Acoustic Properties Foellinger Great Hall in the Krannert Center for the Performing Arts

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Abstract

In this project, we measured various acoustic properties of the Krannert Center for the Performing Arts' Foellinger Great Hall, which was specifically engineered to be an optimal acoustical environment. However, slight inconsistencies are audible to the human ear, so we aimed to pinpoint their locations in the hall and their possible causes. We tested 176 seats, distributed evenly about the concert hall, by recording 220 Hz, 440 Hz, and 880 Hz frequencies generated from a center-stage speaker and taking environmental data, such as the temperature, barometric pressure, and humidity using a printed circuit board device and an audio recording program of our own design. We designed offline analysis programs to determine relationships between the frequency and decay time by studying the amplitude decay of our recordings after our sound source was silenced. We concluded that time decay and amplitude were largely position dependent throughout the hall. We were able to find trends within certain smaller sections (ie: main floor), but not general trends across the entire hall. The effects associated with environmental data are inconclusive, but we hope to further examine these possible correlations in a more controlled environment in future tests.

Introduction

Foellinger Great Hall in the Krannert Center for the Performing Arts opened in 1969. The hall was labeled as an "acoustically perfect space," implying that the performance experience was equally pristine from every seat (see *Acoustical Variation in the Foellinger Great Hall* in Appendix 2). The hall seats 2059 audience members, and is world renowned for its combination of size and acoustic quality. Our goal is to analyze the audio quality of generated sounds in 176 of Foellinger's seats, and find discrepancies, if any, in the sound quality. While there have been previous examinations of the acoustic qualities of Foellinger Great Hall, our methods use modern, inexpensive equipment. Our methods can possibly be replicated and will provide a very affordable way to analyze the acoustic qualities of any space.

Fig. 1: Interior of the KCPA Great Hall

Measurements

We recorded nine sounds at 176 points in Foellinger great hall. There were three frequencies played, three times each: A=220Hz, A=440Hz, A=880Hz. We compared the recordings at each seat by looking at the decay time following the time that our onstage speaker is completely quieted, the peak amplitude of each frequency, and the relative environmental data for each coordinate (temperature, pressure, and humidity). We will analyze the data by comparing distant and close recordings at all three different frequencies. We will then compare these plots to heatmaps of our environmental data to determine if there is any correlation.

Our primary data collection device is an Arduino Mega 2560, which uses an Atmel ATmega2560 at a 16 MHz clock rate with 8 kilobytes of RAM, 256 kilobytes of program flash memory, a built in 16 channel 10 bit ADC, hardware Serial Peripheral Interface (SPI) and Inter-Integrated Circuit communication (I2C), and 54 General Purpose Input/Output (GPIO) pins. We used a custom PCB designed by Professor G. Gollin, which connects various additional components that enable our measurements.

We had a breadboard in earlier stages of our experimental design, but we did not use it in our final data-taking sessions as it operated more loudly (higher RMS value) and was not capable of taking reliable sound data. All of our PCB's averaged an RMS value of 1.5 ADC counts and were therefore more suitable for taking precise sound data.

Listed below is the hardware required to create our devices.

- BME680: a multipurpose sensor we use to measure:
  - Temperature: accurate to 1°C from 0°C to 65°C
  - Pressure: accurate to 0.6 hPa from 300 hPa to 1100 hPa
  - Humidity: accurate to 3%rH from 10%rH to 90%rH
- Keypad: experimenter uses this to control the device
- Liquid Crystal Display (LCD): reports current device status to experimenter
  - Breadboard trim potentiometer (10 kΩ)
- Electret Microphone and MAX4466 amplifier
  - Gain can be set 25x to 125x
  - 3.3 V supply, 1.65 V output bias
  - 600 kHz gain bandwidth
  - Signal/Noise: 60 dBA
  - Sensitivity: -44±2 dB at 1 kHz (1 Pa of sensitivity)
- Real Time Clock, DS3231: used to report current date for file naming
- MicroSD: data are recorded to an 8-GB microSD card in SPI mode formatted with the FAT filesystem using the SdFAT library.
- Sony SRS-X11 bluetooth speaker
  - 6.1cm X 6.1cm X 6.1cm
  - Frequency transmission range: 20-20,000 Hz
  - 44.1 kHz sampling

- Analog Digital Converter (ADC): the Arduino's internal 10-bit ADC was used to read the microphone
    - Uses internal 2.56 V as analog reference
    - Specified to have ±2 LSB absolute accuracy
    - Reading analog signal at 32kHz
- Other installed devices not used in our measurements:
    - INA current sensor
    - ADXL 326 accelerometer
    - Ultimate GPS breakout board

Experimental Setup

Electrical tape was used both to mark on the stage where the bluetooth speaker would go and to mark points equidistant from the speaker (15.3 cm) where our PCB's would sit for every fiducial mark. The diagram below displays our initial set up before each data-taking run. The speaker was placed in the center of the stage with its middle face oriented towards the audience.

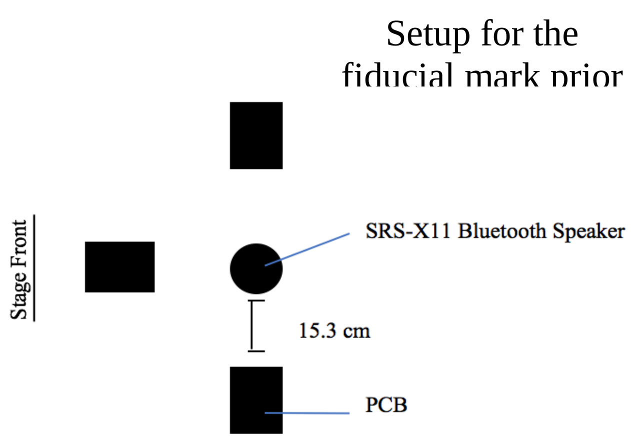


Fig.. 2: Diagram of experimental setup

Fig. 3: Image taken from stage setup

We compiled charts before each data taking session that indicated which PCBs would take data at which coordinates in the hall. Prior to the start of each trial, music stands were set up in the audience at the designated coordinate for each PCB. The height of the stand was just above the back of the seat, at about ear level of the average audience member. We were able to take four data points at a time. We placed all four PCB's on stage at the taped locations (see above image), then moved them to their specified location in the hall after the fiducial tone, and then returned them to the stage for every trial. We needed to have the PCBs on stage at the start and end of the trail because we were using a fiducial mark to synchronize them. A fiducial mark is a sound produced as a reference point that can be identified on every sound recording. In our trials, we use a one-second A = 440 Hz tone. Because the PCBs were equidistant from the speaker at the time of the fiducial mark, it allowed us to properly line up the start of the recording on each PCB. This kind of synchronization is necessary to compare the time delay from when the sound leaves the stage to when it arrives at different seats and to account for slight differences between each PCB.

Data Taking

We took data points at various points that were evenly distributed throughout the concert hall. The data points are marked in green in the seating charts shown below.

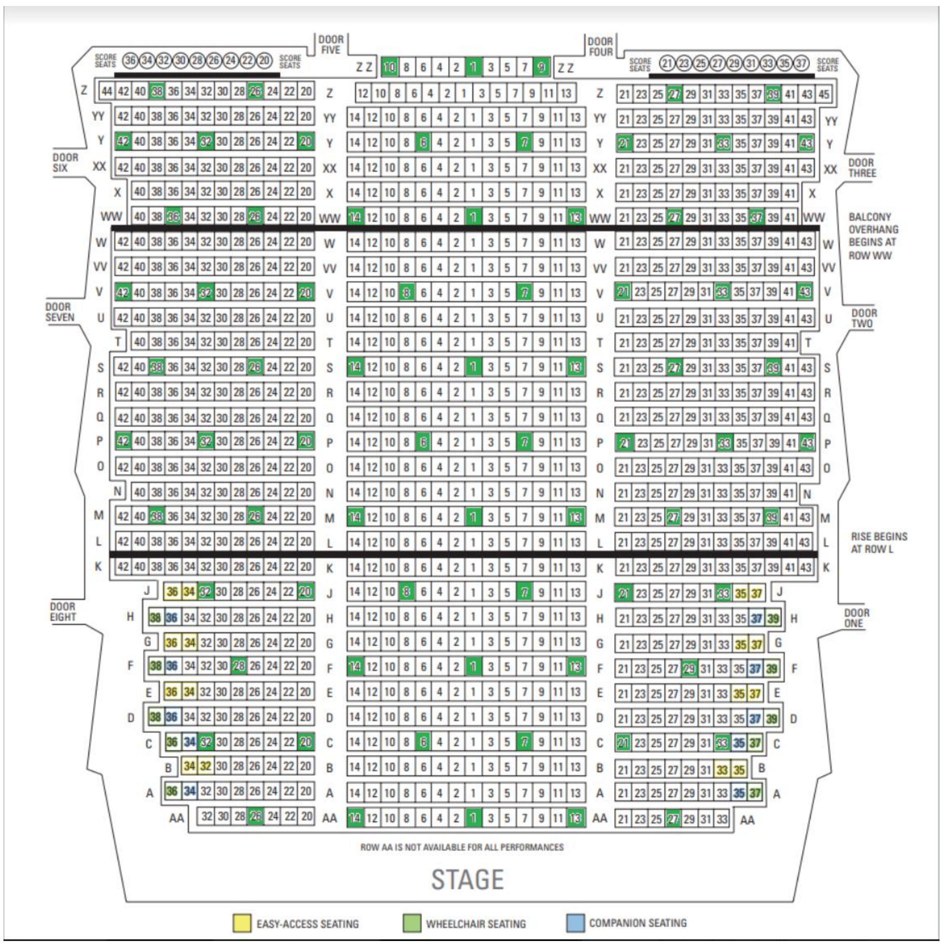


Fig. 4: The green highlighted seats indicate positions where we took data points. The diagram is based on the ticketed seating charts for the main floor made available by the Krannert Center for the Performing Arts

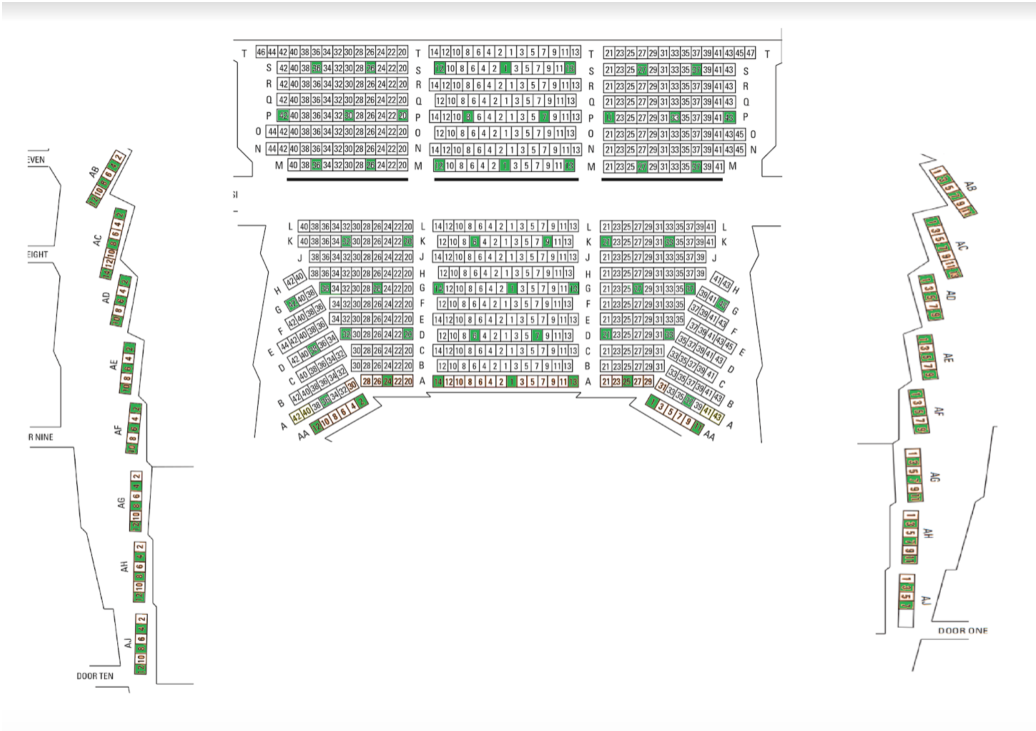
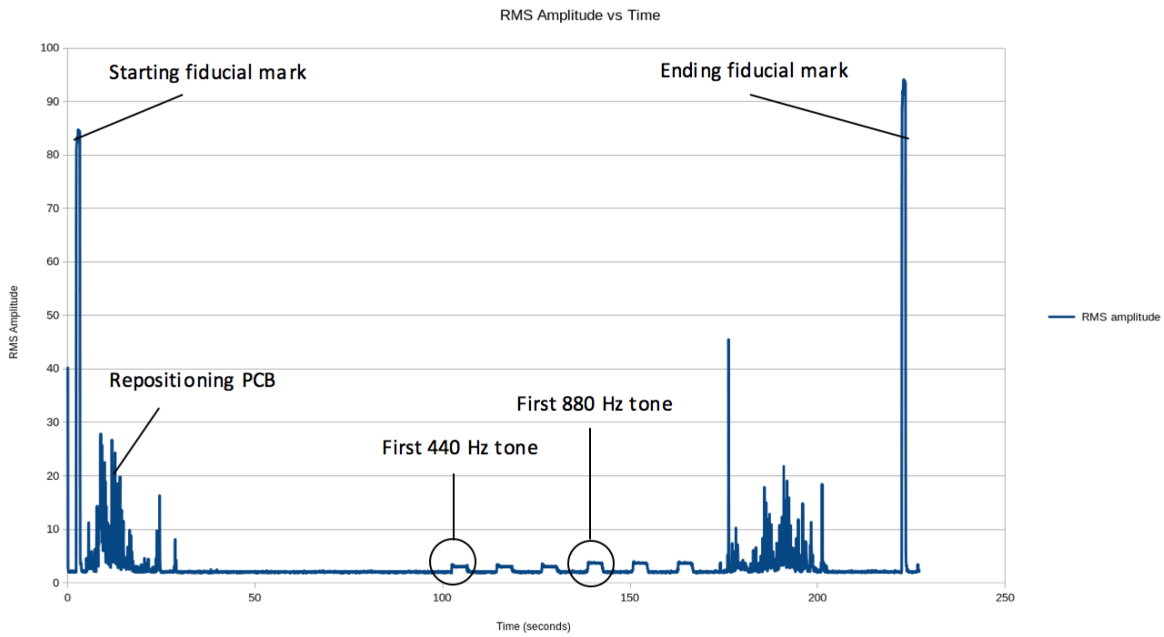


Fig. 5: The green highlighted seats indicate positions where we took data points. The diagram is based on the ticketed seating charts for the balcony and upper level stage-side seating made available by the Krannert Center for the Performing Arts

We decided to play a recording of sinusoidal tones for every trial to make the data as consistent as possible between trials. We used GarageBand to separate different frequency tones with seconds of silence. This GarageBand recording consists of a one-second fiducial mark at 440 Hz, followed by 62 seconds of silence. This allowed us to move the PCBs to their assigned location. Then, a series of nine four-second tones are played, with eight seconds of quiet in between each. We thought eight seconds would allow enough time for decay of each tone. The first three tones played are are 220 Hz, the next three are 440 Hz tones, and the last three are 880 Hz tones. There is then another 56 seconds between the final 880 Hz tone and the ending fiducial mark for the PCBs to be moved back up to the stage. The ending sound is a one- second 440 Hz tone. This recording was saved to an iPhone and connected via bluetooth to the Sony SRS-X11 speaker.

For each trial, we entered in the seat number and row number of the destined coordinate for each PCB and then pressed # on the four keypads to start recording. Once each LCD screen displayed “Recording, press * to stop”, the preset audio recording was played. After the 1 second A=440 Hz fiducial mark occurred, each PCB was taken out into the hall. Within 62 seconds, the PCBs were moved to their respective locations, and the “1” button on the keypad was pressed to instantaneously measure temperature and altitude. We then waited for the nine recorded tones to be played, and then moved the PCBs back up to the stage within 56 seconds and set back equidistant from the speaker for the ending fiducial mark. On the RMS Amplitude vs. Time graph below, you can see the sequence of events that took place following the start of our recording, including the fiducial marks, some repositioning noise, and six of the nine tones from the pre-set recording. Note, the 220 Hz tones cannot be seen with this y-scale.



This concert hall has many possible configurations that can be used depending upon which performance is occurring in the space. There is a wooden divider that can be raised or lowered in the elevated loft in the area behind the stage to allow choruses to perform comfortably. For the stage, there is an extender, about eight meters in length that can be oriented in front of the stage's front edge to provide extra room on the stage for the performers. It is operated by a hydraulic lift beneath the stage, and is interchangeable with an extra row of seating, named row AA that is subsequently available for select performances only. For our experimentation, we kept the hall with the choral divider raised and the stage extended (see below for architectural diagram).

Additionally, the seats throughout the hall, with the exception of those in the back for score study purposes, are covered and padded with material that mimics the density of a clothed human. We took data in an unpopulated hall, but the acoustic properties should be nearly identical with a full audience.

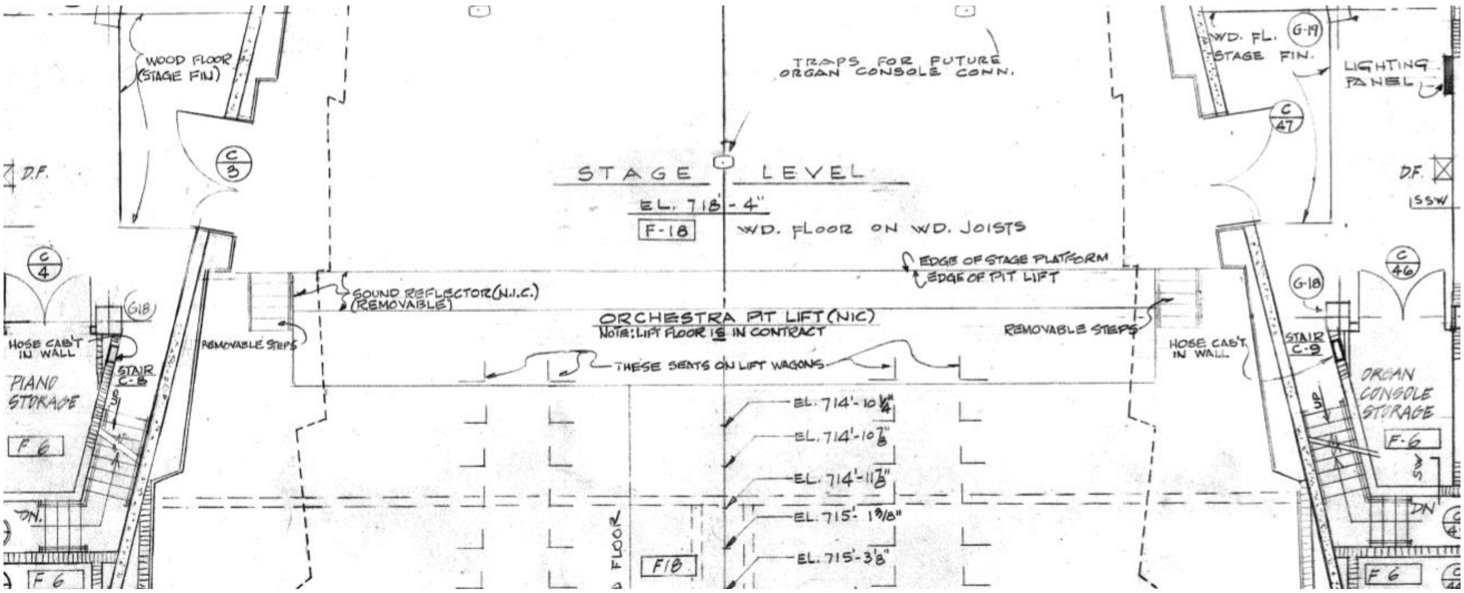


Fig. 6: Here you can see the stage extension present when we did our measurements. It overlaps with one row of seating, which we were not able to take measurements from. In the diagram, it is labeled as the "Orchestra Pit Lift." The diagram is oriented with the back of the stage at the top, and the first few rows of seating at the bottom. This image is available by the courtesy of the University of Illinois Police Department and the Krannert Center for the Performing Arts

Data Acquisition Program

Our Data Acquisition Program prompts first for a two-digit seat number and row number. Every seat in Krannert has a different 4 digit code based on our coordinate system. The LCD then prompts to start recording, and during recording, the user can request that the BME data be taken.

The DAQ has three phases: the setup phase, the information prompting phase, and the recording phase. In the setup phase, the DAQ initializes all hardware, including the BME 680 (temperature, pressure, and humidity sensor), the realtime clock, the LCD screen. Any attached GPS is disabled to reduce noise and then communications with the SD card over SPI at 50 MHz begin. Next, the DAQ retrieves the current date from the RTC, and then creates a folder named the current date in ISO 8601 format, and switches to it. At this point, the information prompting phase begins.

In the information prompting phase, the DAQ asks for the seat and row number of the current data point, and ensures that no datapoint with said numbers already exists. It then constructs the file name, which will be "kDQrr#cc.dat" where the 'r's denote row digits and the 'c's denote column digits. The DAQ then waits for the user to start the recording.

As one might expect, the DAQ records all sound during the recording phase. To prepare for this, the DAQ configures the ADC (analog to digital converter) to take 10-bit samples at 32 kHz using the ATmega2560's internal 2.56 V AREF as the analog reference. Then, it allocates a contiguous temporary file on the SD card to record to, sets all of the bytes in the file to zero, and tells the SD card to begin writing to the start of the file. The empty and full sample block queues are then initialized, and the user is informed that the recording is about to start. The DAQ then starts ADC interrupts -- whenever a new sample is ready, a service routine is called to write it to a buffer block, and if the current buffer is full, move it to the full queue and get a new one from the empty queue. Simultaneously, a loop is entered in which the DAQ writes any full blocks to the SD card and then puts them back in the empty queue, checks for any errors, listens for user input, and takes an asynchronous BME reading if requested. When the user ends the recording, the DAQ stops ADC interrupts, writes out any remaining blocks, then truncates any unused portions of the file and renames it to its final name, and writes out the BME information to a file named "kDQrr#cc.bme". Finally, the DAQ informs the user the the current recording is finished, waits four seconds, and then re-enters the information prompting phase.

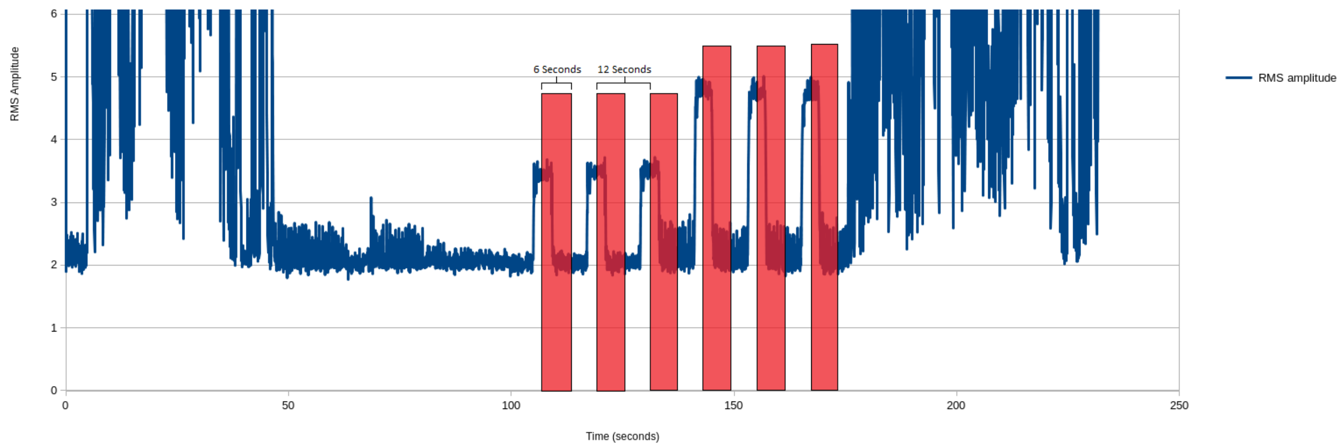
Data Analysis

Sound Decay Data

We needed the amplitudes of the various frequencies over time, so the natural algorithm to use was a Discrete-Time Fourier Transform (DTFT), which slices the sound into small samples and then produces the amplitude of each frequency of the sample. To implement our DTFT, we sliced the data into 50 millisecond slices and used NumPy's Real Fast Fourier Transform (FFT) function on them, and took the absolute value of the result because we did not need the complex phase.

In order to extract the amplitude decay time constant, we fit the decay of amplitude to an exponential function $A(t) = A_0 e^{-t/\tau}$. We graphed the amplitude vs. time for each point in the Great Hall. From those fits, differences in their peak amplitudes and decay times can be analyzed. Examples of 440 Hz sounds and 880 Hz sounds at the front of the main floor, and back of the main floor can be seen below. Our 220 Hz sounds were not loud enough to be sensed at many of the balcony data points, so we have decided not to use any of the 220 Hz data.

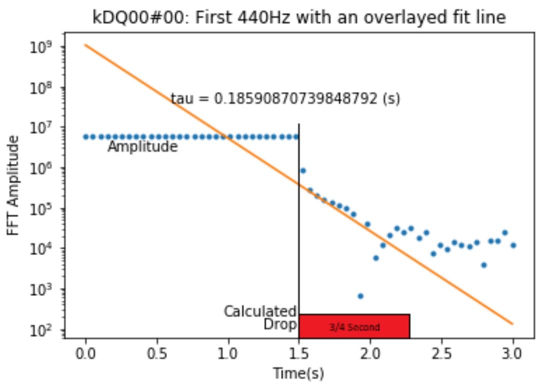
The analysis code finds tau values by reading the FFT amplitude data for six seconds, beginning at a point halfway through a particular tone and ending four seconds after the tone is silenced. For example, the code to find the first tau value for each each trial begins halfway through the first 440 Hz tone. Each subsequent run to find a tau value begins at that base time plus twelve seconds, the length of the four second tone plus the eight second quiet gap (as shown in the red highlighted sections in the sample below). Any fluctuation in the beginning of the analysis time should not be important as long as the sound drop is reasonably centered in the six second analysis frame. This way, we can see the steady tone followed by a drop off in the sound.



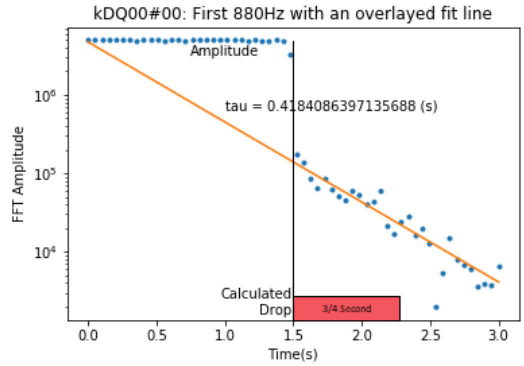
The code then looks for the maximum amplitude over the analysis frame. From that point it parses through the amplitude data until that value drops below half the maximum amplitude. This should give a reasonable estimate of when the sound source turns off. Then the next 750 ms of amplitude data after the half-max time is fitted to a straight line on a log scale using the Numpy function polyfit. The fit line begins at the next data point after the determined half-maximum time. Starting the fit slightly after this drop helps to give a little extra room to avoid analyzing any sound coming directly from the speaker. A 750 ms time-slice was chosen because it included enough amplitude data to find a representative best-fit line, yet not so much as to include sound after the tone could no longer be distinguishable from background noise.

When looking at these graphs, the amplitude should start as a straight horizontal line, followed by a sudden drop. The horizontal line portion represents the time when the bluetooth speaker is playing a constant amplitude tone. The rest of the graph represents how that frequency persists in the hall once the speaker tone ends, as marked by the vertical line, and the part of the graph to the right of the line is what is needed for the analysis of the decay. The best fit line is fitting a τ value (the time constant), which is the negative of the reciprocal of the slope. A smaller τ value means that the sound decays quicker. It should be noted that we are plotting the amplitude of the sound and not the intensity. The fitted line may not follow closely with the data over all time, in some cases the amplitude dropped to the level of background noise really quickly and that is shown in some graphs when the data levels out and the fit line continues downward.

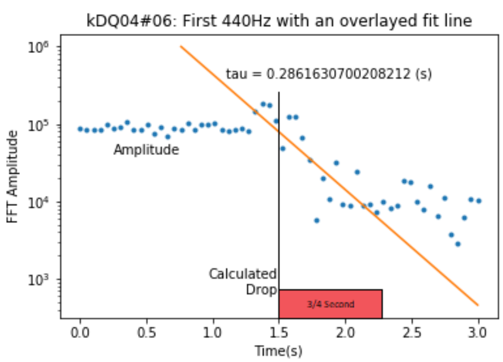
kDQ00#00 is in the front of the great hall, 15.29 cm from the sound source
Tau = 0.185908707



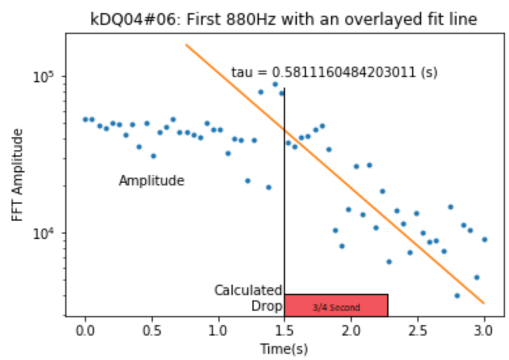
kDQ00#00 is in the front of the great hall, 15.29 cm from the sound source
Tau = 0.4184086397



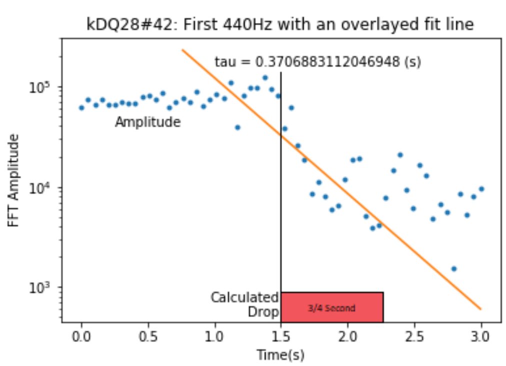
kDQ04#06 is in the front of the great hall, in the 4th row near the center.
Tau = 0.28616307



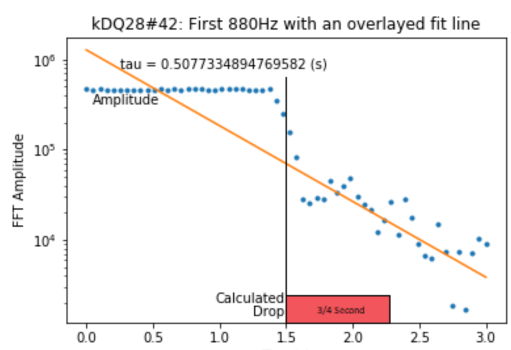
kDQ04#06 is in the front of the great hall, in the 4th row near the center.
Tau = 0.581116



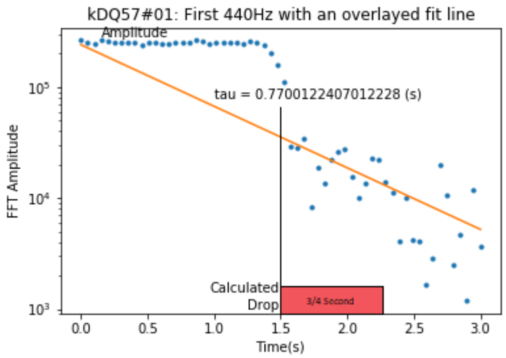
kDQ28#42 is in the back of the great hall, in the 28th row on the far right side.
Tau = 0.370688



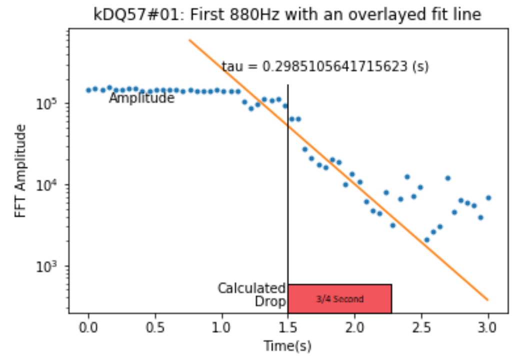
kDQ28#42 is in the back of the great hall, in the 28th row on the far right side.
Tau = 0.507733



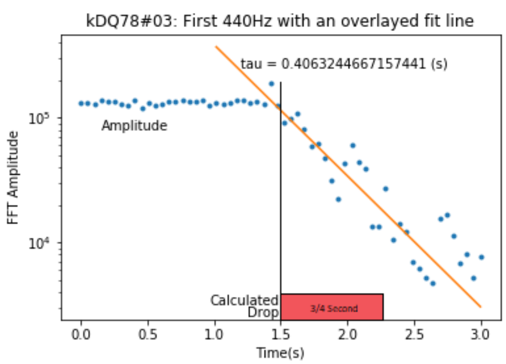
kDQ57#01 is in the center of the balcony, about halfway up
Tau = 0.7700122



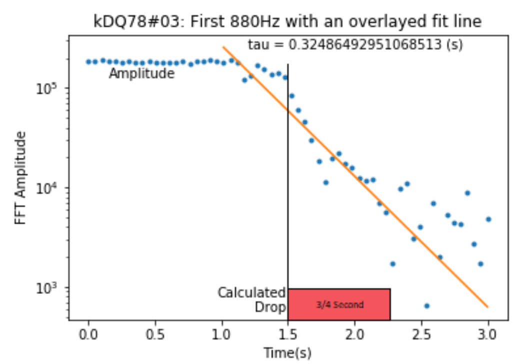
kDQ57#01 is in the center of the balcony, about halfway up
Tau = 0.2985105



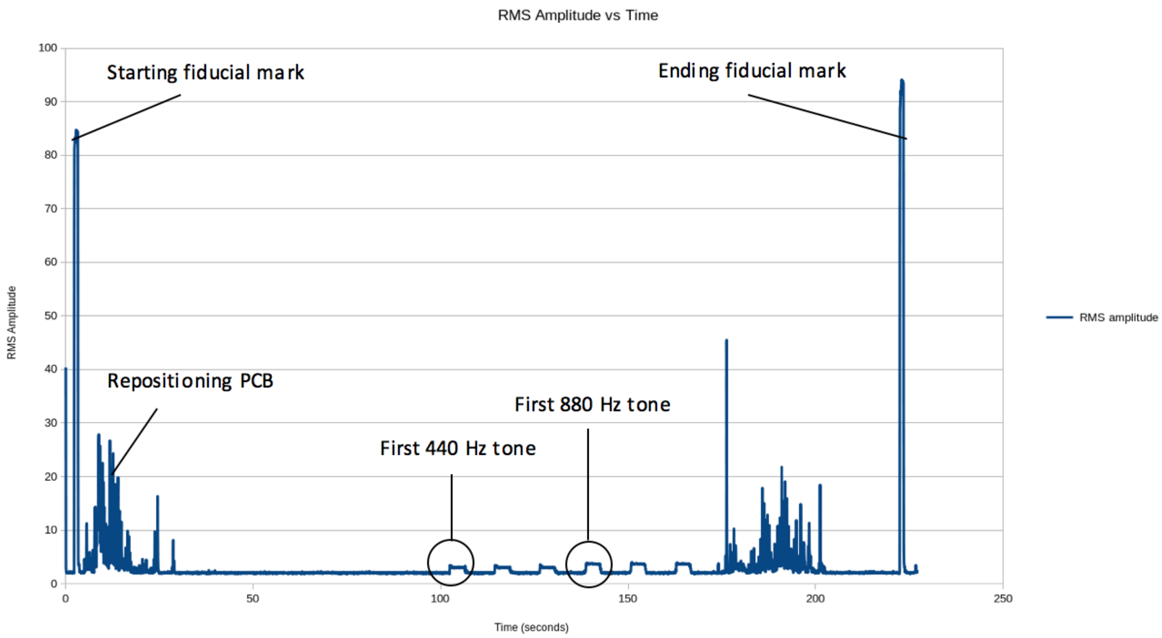
kDQ78#03 is in the side balcony of the great hall, in the 1st row on the left side.
Tau = 0.406324



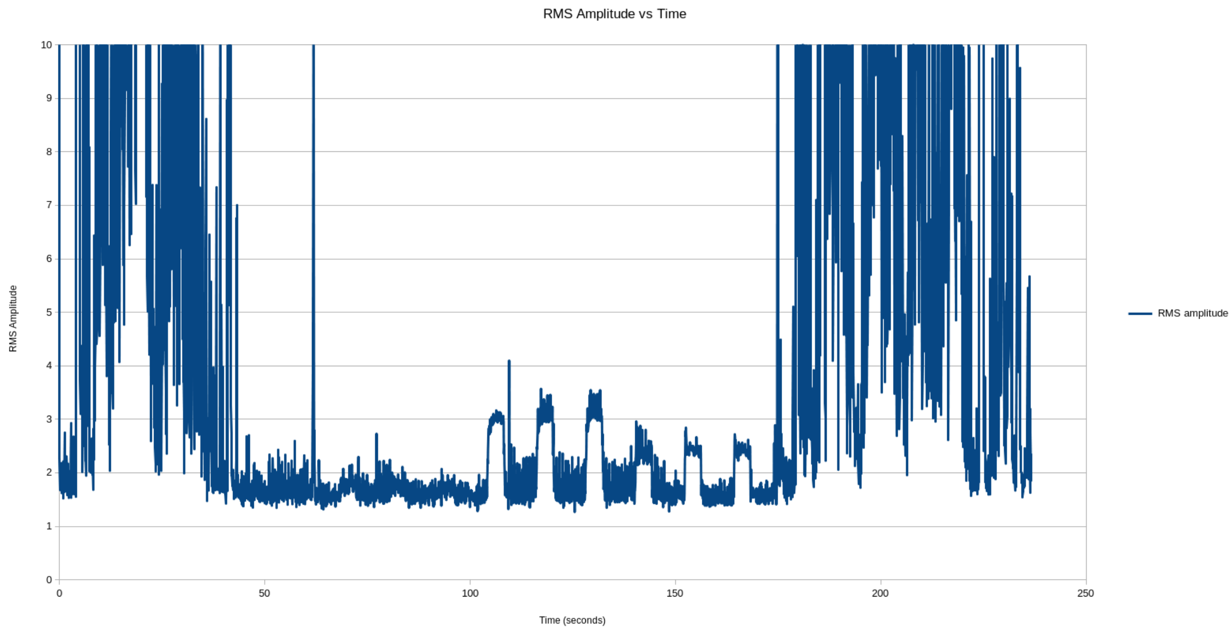
kDQ78#03 is in the side balcony of the great hall, in the 1st row on the left side.
Tau = 0.32486



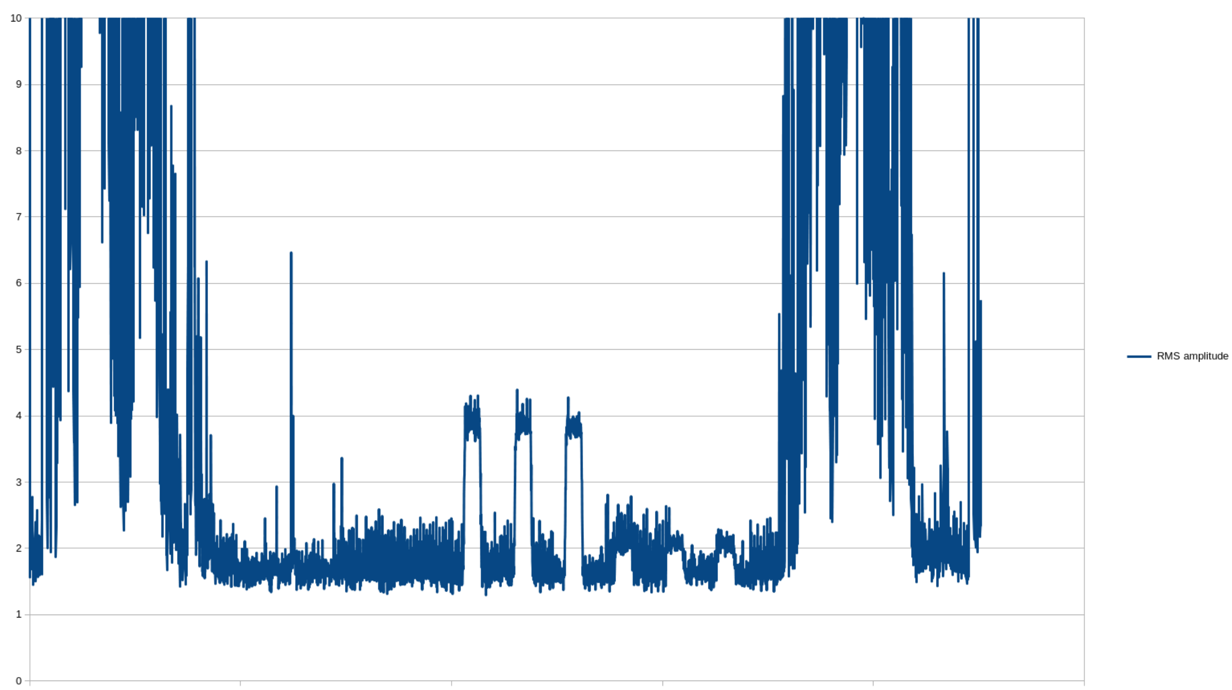
RMS Amplitude



We have included a selection of graphs that showcase the RMS amplitude of some of our trials. A couple things to note in the sample diagram above are the large amplitude fiducial marks at the very beginning and end of the recording. Immediately after the first mark and before the final mark are areas of large and random sound, which is just ambient repositioning sound caused from physically moving the devices from the center stage to their respective recording positions in the audience space. We played nine tones during the recording segment of each trial, six of which are very clear in large y-scales. The 220 Hz tones cannot be easily seen unless looking at very y-small scales, one of the reasons why we have chosen to exclude those tones from our analysis.

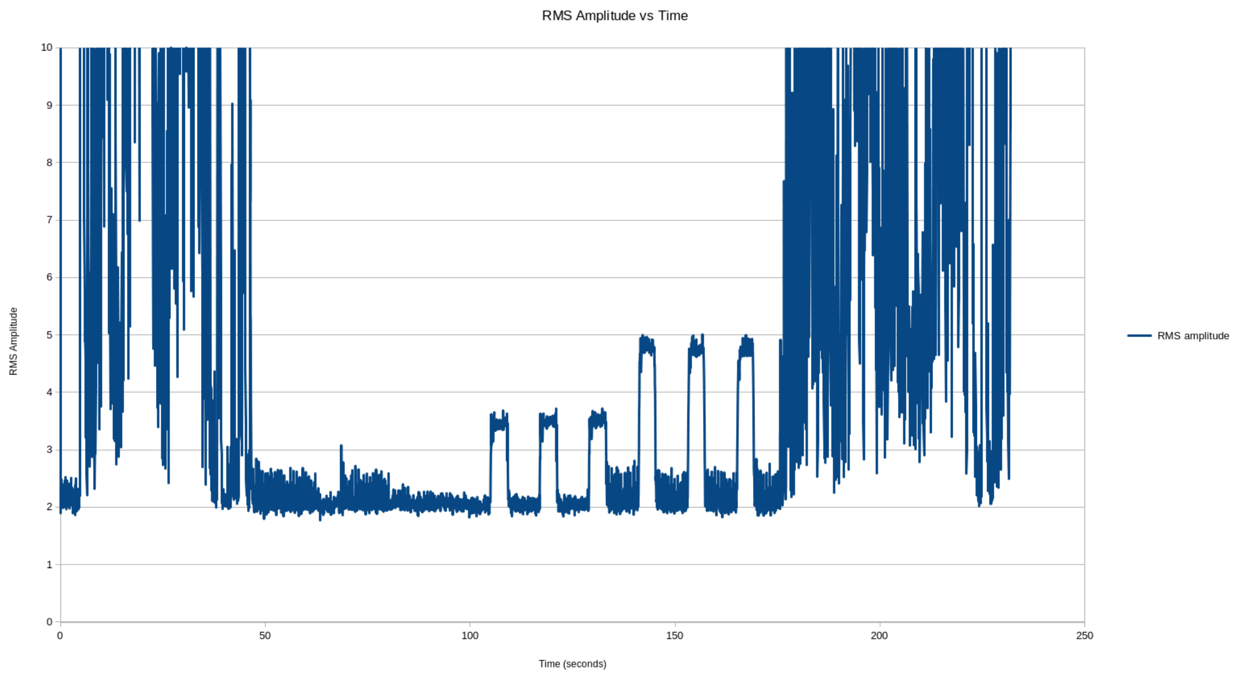


51#37, PCB 1, trial 1, far left front row balcony

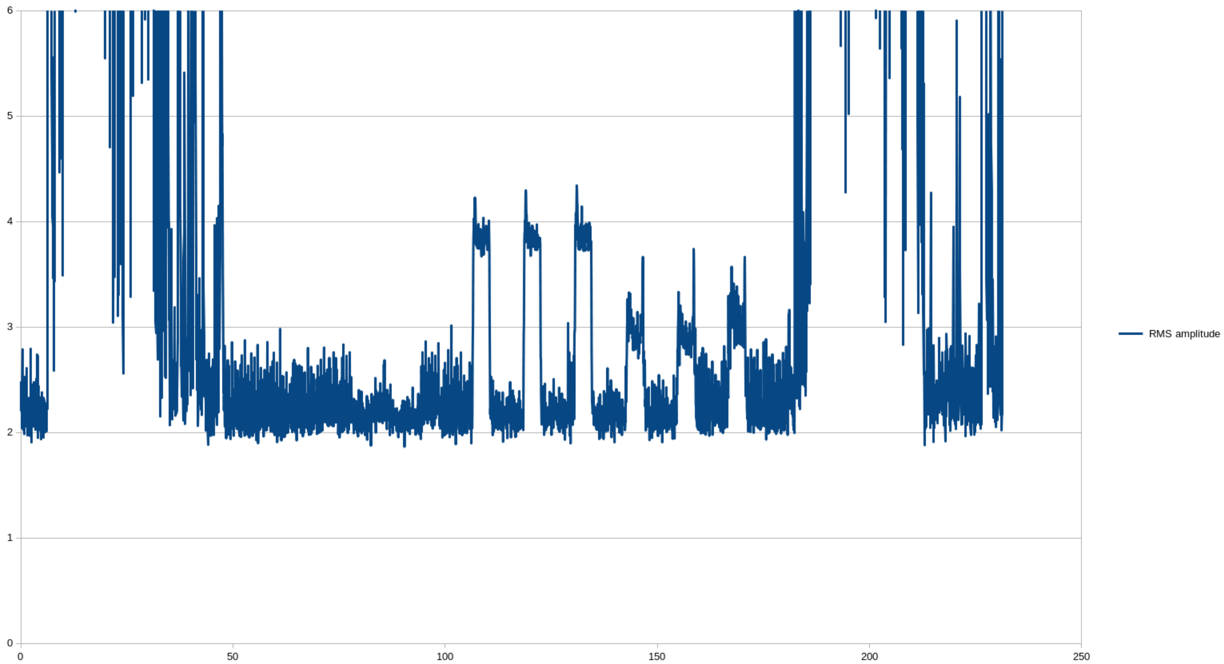


51#13, PCB 1, trial 2, left front row balcony

The data points taken from points 51#37 and 51#13 are both in the same row in the balcony, at similar distances to the sound source, and the recordings were taken by the same PCB. In point 51#37, we see that the amplitude of the 440 Hz tone is nearly twice the 880 Hz amplitude above noise. This relationship between frequencies is entirely subverted by point 51#13 which shows a 440 Hz amplitude three to four times that of the 880 Hz tone. This experimental data leads us to believe that the listening experience in the Krannert Great Hall is not consistent across all locations, even when close together. In instances like these, the balance of low and high pitched instruments in a symphony orchestra could be heard differently depending on the listener's location.

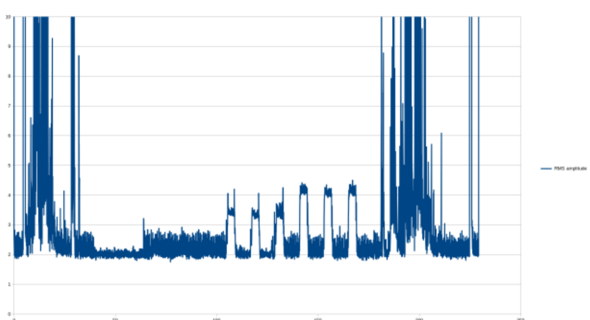


71#03, PCB 2, trial 1, left side balcony

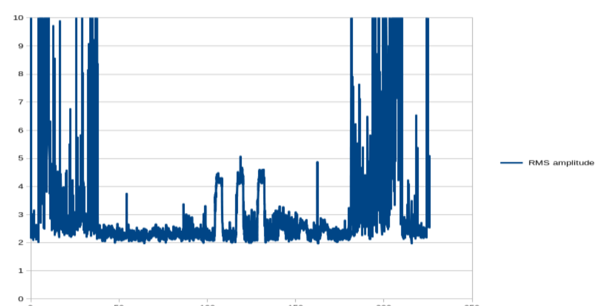


71#11, PCB 2, trial 2, left side balcony

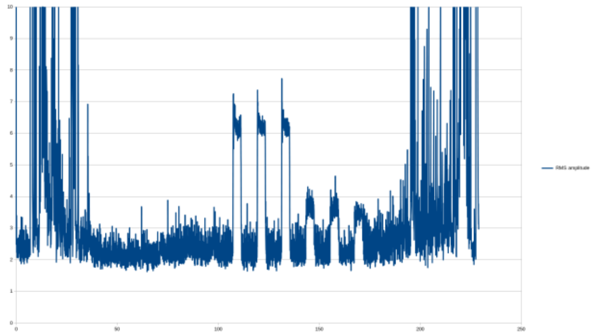
71#03 and 71#11 were taken by the same device in the same row of the side balcony. There are only 3 seats separating these points. What is odd is that the 880 Hz tones of 71#03 are about double the 440 Hz tones, while 71#11 shows the opposite. Because these were taken by the same device within a 10 minute span of time, there aren't many environmental explanations for this difference in frequency perception. The testing that has been done in the Great Hall so far has only been done with a mix of frequencies. Our tests at different frequencies show that the relative amplitudes of these frequencies depend on position. Further testing is needed to expand and model this relationship.



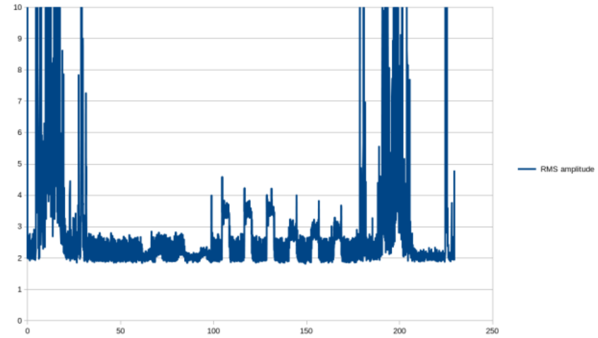
04#07, PCB 3, Trial 1
Main Floor middle-left



04#33, PCB 3, Trial 2
Main floor far left



04#32, PCB 4, Trial 1
Main floor far right



04#21, PCB 4, Trial 2
Main floor left

One argument explaining discrepancies in amplitude could be that the speaker altered the pure sine waves in our recording and that each emitted frequency was at a relatively different amplitude in each trial. We consider this to be unlikely not only because our ears perceived a consistent amplitude, but also because recordings taken in the same trial by different PCBs in close proximity still showed dissimilar results. In trial one, PCBs three and four showed drastically different readings, though they were taken at the same time, particularly for the 440 Hz tone. In trial two, the 880 and 440 Hz amplitudes were closer together for PCB 4 than they were for PCB 3. These changing sound perceptions can be better explained by strong position dependance rather than by an inconsistent sound source.

Environmental Factors

All of the environmental data were obtained using the BME680 sensor. For each data point, a single sample of the temperature, pressure, and humidity was taken. After the data collection, these values were combined into a chart based on seat location, and then transformed into heatmaps, which can be seen on page 20.

Results

Sound Decay

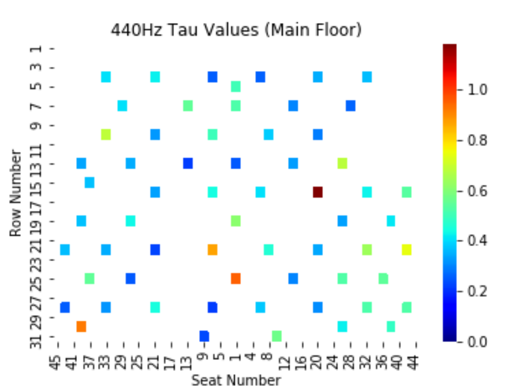
We found that 880 Hz tones tend to persist longer than 440 Hz tones on the main floor, but on the balcony the relationship between 440 Hz and 880 Hz is strongly position dependent. Also, we can conclude that 440 Hz tones last significantly longer in the balcony than on the main floor. The average τ values on the main floor for 440 Hz and 880 Hz are 0.49 and 0.64, respectively. The average τ values in the main floor for 440 Hz and 880 Hz are 0.63 and 0.66, respectively.

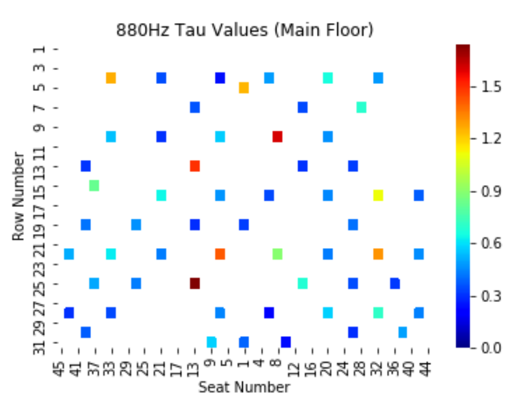
Because our speaker was directional, the main floor recordings received both direct sound and some reverberation, while the balcony seats probably experienced more reverberant sounds compared to the main floor. It makes sense that the 880 Hz tone persists longer in the balcony because higher frequency modes tend to travel up into the space and linger. On the main floor the difference between the 440 Hz and 880 Hz decay rates is much smaller, which makes sense because more of the sound was direct. It would be interesting to try this experiment again with a less directional sound source.

A more rigorous analysis program and a lower signal to noise ratio on the hardware will be necessary to get more accurate numbers. Our offline analysis program had some bugs, and around 15 of our trials were excluded because their tau values didn't reflect a feasible time value. Many of the trials that couldn't be analyzed have odd slopes caused in part by an excessive noise. Many other data points had to be thrown out because they were negative when they should have been positive, or they deviated too far from the nominal range. We also excluded any tau values that were negative or greater than two. This value was chosen both because there were very few points with such anomalous tau values, so it is likely that they were mishandled, and additionally, their inclusion stretches the scales of the graphs, which makes them much less useful.

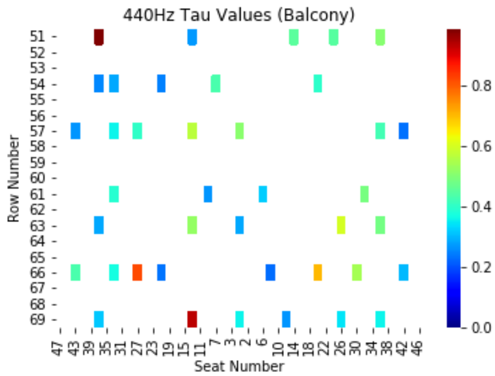
Below, we have colored maps graphing the sound decay on the main floor and balcony for both the 440 Hz and 880 Hz frequencies. The stage is at the top of the graphs, and each successive row is further back from the stage. Ideally, we're looking for some kind of color gradient within the graphs, but note the scales on each graph are different, so the coloration between graphs is not directly comparable.

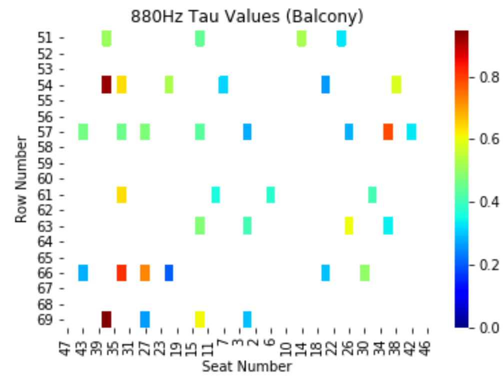
Statistical testing[1] shows a significant difference in the 440 Hz and 880 Hz tau values on the main floor, with the 880 Hz tau values being larger by 2.04 standard deviations (p=0.0206902). Testing did not show significance of any other differences in the tau values. However, the the statistical analysis we have been able to perform has been extremely crude and thus may not be indicate of the actual significance. In particular, the amplitudes were unable to be analyzed due to lack of a model to test against-- we see large differences in the RMS amplitudes of particular frequencies in nearby locations, which indicates that more complicated effects are going on.



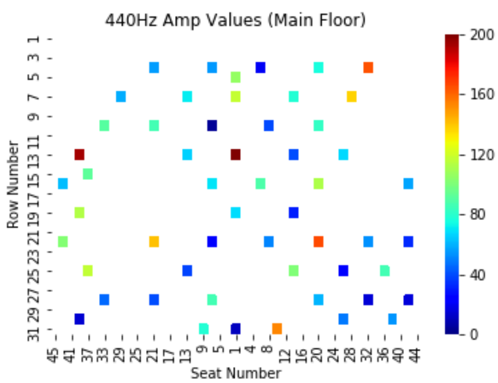


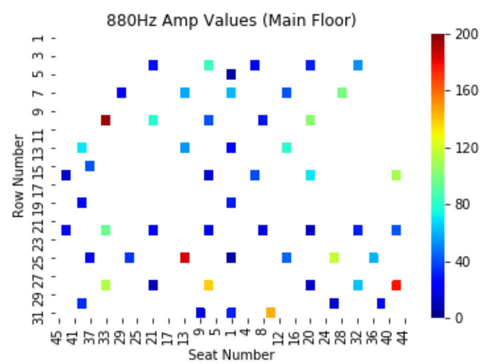
[1] We used a 1-tail two sample unequal variance t-test

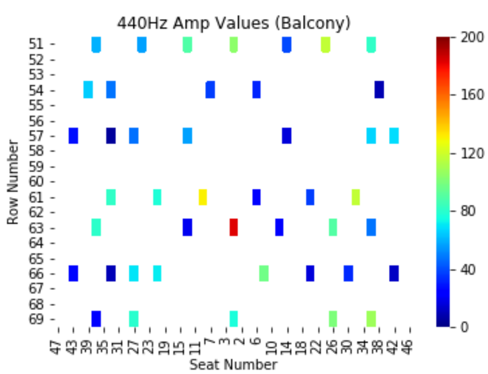


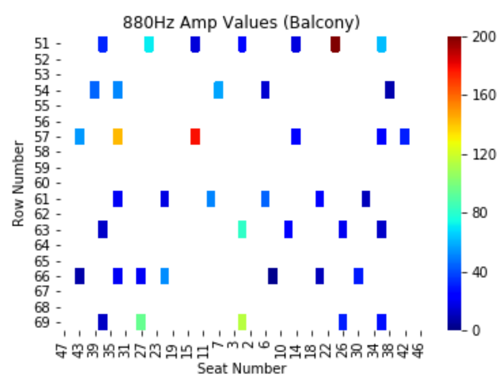


Maximum RMS Amplitude



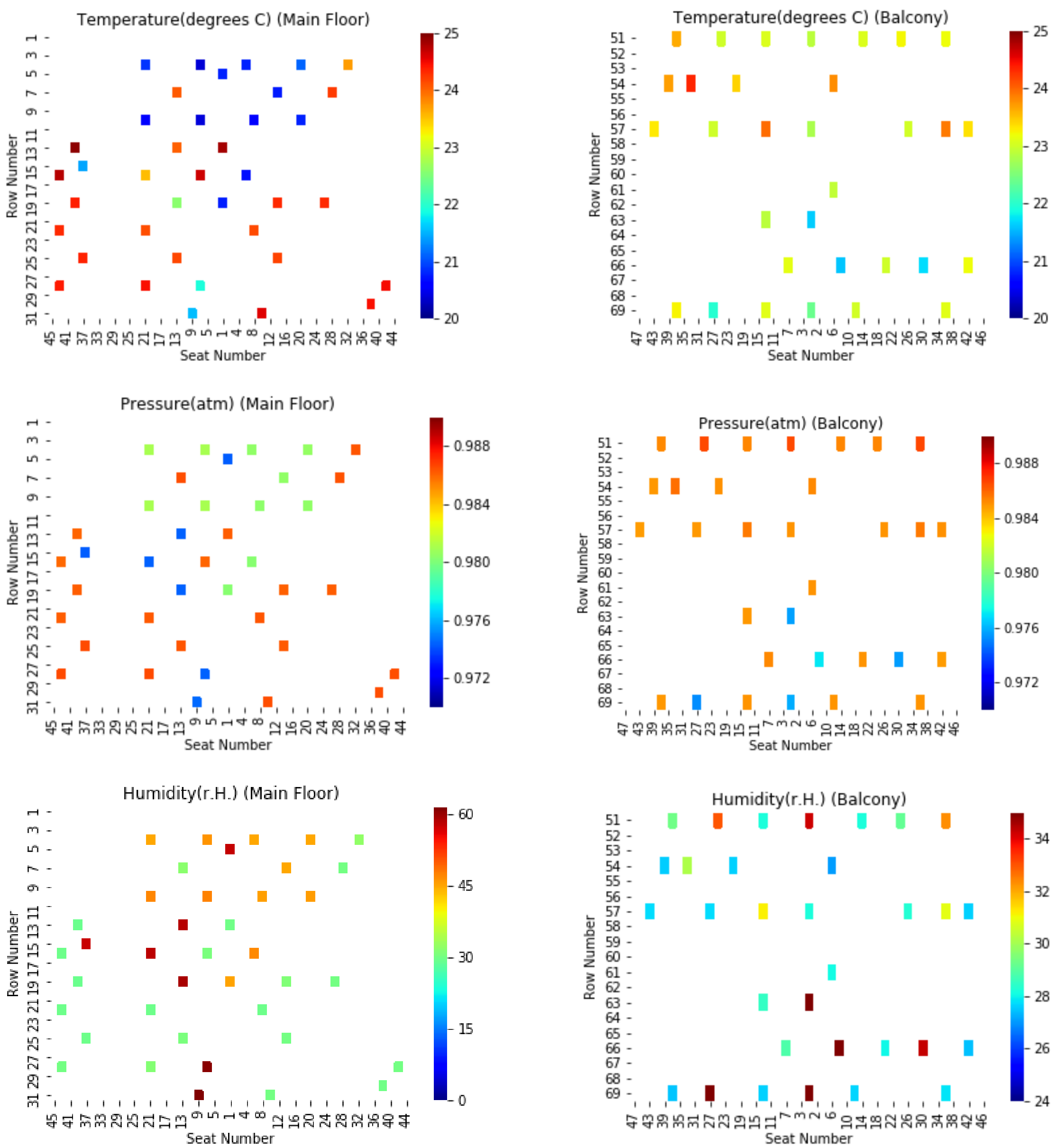






Our RMS amplitude data trends show that the sounds on the main floor get quieter as you move backwards into the hall. Especially at row 22, the sounds noticeably decrease in volume. This makes sense, as the balcony overhang starts at about row 21, and likely blocks some of the persisting sound. In the balcony, the 880 Hz tones are quieter than most other tones in the hall. The values were computed by integrating over the raw RMS amplitudes of the 50 millisecond slices during the center two seconds of each tone and subtracting the integrated RMS amplitudes of silence from three to one seconds before each tone.

Environmental Factors



Accuracy

A large obstacle in the accuracy of our equipment was the quality of the electret microphone. In our recordings, there was a lot of background noise, and sound decay couldn't be detected in the higher frequencies beyond 1-2 seconds after the end of each tone. However, in the higher frequencies, especially in the balcony, a sound decay could be heard by the human ear for 3-4 seconds. Also, the largest decay time ever recorded in the hall was closer to 7 seconds, so our equipment likely was not advanced enough to find comparable data to what's been found before. Our sound source, the SRS-X11 bluetooth speaker was also limited in output amplitude. While the tones could be heard from each seat, more accurate data would have been found with a louder initial amplitude.

Conclusions

We were able to find significant trends in our decay time data. On the main floor only, 880 Hz tones persist longer than 440 Hz tones. Looking at trends involving the whole hall, 440 Hz tones persist longer in the balcony than on the main floor. Our RMS amplitude data surprisingly showed that amplitudes of relative frequencies are largely position dependent. This data also confirmed the prior knowledge that maximum amplitudes decrease as you move backward in the hall. Our environmental data is proving to be irrelevant to the acoustic properties of the hall.

Due to inaccuracies with equipment, we would need to invest in a better speaker, a more sensitive microphone, and a better ADC to obtain more definitive results. During the experiment process, we aurally noticed some discrepancies in the emitted sound that would indicate an impure sine wave, which could explain some of the sound quality imperfections. For future testing, we would consider using an omnidirectional microphone with better frequency response, a louder sound source, and an amplifier that will not distort the emitted sound to a distinguishable degree.

We are confident in our experimental data taking process, and the new perspective it examines with each individual listening experience in mind. We believe the hall to have a position dependent listening experience; however, we are unable to model this specific relationship at this time.

Appendix 1: Raw Data

Due to slight complications in our first testing sessions, a number of our data points do not have reliable environmental data. For all of the graphs and analysis above, only select environmental data points were plotted, denoted below as "N/A." Additionally, some of our maximum RMS amplitude values were negative. For the purposes of our experiment, we are only considering positive values. Maximum RMS amplitude values that were negative are denoted below as "N/A."

Ticketed Row and seat #	**Our Coord-inate System**	**880 Tau Values (in seconds)**	**880 Maximum Amplitude Values (RMS ADC counts)**	**440 Tau Values (in seconds)**	**440 Max Amplitude Values (RMS ADC counts)**	**Temp. (in °C)**	**Humidity (in%)**	**Pressu re (in Pa)**
C6	**(04,06)**	0.4836560955	23.527171	0.2608672156	20.5914653	20.799999	44.914001	99347
C7	**(04,07)**	0.2402542553	83.983531	0.2566396551	54.7282987	20.389999	46.283001	99407
C20	**(04,20)**	0.6611741196	30.551689	0.3503223164	75.8724723	21.129999	44.913696	99361
C21	**(04,21)**	0.3491678009	27.764243	0.4260711936	55.6513093	20.889999	45.103001	99403
C32	**(04,32)**	0.481301424	53.1778732	0.3658922831	164.243746	23.719999	32.384998	99940
C33	**(04,33)**	1.261662615	N/A	0.4073667923	N/A	N/A	N/A	N/A
F1	**(07,01)**	-12.14522491	61.4689283	0.5226803283	117.7349827	N/A	N/A	N/A
F13	**(07,13)**	0.3655444013	58.3237013	0.551331768	71.6613987	24.080000	31.781000	99956
F29	**(07,29)**	2.572006541	20.49146633	0.4094407094	58.95623133	N/A	N/A	N/A
F14	**(07,14)**	0.3458518043	41.691805	0.3036678927	78.4252503	20.760000	44.999001	99349
F28	**(07,28)**	0.6991695741	99.184191	0.2634865424	137.122844	24.219999	30.177999	99950
J7	**(10,07)**	0.5670563945	41.303474	0.5029710371	4.511522667	20.400000	47.365002	99409
J8	**(10,08)**	1.611400739	28.17012467	0.3863636912	39.123022	20.559999	45.530998	99343

J20	**(10,20)**	0.4673615976	102.6982583	0.2935392775	82.13361333	20.790001	45.866001	99349
J21	**(10,21)**	0.303683008	79.356377	0.3258216915	86.606498	20.620001	47.173000	99409
J33	**(10,33)**	0.5451830946	195.23004	0.6841327945	90.86023833	N/A	N/A	N/A
M1	**(13,01)**	-55.21199268	22.18350267	0.2529161696	317.1799517	24.840000	29.789000	99928
M13	**(13,13)**	1.491732614	55.34955067	0.2207951577	65.943015	24.030001	58.462002	98735
M14	**(13,14)**	0.3016587101	80.08681733	0.331052944	40.49634033	N/A	N/A	N/A
M26	**(13,26)**	0.3201465199	N/A	0.6794943478	67.346506	N/A	N/A	N/A
M27	**(13,27)**	-2.5866422	N/A	0.3490439296	N/A	N/A	N/A	N/A
M39	**(13,39)**	0.3095107738	70.481291	0.3412375315	193.2220817	24.940001	29.434999	99911
P6	**(16,06)**	0.3438994715	39.93140833	0.4081764664	88.467522	20.690001	46.889999	99327
P7	**(16,07)**	0.4719999319	14.08409	0.4475740891	69.855608	24.650000	30.669000	99909
P20	**(16,20)**	0.4551454589	71.093616	1.181604716	111.8950337	N/A	N/A	N/A
P21	**(16,21)**	0.6420201329	N/A	0.3331322039	N/A	23.549999	58.294998	98735
P32	**(16,32)**	1.113136356	N/A	0.42981496	N/A	N/A	N/A	N/A
P42	**(16,42)**	0.3779017888	110.344705	0.5360830168	57.80655433	N/A	N/A	N/A
S26	**(19, 26)**	0.4105939784	N/A	0.3323704266	N/A	24.330000	30.044001	99924
S1	**(19,01)**	0.3205189712	30.40028933	0.6105548191	68.70434233	20.770000	45.320000	99323
S13	**(19,13)**	0.2986173156	N/A	2.46469948	N/A	22.590000	59.250000	98735
S27	**(19,27)**	0.4661334954	N/A	0.4354633265	N/A	N/A	N/A	N/A
S38	**(19,38)**	2.455815674	N/A	0.415783393	N/A	N/A	N/A	N/A

S39	**(19,39)**	0.4156869808	26.495116	0.3699976188	112.908117	24.389999	29.525000	99924
V7	**(22,07)**	1.419875002	19.89687367	0.871224701	23.75531333	N/A	N/A	N/A
V8	**(22,08)**	0.896884841	17.61850867	0.4617908427	51.07943833	24.160000	29.716000	99940
V20	**(22,20)**	0.4349176288	11.737468	0.3439708533	166.3500023	N/A	N/A	N/A
V21	**(22,21)**	0.4303263409	22.0609	0.2264852445	140.809747	24.139999	29.716125	99938
V32	**(22,32)**	1.311326701	30.872101	0.6383907785	53.453445	N/A	N/A	N/A
V33	**(22,33)**	0.6258351659	94.66727	0.3496897963	N/A	N/A	N/A	N/A
V42	**(22,42)**	0.4579898589	41.762408	0.7449255442	33.36414233	N/A	N/A	N/A
V43	**(22,43)**	0.514368997	25.461126	0.3649738158	102.159319	24.330000	29.761999	99924
WW26	**(25, 26)**	0.3528011754	117.007342	0.5293939167	23.89897367	N/A	N/A	N/A
WW1	**(25,01)**	-1.630700977	6.628965333	0.9549977721	N/A	N/A	N/A	N/A
WW13	**(25,13)**	1.742003475	184.5657477	-2.752157604	38.72719433	24.170000	30.645000	99942
WW14	**(25,14)**	0.6857633789	44.746462	0.3040585819	101.3761377	24.190001	30.184999	99938
WW27	**(25,27)**	0.4353025942	35.88396733	0.2498318412	N/A	N/A	N/A	N/A
WW36	**(25,36)**	0.31455422	60.47894267	0.5474196891	86.24879133	N/A	N/A	N/A
WW37	**(25,37)**	0.5070420741	22.89894067	0.5510672119	116.6071007	24.360001	29.614000	99971
Y6	**(28,06)**	0.2186191883	N/A	0.3807652089	N/A	N/A	N/A	N/A
Y7	**(28,07)**	0.4450750064	138.419721	0.2202811188	85.96988567	21.920000	60.764999	98735
Y20	**(28,20)**	0.574591818	12.69286333	0.3093670144	60.707056	N/A	N/A	N/A
Y21	**(28,21)**	-1.2006887380	8.900208	0.4484051975	40.231796	24.459999	31.427000	99965

Y32	**(28,32)**	0.7081293859	63.003244	0.5235760412	15.510521	N/A	N/A	N/A
Y33	**(28,33)**	0.3437295739	112.627946	0.3223858846	45.48649767	N/A	N/A	N/A
Y42	**(28,42)**	0.4378180988	178.118084	0.5269406448	15.77155	24.480000	30.170000	99962
Y43	**(28,43)**	0.300820365	N/A	0.258028282	N/A	24.400000	30.211000	99967
Z26	**(30,26)**	0.2953757587	13.50061233	0.4259025401	48.90985433	N/A	N/A	N/A
Z38	**(30,38)**	0.4944971518	24.24658	0.4886135647	54.02256267	24.459999	29.819000	99960
Z39	**(30,39)**	0.3746470677	33.24451867	0.9195749303	14.39602567	N/A	N/A	N/A
ZZ1	**(31,01)**	0.3913268614	31.18512333	23.94073144	11.311909	N/A	N/A	N/A
ZZ9	**(31,09)**	0.577153672	17.42453267	23.94073144	78.16945033	21.549999	61.480000	98745
ZZ10	**(31,10)**	0.2334274012	144.6057207	0.5679873815	153.3396147	24.580000	30.106001	99956
Balcony								
AA1	**(50,01)**	0.9131734407	47.060453	0.4270062684	85.427619666	24.070000	32.603001	99968
AA2	**(50,02)**	0.400090646	30.625672999	0.2675558597	54.64210933	23.920000	33.408001	99975
AA11	**(50,11)**	0.620846725	7.73276233	0.237754163	139.86406233	24.110001	32.283001	99981
AA12	**(50,12)**	0.4340565726	77.027102333	0.237754163	56.583018666	24.150000	32.861000	99981
A1	**(51,01)**	0.7074444338	25.976027666	0.3946370414	104.39295466	22.889999	34.250999	99969
A13	**(51,13)**	0.4465983722	16.055069666	0.2714056265	89.363064666	23.080000	28.252001	99838
A14	**(51,14)**	0.5256325586	17.176764666	0.4551966258	39.823232333	23.080000	28.252001	99838
A24	**(51,24)**	0.3329586001	202.32155	0.4502476827	116.947721	23.230000	29.195999	99844
A36	**(51,36)**	-0.0818050772	62.01910433	0.5091671334	81.641893	23.190001	32.369999	99974

A37	**(51,37)**	0.5076393314	32.34906966	0.9890765992	59.4096533	23.639999	29.365999	99832
D6	**(54,06)**	-6.061401261	14.54403366	1.13973268	32.33346566	23.799999	27.068001	99836
D7	**(54,07)**	0.3160092576	57.73756999	0.434300909	36.806712999	N/A	N/A	N/A
D20	**(54,20)**	0.2603371216	N/A	0.3993135903	N/A	N/A	N/A	N/A
D21	**(54,21)**	0.528641143	N/A	0.2499423788	N/A	23.430000	27.636000	99818
D33	**(54,33)**	0.638764258	51.8385100	0.2863559901	47.685675666	24.350000	30.162001	99885
D37	**(54, 37)**	0.9280670376	N/A	0.2561740737	N/A	N/A	N/A	N/A
D38	**(54,38)**	0.5817652693	8.22508566	2.015834614	8.71531333	N/A	N/A	N/A
D39	**(54,39)**	-112.3615477	46.32846966	0.3639471193	80.22582600	23.7000001	27.597000	99802
G1	**(57,01)**	0.2784602524	N/A	0.5130721812	N/A	22.790001	28.226000	99808
G13	**(57,13)**	0.4336657204	178.89490766	0.5715106836	56.61433200	23.980000	31.200001	99866
G14	**(57,14)**	3.561645387	24.371452333	1.255111986	15.75988133	N/A	N/A	N/A
G26	**(57,26)**	0.282275518	N/A	1.360432359	N/A	23.020000	28.298000	99812
G27	**(57,27)**	0.4768946265	N/A	0.4031514581	47.33103966	22.990000	27.739000	99800
G36	**(57,36)**	0.7859622864	23.02577400	0.4251963099	66.97121500	23.900000	30.889999	99866
G42	**(57,42)**	0.335990559	31.22371166	0.2331826873	68.200045	23.340000	27.625000	99814
G43	**(57,43)**	0.4649769117	55.300364666	0.2670563046	27.937470666	23.320000	27.756001	99791
K6	**(61,06)**	0.3800928824	44.54794533	0.3243173668	25.39967500	22.920000	28.101000	99808
K9	**(61,09)**	0.3600617416	51.464706	0.2700606361	131.133883	N/A	N/A	N/A
K32	**(61,32)**	0.4106404502	10.61653166	0.4896030187	116.48276033	N/A	N/A	N/A

K33	**(61,33)**	0.6397868864	20.9121466	0.3908504985	81.52738066	N/A	N/A	N/A
M1	**(63,01)**	0.4086837961	81.77149266	0.287480933	183.00159533	21.629999	35.522999	98860
M13	**(63,13)**	0.4797588327	N/A	0.5246361238	19.5885466	22.879999	28.528000	99800
M26	**(63,26)**	0.6063473939	20.22586033	0.5992962036	89.875003999	N/A	N/A	N/A
M36	**(63,36)**	0.3415254794	13.248733	0.4831964469	47.83363266	N/A	N/A	N/A
M37	**(63,37)**	1.293855316	12.85674866	0.2885018976	80.84052600	N/A	N/A	N/A
P7	**(66,07)**	10.0455044	N/A	-4.110197054	N/A	23.129999	28.871000	99830
P8	**(66,08)**	1.509977573	2.589274666	0.2299105435	96.989371	21.600000	35.520000	99002
P20	**(66,20)**	0.2979915524	10.51681533	0.7052620766	16.176180000	22.990000	28.080000	99810
P21	**(66,21)**	0.2043298132	52.77973466	0.2361002892	71.372437999	N/A	N/A	N/A
P30	**(66,30)**	0.4996355016	30.13020066	0.5428531909	32.986480999	21.709999	34.348000	98852
P33	**(66,33)**	0.8122918544	20.39893866	0.372294785	9.92228833	N/A	N/A	N/A
P42	**(66,42)**	1.27039015	N/A	0.3022702889	12.1555133	23.190001	27.469999	99791
P43	**(66,43)**	0.2818991562	7.29249800	0.4365282002	26.29815866	N/A	N/A	N/A
S1	**(69,01)**	0.2963217912	114.66418233	0.3593433503	77.17265533	22.389999	35.960999	98882
S12	**(69,12)**	1.417637989	N/A	0.2674482531	N/A	23.020000	27.653000	99808
S13	**(69,13)**	0.6120432917	N/A	0.9365258692	N/A	23.120001	27.628000	99812
S26	**(69,26)**	-0.7378928511	31.15506966	0.3474997227	100.6081766	N/A	N/A	N/A
S27	**(69,27)**	0.2648223665	94.97433400	4.41318725	79.927782	21.980000	35.271000	98821
S37	**(69,37)**	0.9481590439	12.33267266	0.3169210416	23.72962866	23.250000	27.521000	99804

Side Balcony								
AB3	**(71,03)**	0.657473312	108.62958433	0.3198091186	59.28612299	22.959999	33.119999	99920
AB4	**(71,04)**	0.4638430076	123.18448966	0.3813858627	98.02771033	23.809999	32.688000	99928
AB7	**(71,07)**	0.516279763	34.59247433	1.353710471	75.47924566	23.620001	32.588001	99852
AB8	**(71,08)**	0.5329012826	26.6792733	0.3940660441	26.6792733	20.730000	31.885000	98903
AB11	**(71,11)**	0.3372112847	32.497262	0.8484464704	67.94738533	23.000000	33.657001	99922
AB12	**(71,12)**	0.5891201398	41.64186166	0.3417172302	55.44180600	23.770000	32.192001	99930
AC1	**(72,01)**	0.2010922691	107.392938	0.2730309411	308.079405	23.600000	31.839001	99854
AC2	**(72,02)**	0.2273579544	93.74707833	0.3163522955	173.55836866	21.420000	35.043999	98997
AC7	**(72,07)**	0.3224085012	62.11119400	0.3445712108	114.47771766	23.190001	33.161999	99940
AC8	**(72,08)**	0.5133258694	129.25871800	0.2738834685	44.75129066	23.820000	32.953999	99952
AC13	**(72,13)**	0.2908205041	N/A	0.355710969	N/A	23.910000	26.872000	99910
AC14	**(72,14)**	0.6254047106	9.66831266	0.6271279058	58.72689966	20.740000	31.728001	98899
AD1	**(73,01)**	0.355780044	53.61330133	0.642453399	70.93957133	23.270000	32.381001	99944
AD2	**(73,02)**	0.3562337348	138.64628533	0.2888404908	93.293835	23.750000	31.986000	99966
AD5	**(73,05)**	0.2498368313	62.32200033	0.3379125921	106.211616	24.280001	31.125999	99991
AD6	**(73,06)**	1.289794515	71.13250133	0.4924281439	82.33633200	21.469999	35.924999	98991
AD9	**(73,09)**	0.3810303884	11.01688733	0.3201109372	76.7353133	N/A	N/A	N/A
AD10	**(73,10)**	0.4740294876	60.37622033	0.5795409216	48.64925133	22.240000	52.888000	98843
AE2	**(74,02)**	0.3373335625	46.54776599	0.4804631867	110.10062833	22.240000	52.775002	98835

AE5	**(74,05)**	0.4018477686	17.13669133	0.6742225896	42.871603	24.180000	31.927000	99944
AE9	**(74,09)**	0.3696305089	150.71002766	0.2791321124	104.10349266	N/A	N/A	N/A
AE10	**(74,10)**	0.2875150178	28.49615033	0.3096818348	88.78268966	22.059999	53.702999	98825
AF1	**(75,01)**	0.5321987116	9.85923833	0.265244205	271.918153	23.990000	32.091999	99938
AF2	**(75,02)**	0.3163968288	54.78639899	0.6447703779	184.0851166	22.040001	54.640999	98823
AF5	**(75,05)**	0.2911698072	N/A	3.133132181	N/A	23.379999	26.556999	99900
AF6	**(75,06)**	0.340413548	80.24377766	0.2268998591	48.82552900	22.190001	54.500000	98812
AF9	**(75,09)**	0.4323788722	31.19207466	0.47137618	103.38278599	24.020000	31.836000	99924
AG3	**(76,03)**	0.5218157681	53.58569299	0.3956533982	93.16870066	23.870001	31.320999	99983
AG8	**(76,08)**	-1.358640054	69.353451	0.6282492389	33.42514833	22.080000	57.102001	98823
AG11	**(76,11)**	0.2692974401	N/A	0.2518908773	N/A	23.330000	26.754000	99897
AG12	**(76,12)**	1.62081425	46.02168933	0.2993851784	7.85757266	N/A	N/A	N/A
AH3	**(77,03)**	0.440953548	42.09513833	0.3637707769	101.78191733	23.530001	32.360001	99922
AH4	**(77,04)**	0.3200019196	102.335700999	1.29889328	185.7407783	21.150000	32.324001	98913
AH7	**(77,07)**	0.6432263951	4.75381733	0.2494031163	57.6371560	23.620001	31.830999	99973
AH8	**(77,08)**	0.49177	58.209937999	0.344256885	72.35437633	21.889999	58.317001	98776
AH11	**(77,11)**	0.2202752019	44.1783693	0.3193699169	144.4170743	23.340000	33.098000	99938
AJ3	**(78,03)**	0.394256788	58.9249553	0.377800707	41.5064216	23.360001	27.087999	99897
AJ7	**(78,07)**	0.237216118	65.6874973	0.3959195738	198.5503003	23.340000	32.998001	99938
AJ8	**(78,08)**	0.3714107471	4.2004203	-7.595753605	105.1024713	21.309999	60.035999	98741

AJ12	**(78,12)**	0.2444888883	116.0331756666	0.2154350433	78.933433	21.530001	60.101002	98741

Appendix 2: Cited Sources

Adafruit Industries. (2018)

Adafruit BME 680 - Temperature, Pressure, Humidity, and Gas Sensor, https://www.adafruit.com/product/3660

Adafruit DS3231 Precision RTC Breakout, https://www.adafruit.com/product/3013

Electret Microphone Amplifier - MAX4466 with Adjustable Gain, https://www.adafruit.com/product/1063

MicroSD card breakout board+, https://www.adafruit.com/product/254

Harrison & Abramovitz Architects, Lev Zetlin & Associates Structural Engineers, and Cosentini Associates Mechanical & Electrical Engineers. (1966) "Phase 2: Krannert Center for the Performing Arts," *A-24, A-25, A-26*, and *A-27*, Access provided by the University of Illinois at Urbana-Champaign Police Department and the Krannert Center for the Performing Arts

Hook, Julian Lee. (1989) *Acoustical Variation in the Foellinger Great Hall, Krannert Center for the Performing Arts*

Krannert Center for the Performing Arts. (2018) Retrieved from https://krannertcenter.com/about-center/our-venues/foellinger-great-hall

Krannert Center for the Performing Arts. (2018) "Great Hall Balcony" Retrieved from https://krannertcenter.com/sites/krannertcenter.com/files/GreatHallBalcony.pdf

Krannert Center for the Performing Arts. (2018) "Great Hall Main" Retrieved from https://krannertcenter.com/sites/krannertcenter.com/files/GreatHallMain.pdf

Wimsatt, Jeff . *(1978) An Acoustical Study of Four Concert Halls at the University of Illinois, Urbana*