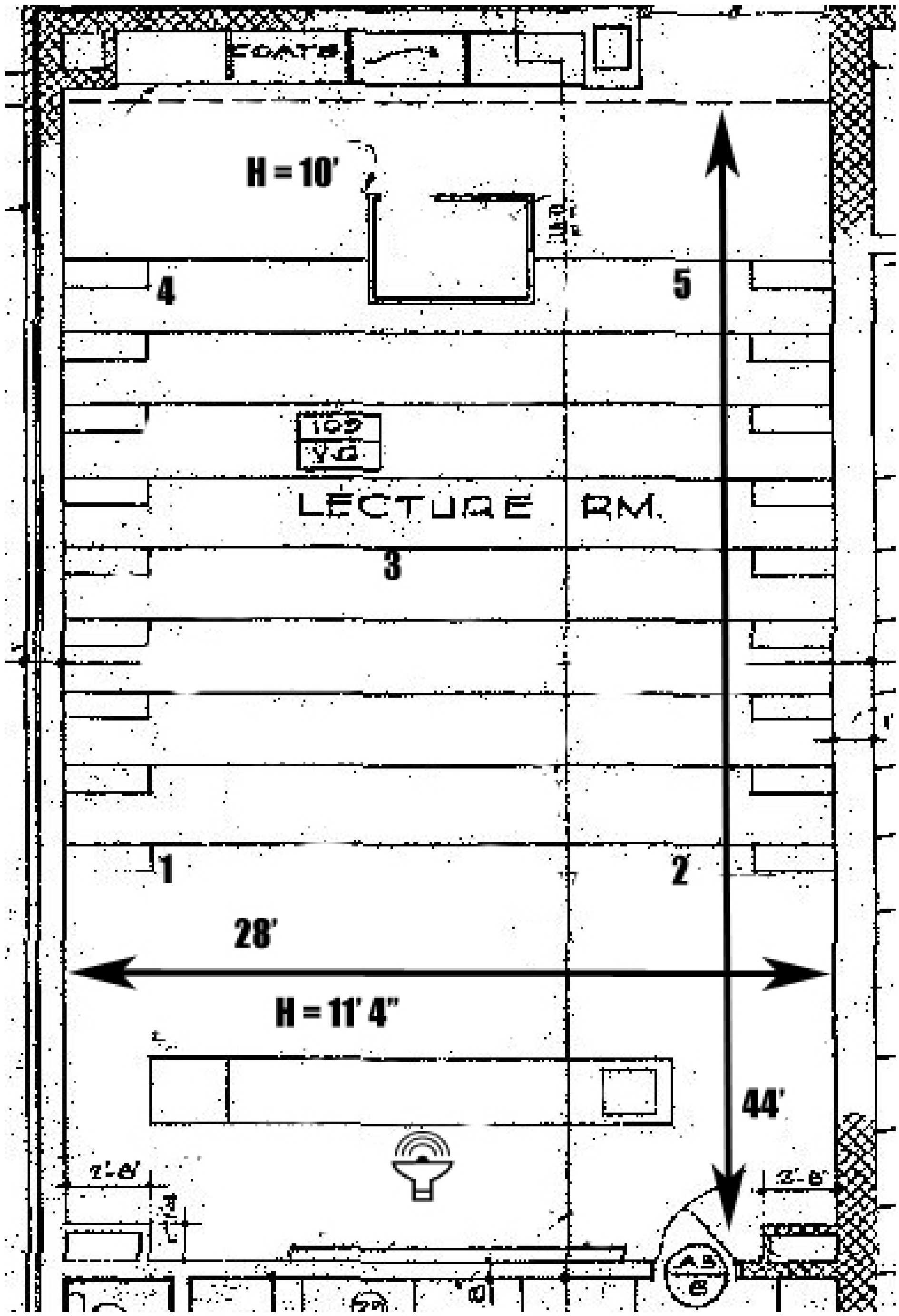

Figure 20: Small109 Floor Plan, Speaker Location, and Recording Points

Small 113

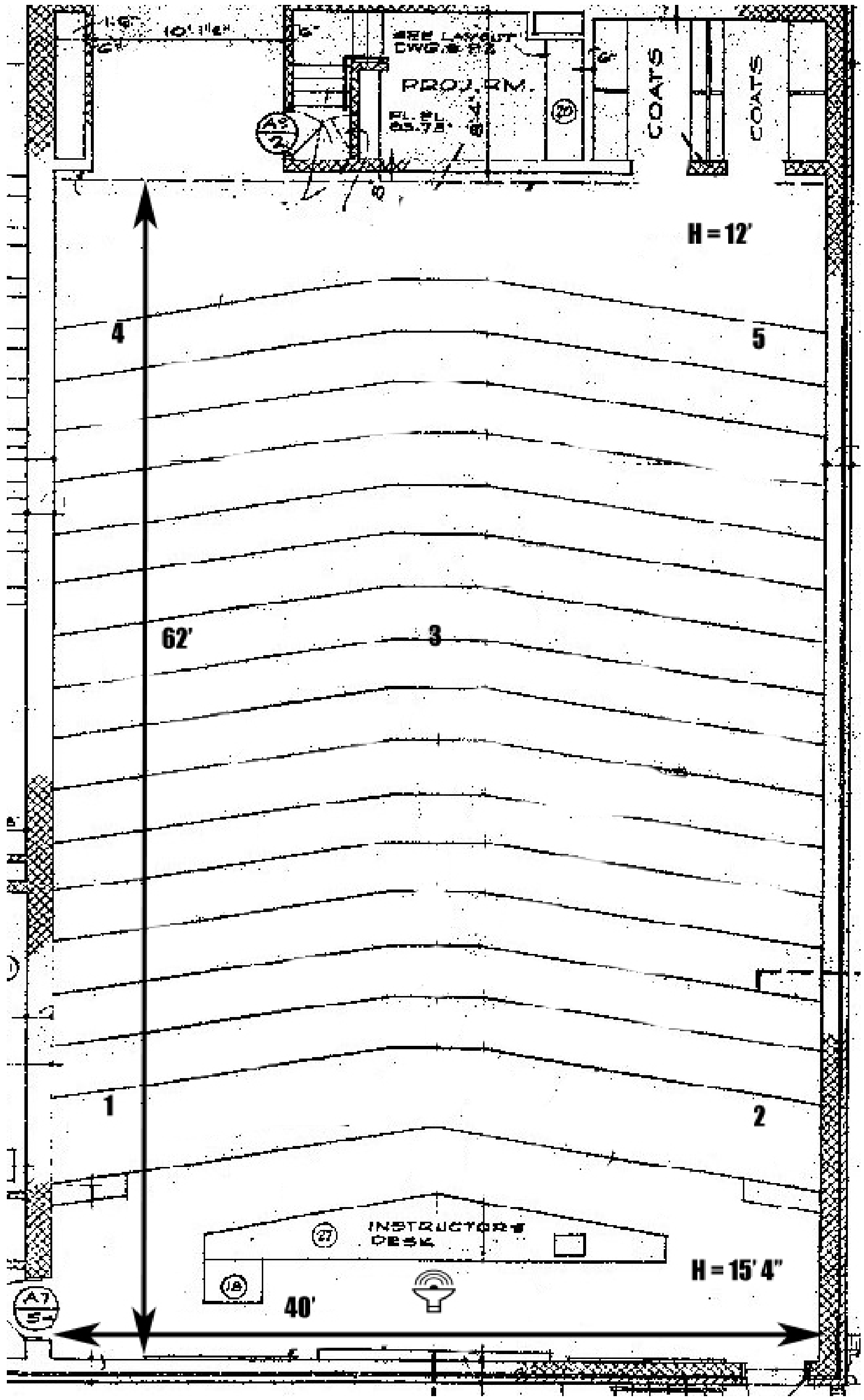

Figure 21: Small 113 Floor Plan, Speaker Location, and Recording Points

Tucker 120

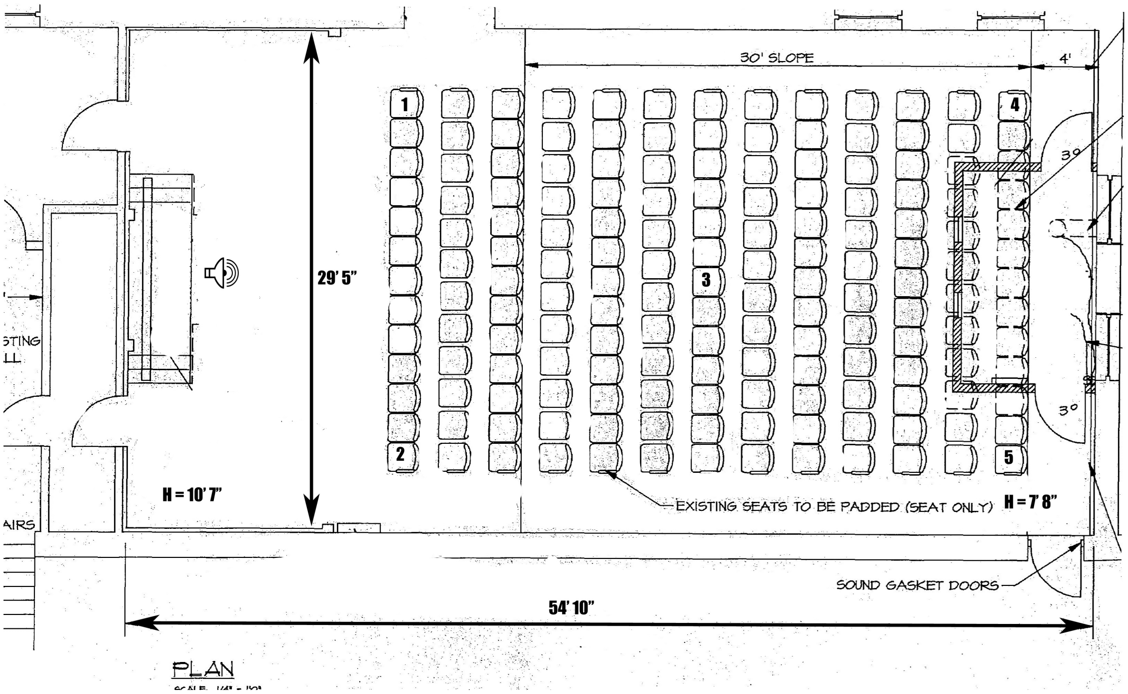

Figure 22: Tucker 120 Floor Plan, Speaker Location, and Recording Points

Tyler 201

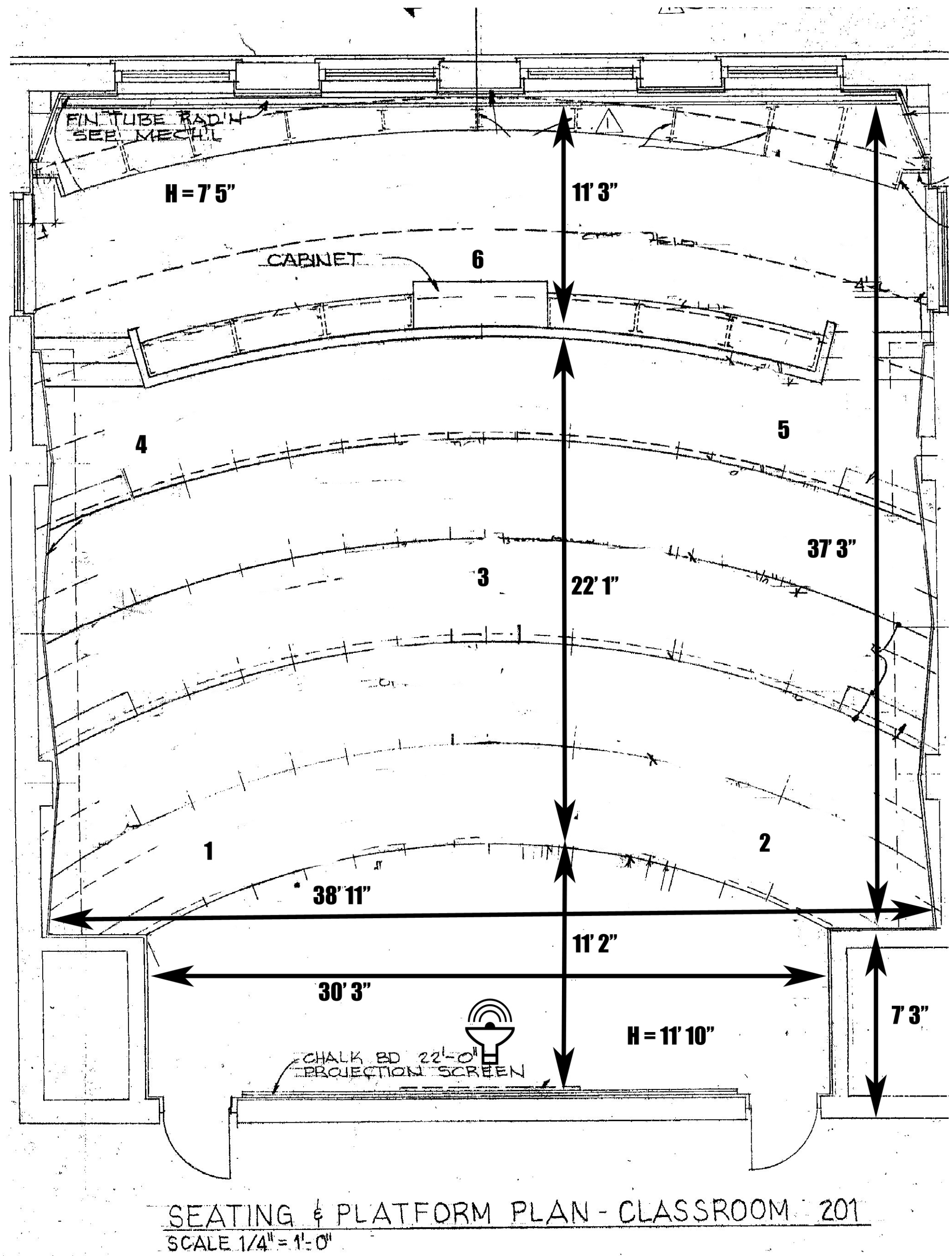

Figure 23: Tyler 201 Floor Plan, Speaker Location, and Recording Points

Washington 201

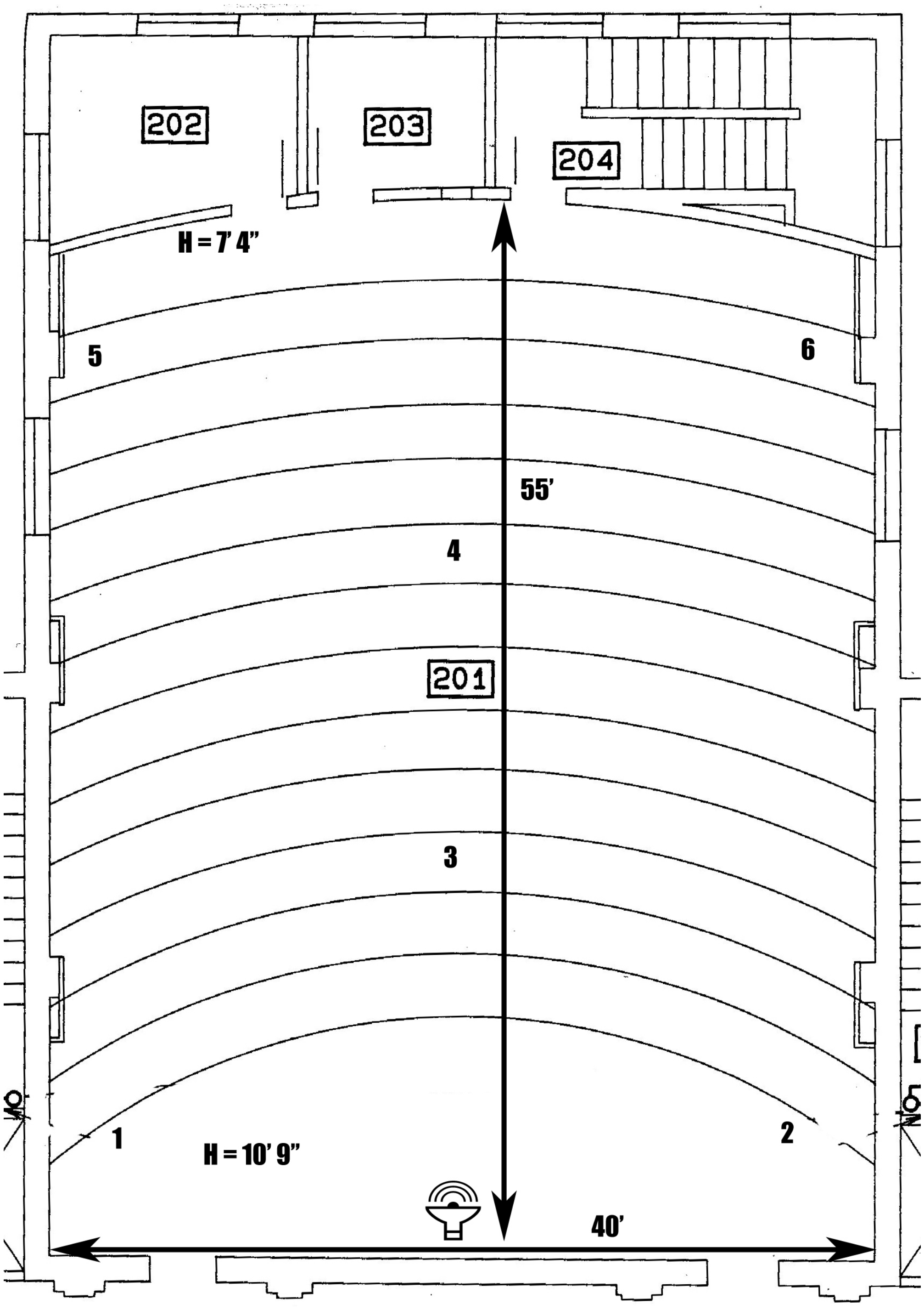

Figure 24: Washington 201 Floor Plan, Speaker Location, and Recording Points

Washington 301

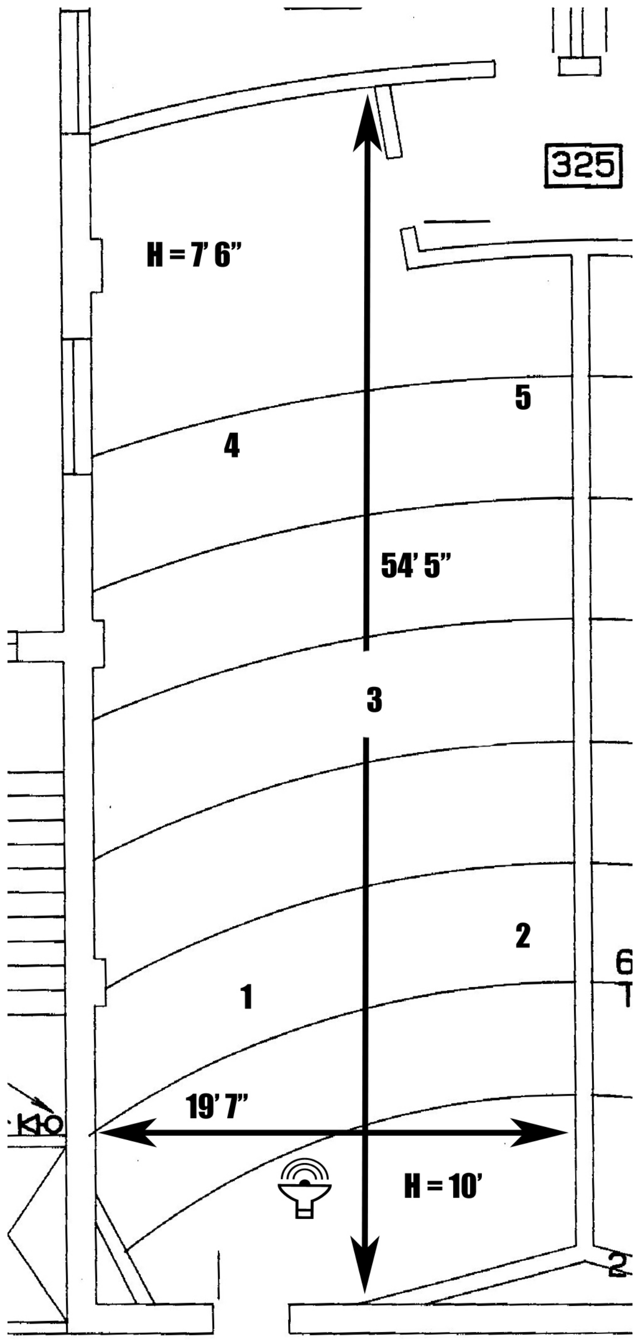

Figure 25: Washington 301 Floor Plan, Speaker Location, and Recording Points

Wren Grammar School Room

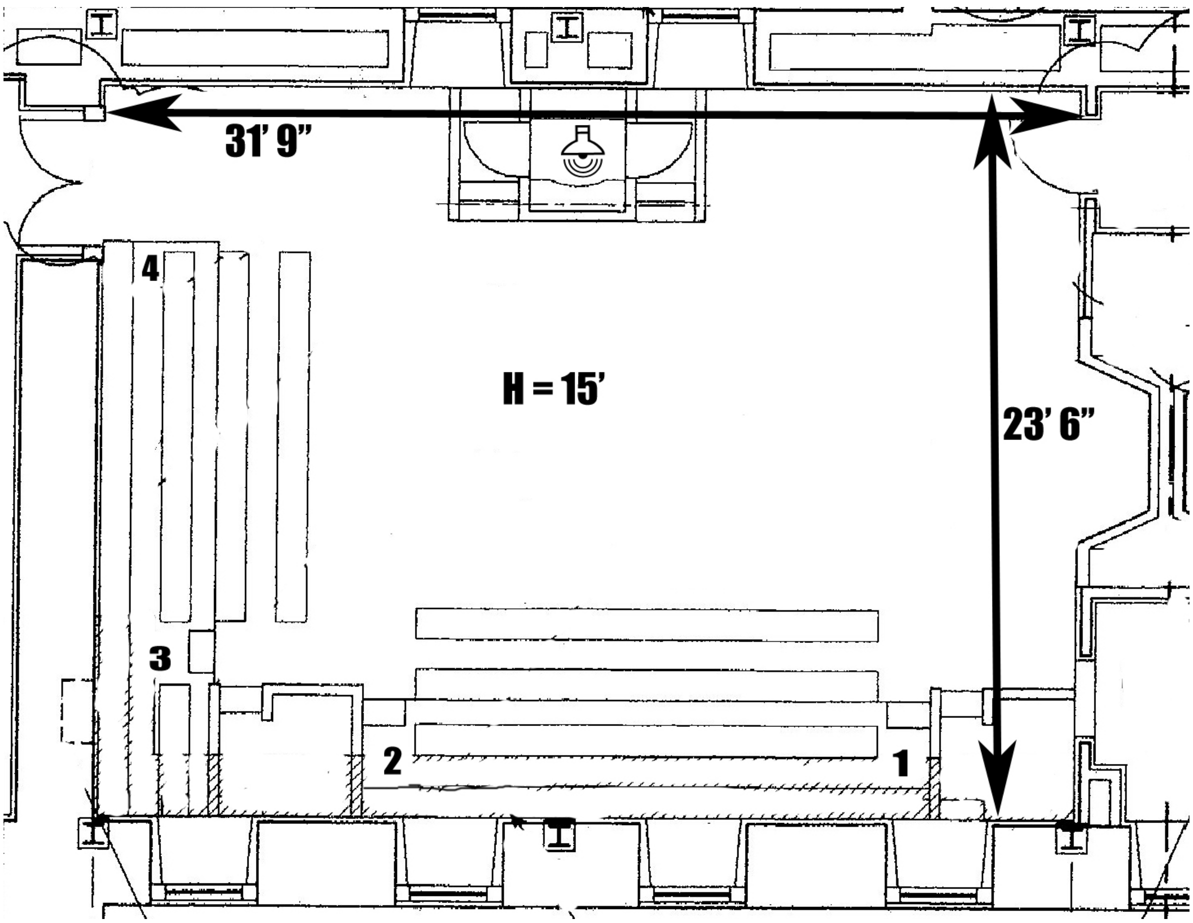

Figure 26: Wren Grammar School Room Floor Plan, Speaker Location, and Recording Points

21 Acknowledgements

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References

[1] Kurt Eggenschwiler. Lecture Halls - Room Acoustics and Sound Reinforcement *ForumAcusticum*, 2005.

[2] Yuki Ishibashi. "A Study of Concert Acoustics: Understanding Phi Beta Kappa Hall." Undergraduate Thesis, College of William & Mary, 2003.

[3] Technical Committee on Speech Communication. Acoustical Barriers to Learning, 2002.

[4] Thomas D. Rossing. *The Science of Sound*. Addison-Wesley, 2nd edition, 1990.

[5] Technical Committee on Architectural Acoustics of the Acoustical Society of America. Classroom Acoustics. August, 2000.

[6] Harold Burris-Meyer & Lewis S. Goodfriend. *Acoustics for the Architect*. Reinhold Publishing Corporation, 1957.

[7] Leo L. Beranek. *Music, Acoustics & Architecture*. John Wiley & Sons, Inc. 1962.

[8] George W. Swenson, Jr. *Principles of Modern Acoustics*. Boston Technical Publishers, Inc. 1965.