Acoustics Measurements and Model of NEST+m's Auditorium

The Cooper Union for The Advancement of Science and Art

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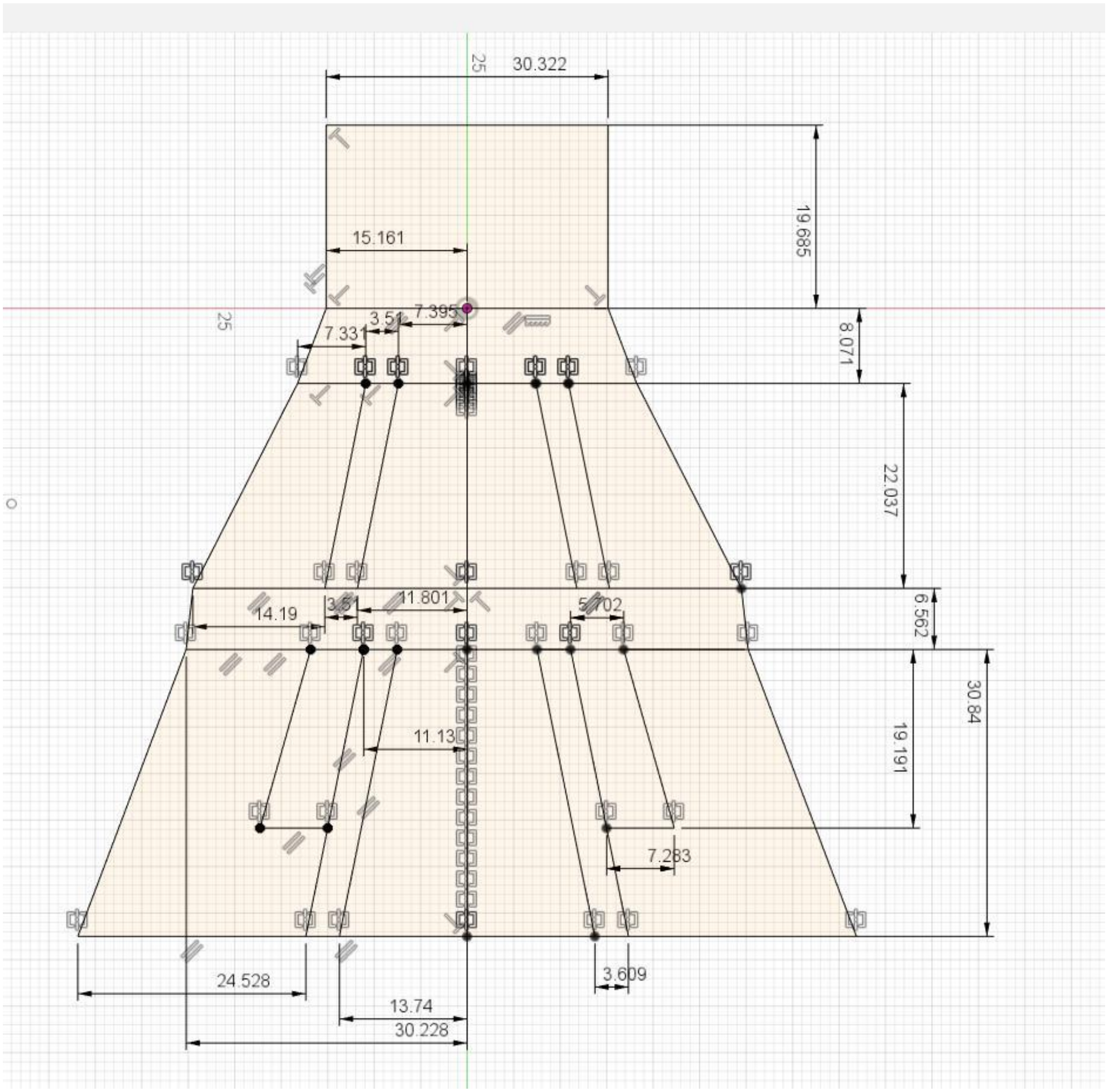
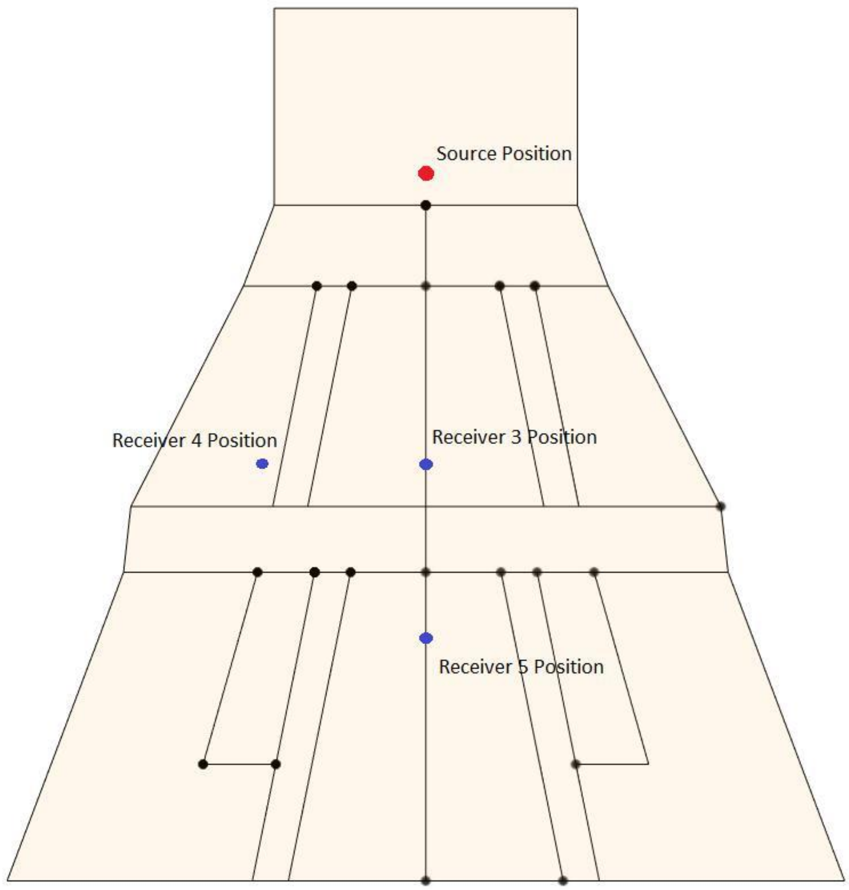
Contents

Schematic of NEST+m Auditorium

Below is a detail schematic of the top-viewed NEST+m auditorium. Dimensions are labeled in feet.



Below is a schematic of the NEST+m auditorium with source and receiver position labeled. Initially, 8 receiver location were measured. However, for the purpose of this project, only data recorded from receiver position 3, 4, and 5 is being analyzed. The distance between receiver 3 and source is 29.12ft, distance between receiver 4 and source is 31.52ft, and distance between receiver 5 and source is 46.51ft.



Data Acquisition and Measurement Analysis

Data Acquisition

For each receiver position, measurement of the data is performed using data acquisition (DAQ) NI USB 4431 interface, and microphones are configured with IEPE power. Sampling rate is set at 44100.

The signal analyzed is a logarithmic sine sweep with frequency range from 20 Hz to 22000 Hz. The signal time series is plotted after recording to ensure that data is properly collected. The sine sweep lasts for 2 second and then followed by a 2 second silence for response decay. The sine sweep is given by $\sin(\phi(t))$, where the phase $\phi(t)$ is given by

$$\phi(t) = 2\pi f_1 \left[\left(\frac{f_2}{f_1} \right)^{\frac{t}{T_p}} - 1 \right] \left(\frac{T_p}{\ln \frac{f_2}{f_1}} \right)$$

Where f_1 and f_2 are the minimum and maximum frequency, respectively. T_p is the length of the sine sweep.

From the collected signal data, a synchronous average with 10 data sets of the response is performed to reduce the signal noise level. From the averaged results, we apply fast-Fourier transform (FFT) to obtain the output signal linear spectrum. We also perform FFT on the input signal to obtain the input signal linear spectrum. The ratio of the output linear spectrum Y(f) to input linear spectrum X(f) is the frequency response function (FRF) H(f), from which we take the inverse fast-Fourier transform (IFFT) to calculate the impulse response function.

$$H(f) = \frac{Y(f)}{X(f)}$$

In this analysis, we specifically look at the octave band frequencies of 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz. Since our measured signal is a sine sweep from 20 Hz to 22000 Hz, we apply octave band filter on the calculated impulse response using filter b and a coefficients. These coefficients are determined with MATLAB command butter, assuming a third order filter.

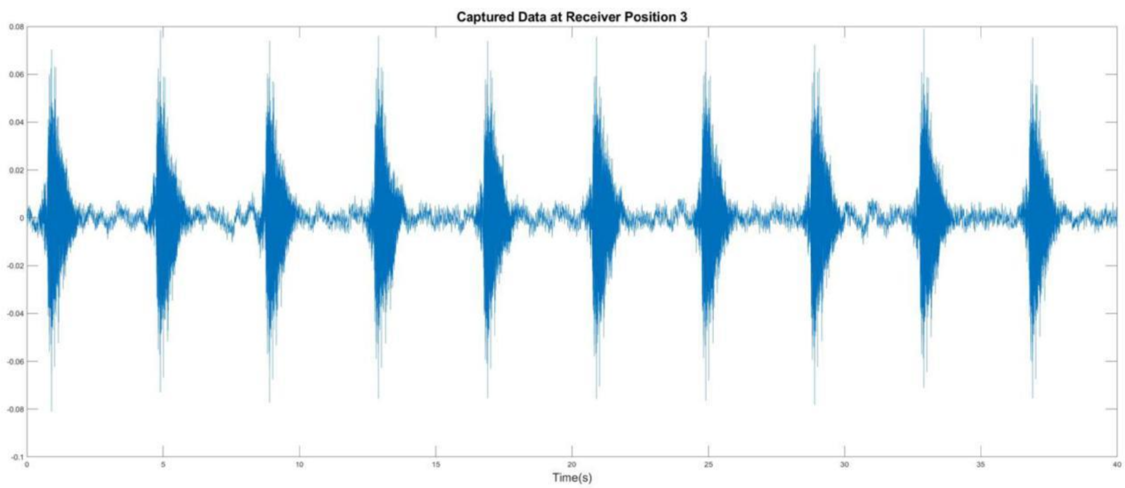
With the octave band filtered impulse response, we calculated and plotted the Schroeder Energy Decay Curve (EDC) in decibel for each octave band frequency. Using the EDCs, we compute the reverberation time RT60 using the following scheme:

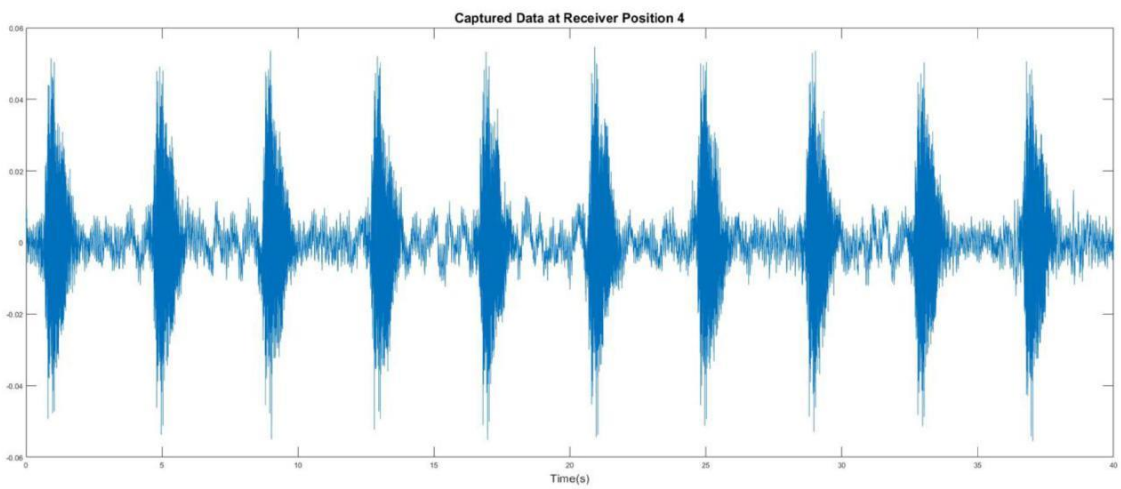
1. Locate on plot the time when EDC graph drops 60 dB below reference (-5 dB), this is the RT60 reverberation time
2. If the EDC does not reach a 60 dB drop, locate the time when 30 dB drop is achieved, and multiply the time by 2 to obtain equivalent reverberation time T30. If EDC does not reach 30 dB drop, locate time of 20 dB drop, and multiply time by 3 to get T20. If EDC does not reach 20 dB drop, locate time of 15 dB drop, and multiply time by 4 to get T15.

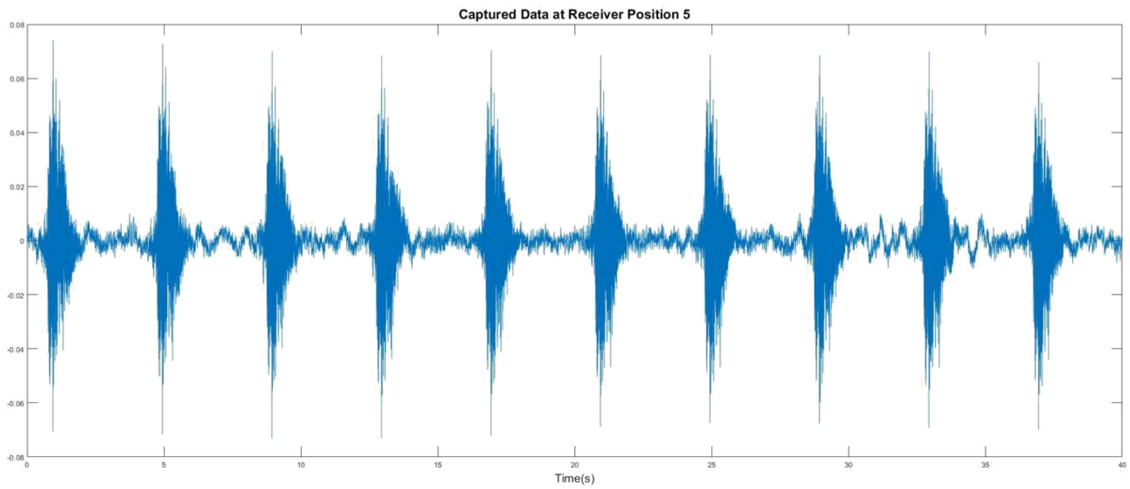
See Appendix A for measurement analysis code, and Appendix B for reverberation time calculation.

Results

Captured Data at each receiver position

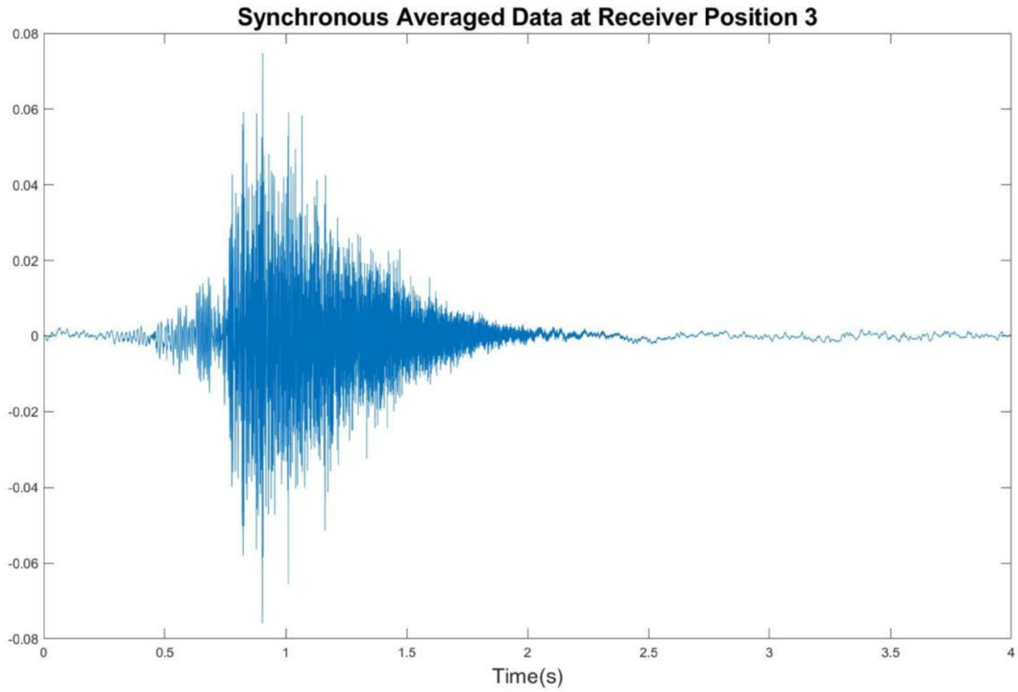


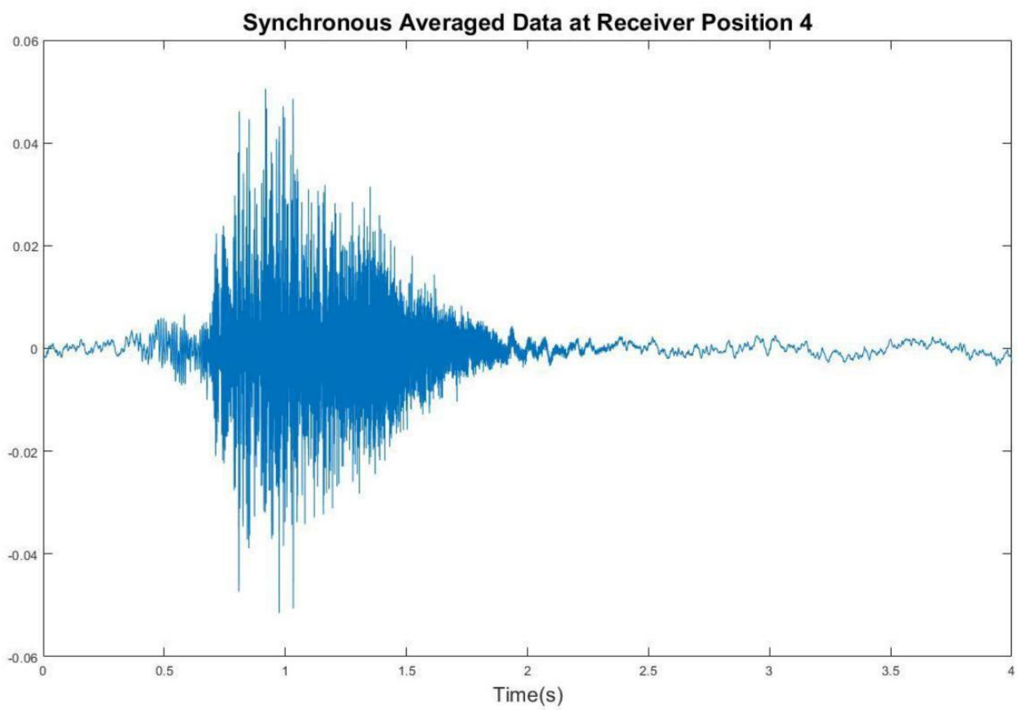


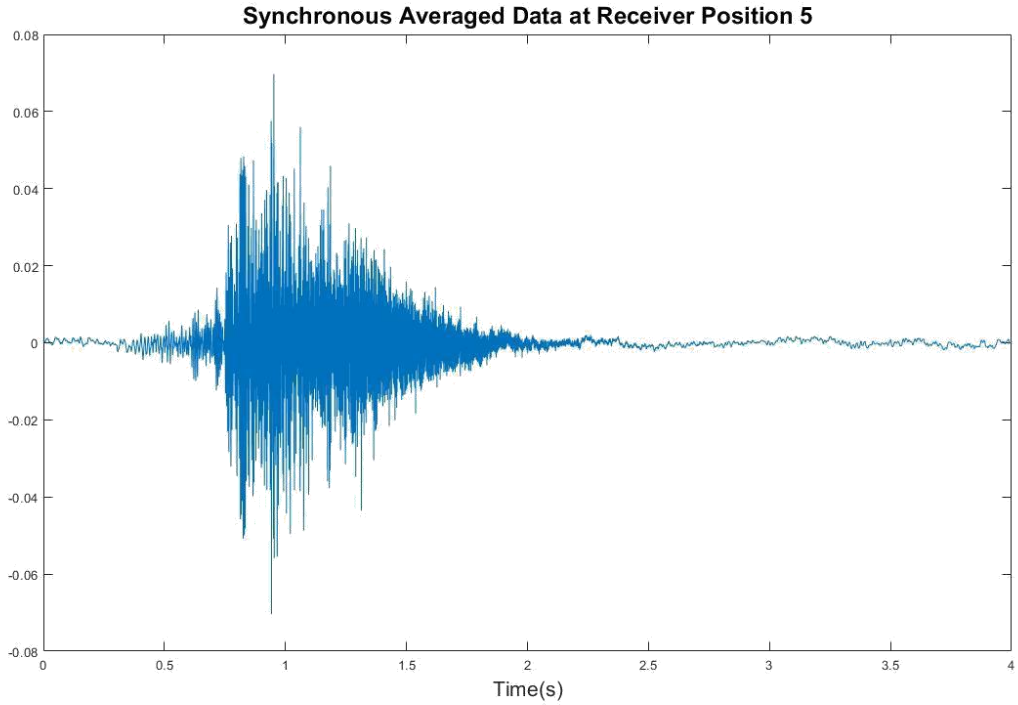


Captured Data at Receiver Position 5
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
0
5
10
15
20
25
30
35
40
Time(s)

Synchronous Averaged Data

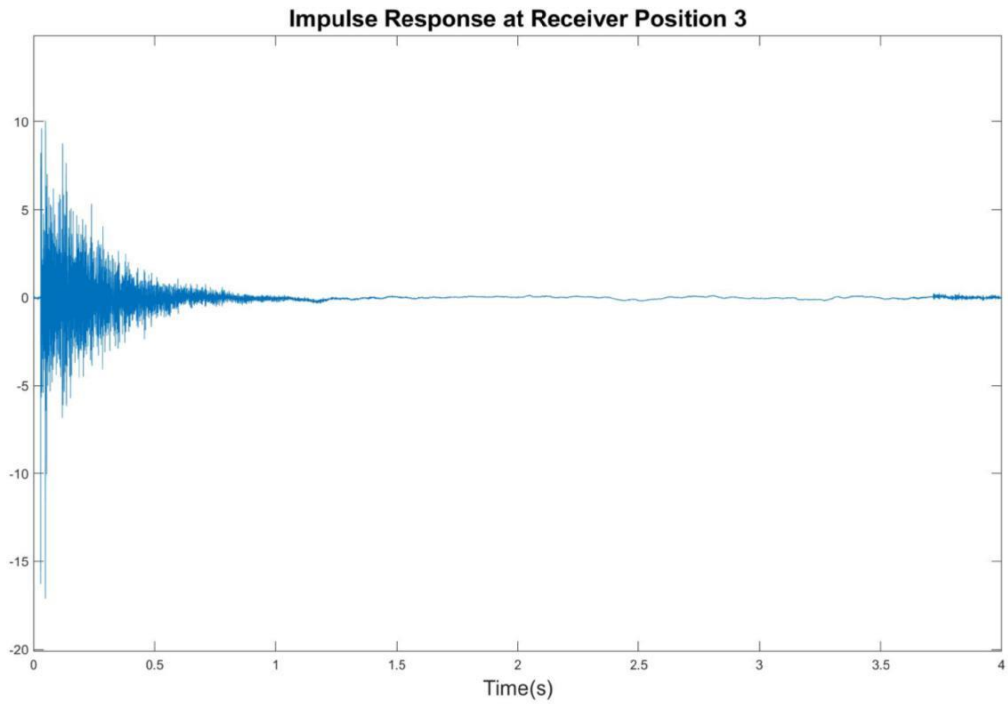


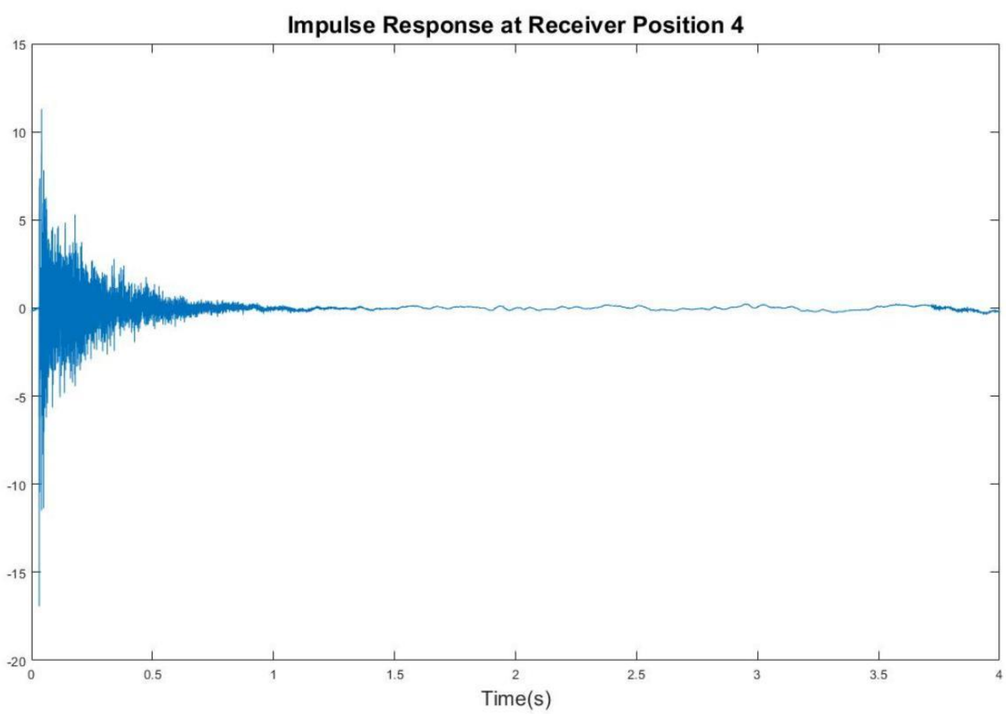


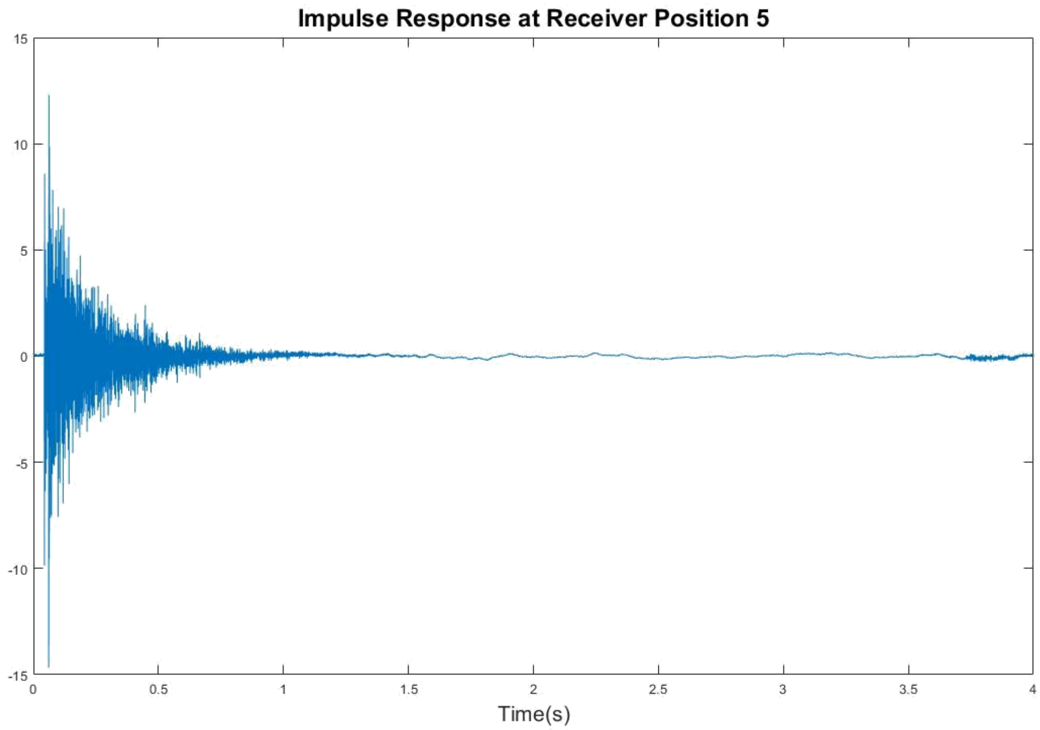


Synchronous Averaged Data at Receiver Position 5
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
0
0.5
1
1.5
2
2.5
3
3.5
4
Time(s)

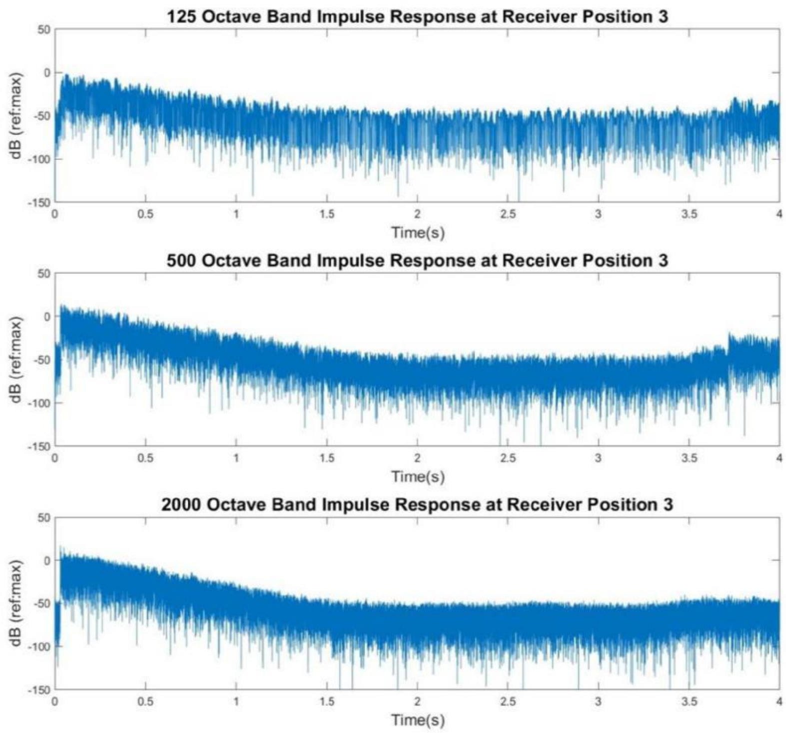
Impulse Response

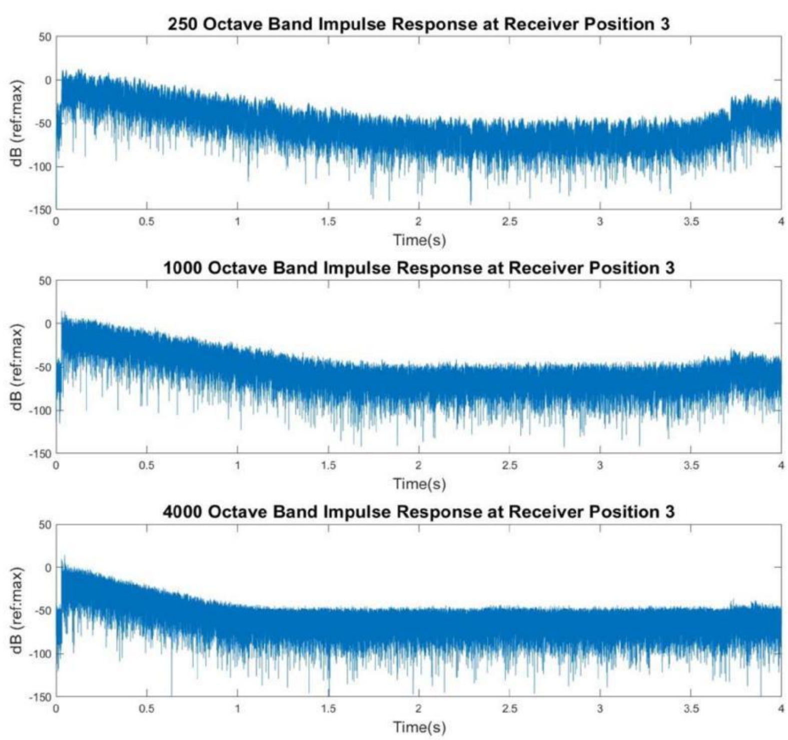


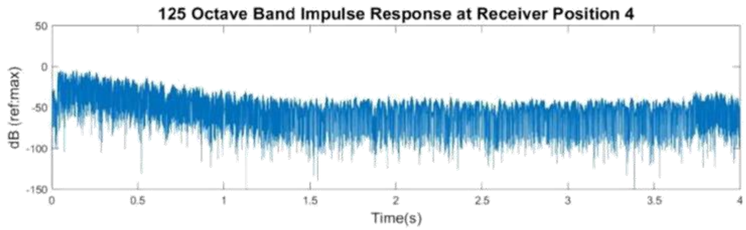


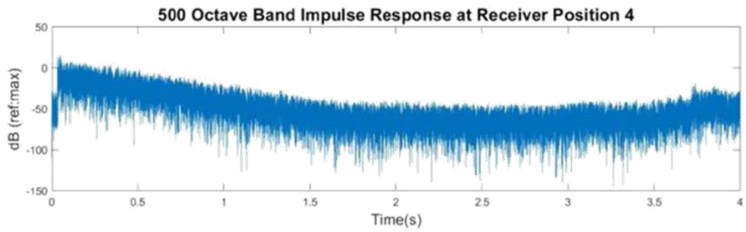

Impulse Response at Receiver Position 5
15
10
5
0
-5
-10
-15
0
0.5
1
1.5
2
2.5
3
3.5
4
Time(s)

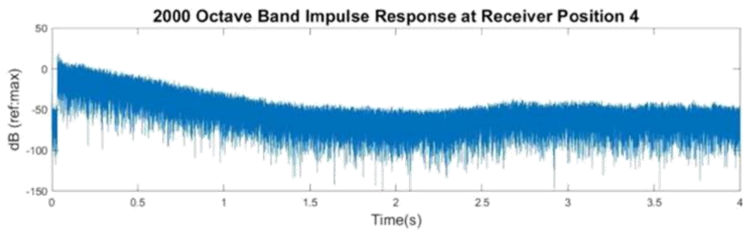
Octave Band Filtered Impulse Response

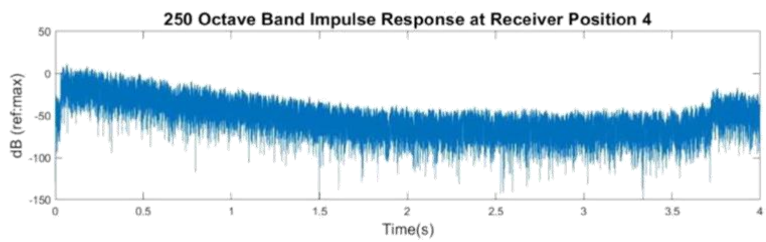


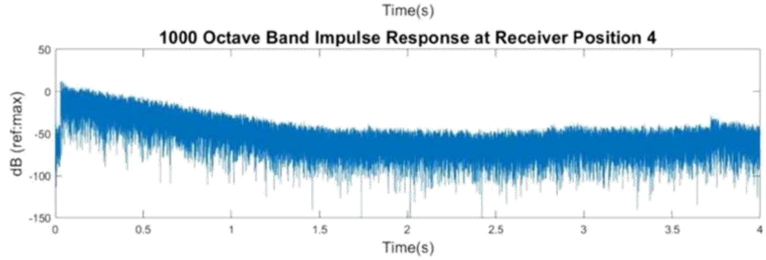


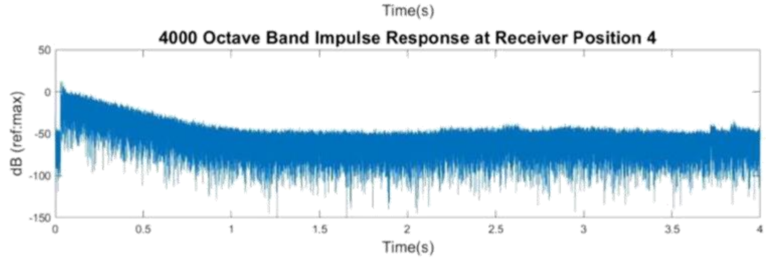

125 Octave Band Impulse Response at Receiver Position 4
dB (ref:max)
Time(s)

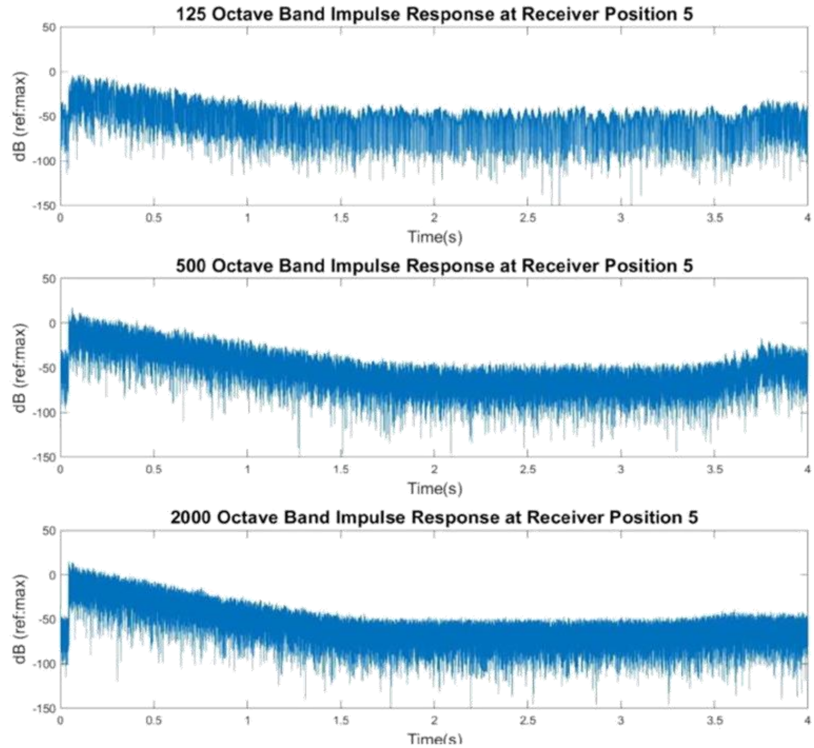

500 Octave Band Impulse Response at Receiver Position 4
dB (ref:max)
Time(s)

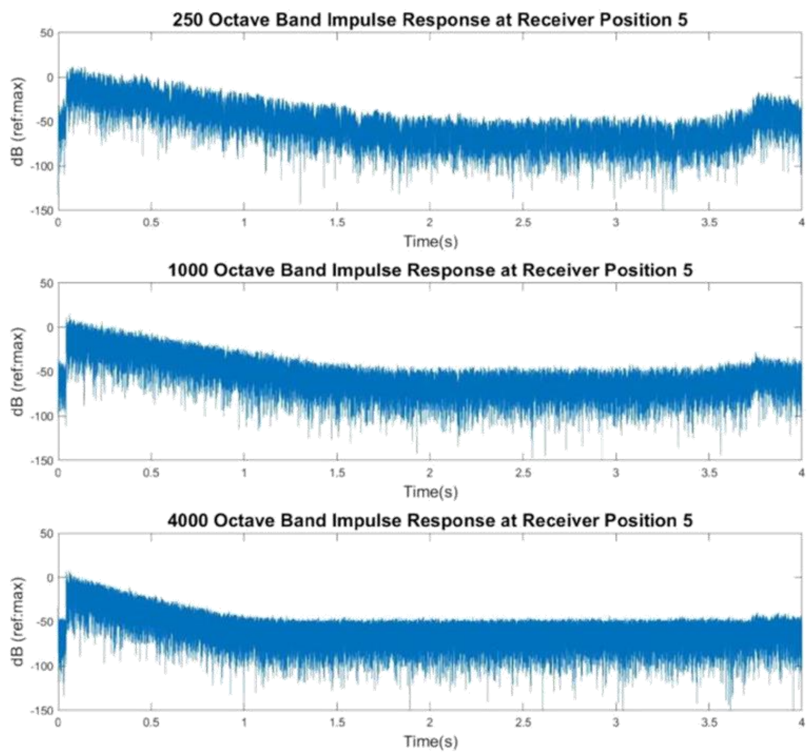

2000 Octave Band Impulse Response at Receiver Position 4
dB (ref:max)
Time(s)


250 Octave Band Impulse Response at Receiver Position 4
dB (ref:max)
Time(s)

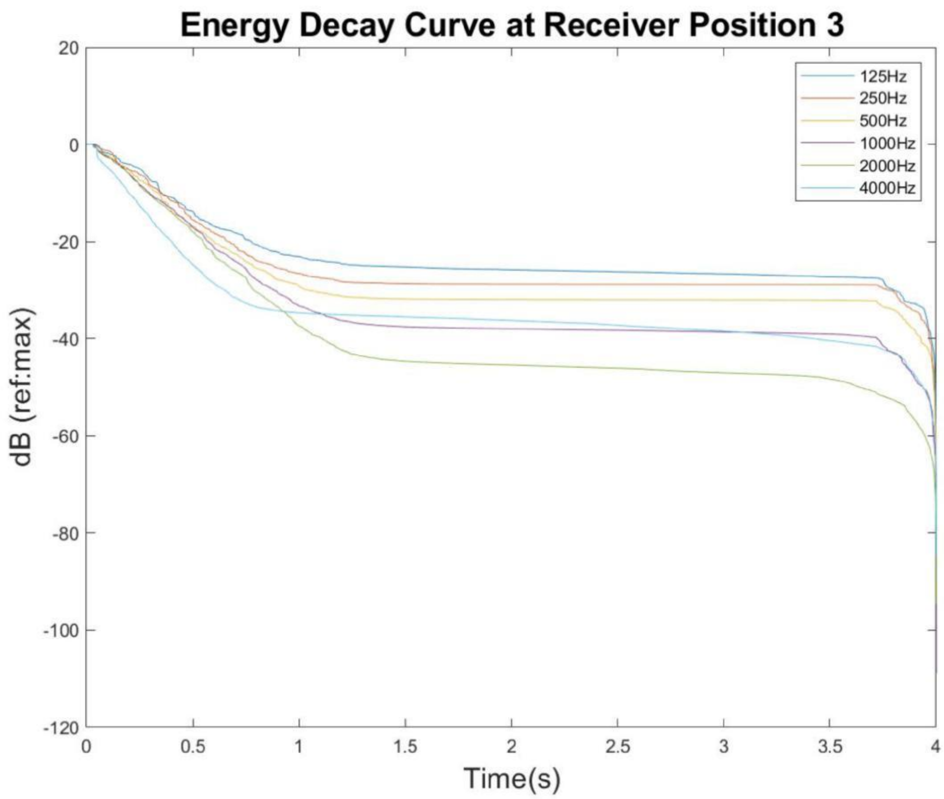

1000 Octave Band Impulse Response at Receiver Position 4
dB (ref:max)
Time(s)

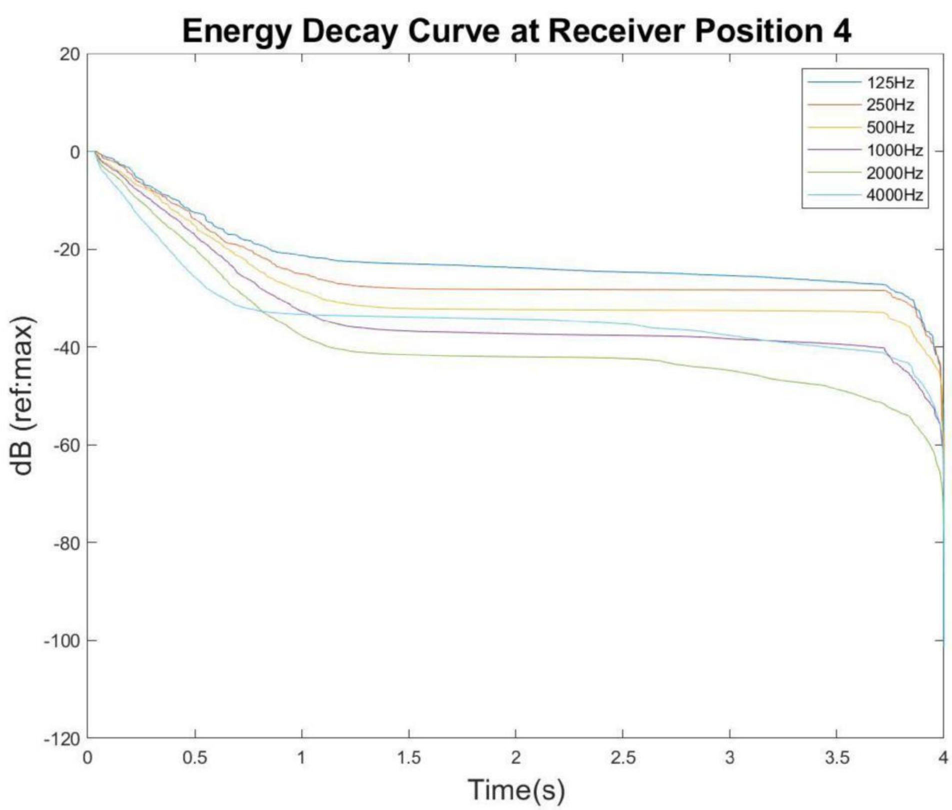

4000 Octave Band Impulse Response at Receiver Position 4
dB (ref:max)
Time(s)

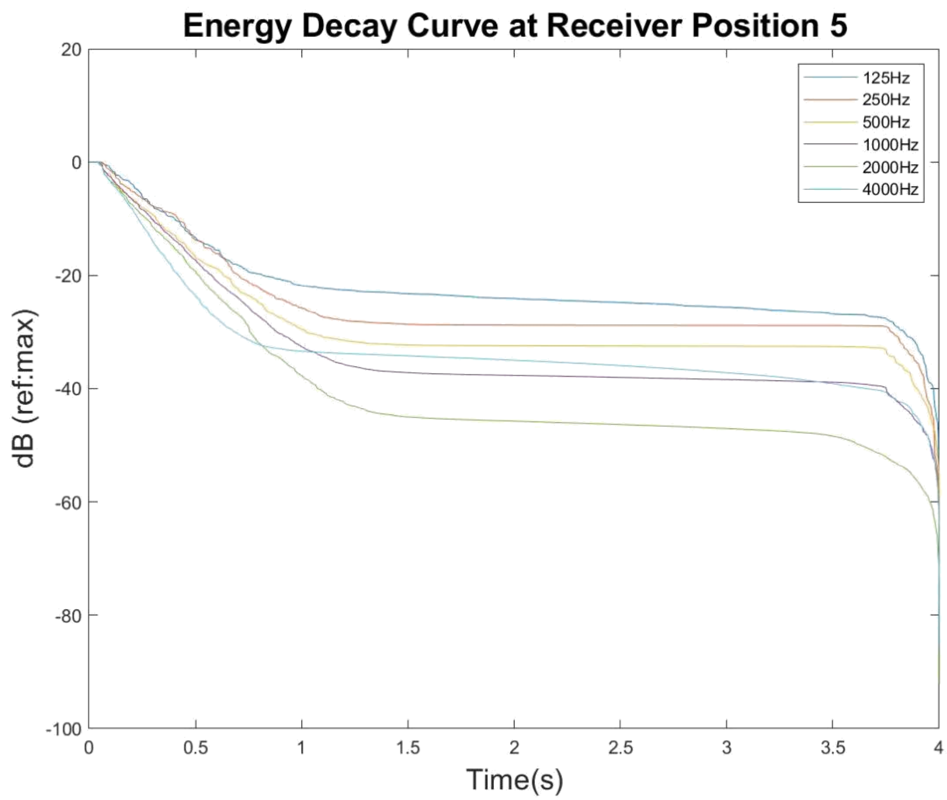

125 Octave Band Impulse Response at Receiver Position 5
dB (ref:max)
Time(s)
500 Octave Band Impulse Response at Receiver Position 5
dB (ref:max)
Time(s)
2000 Octave Band Impulse Response at Receiver Position 5
dB (ref:max)
Time(s)


250 Octave Band Impulse Response at Receiver Position 5
dB (ref:max)
Time(s)
1000 Octave Band Impulse Response at Receiver Position 5
dB (ref:max)
Time(s)
4000 Octave Band Impulse Response at Receiver Position 5
dB (ref:max)
Time(s)

Energy Decay Curves





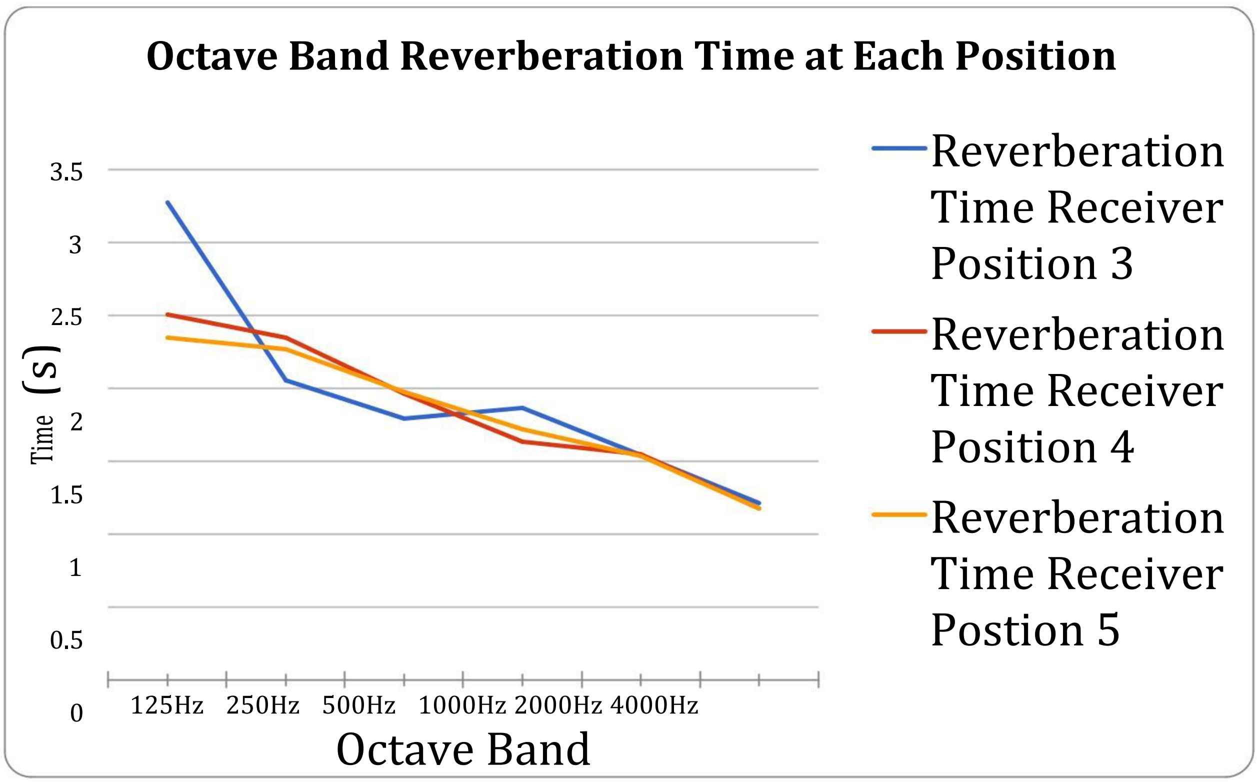


Energy Decay Curve at Receiver Position 5
125Hz
250Hz
500Hz
1000Hz
2000Hz
4000Hz
dB (ref:max)
20
0
-20
-40
-60
-80
-100
0
0.5
1
1.5
2
2.5
3
3.5
4
Time(s)

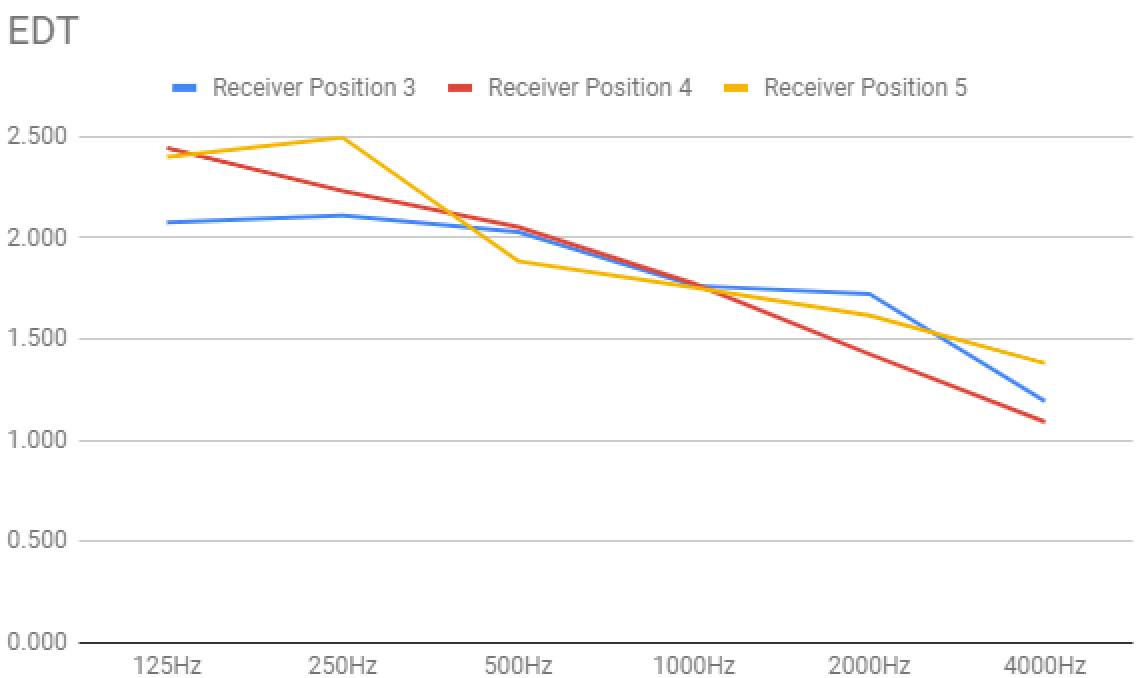
Charts and Plots

Reverberation Time. All entries are time in seconds.

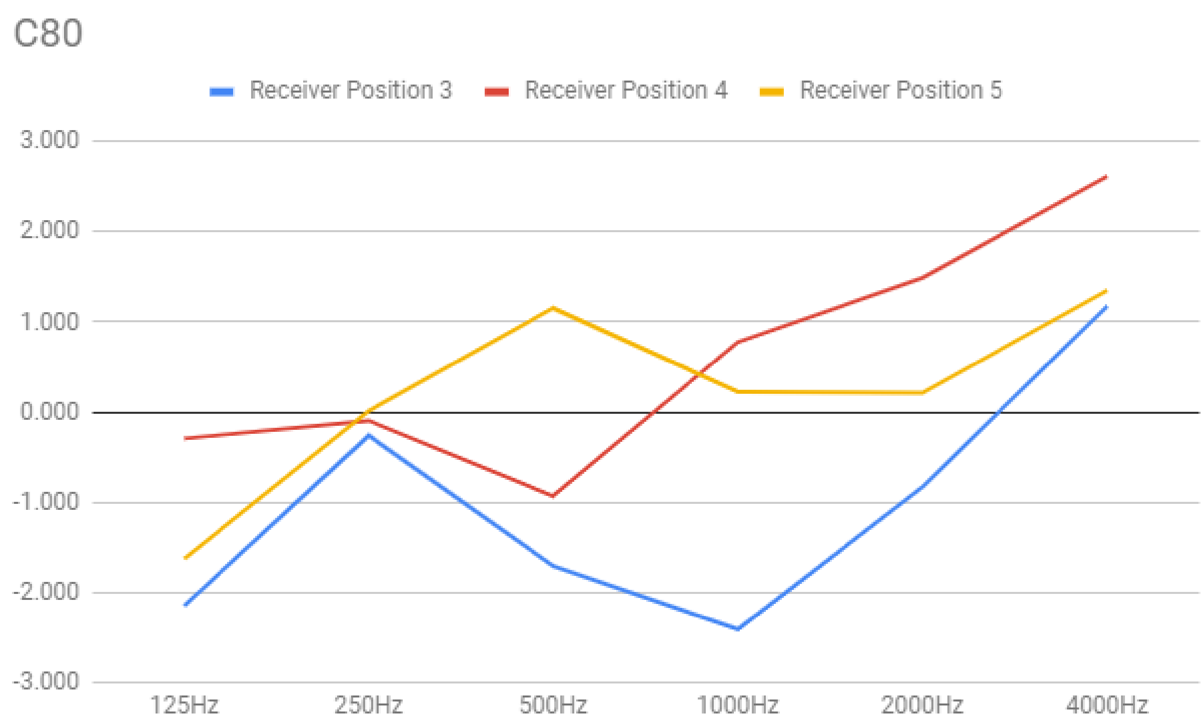
Frequency (Hz)	Receiver Position 3	Receiver Position 4	Receiver Position 5
125	3.276	2.504	2.3468
250	2.0529	2.3454	2.2653
500	1.7898	1.959	1.9761
1000	1.862	1.6344	1.7214
2000	1.542	1.5466	1.5354
4000	1.2138	1.1727	1.1757



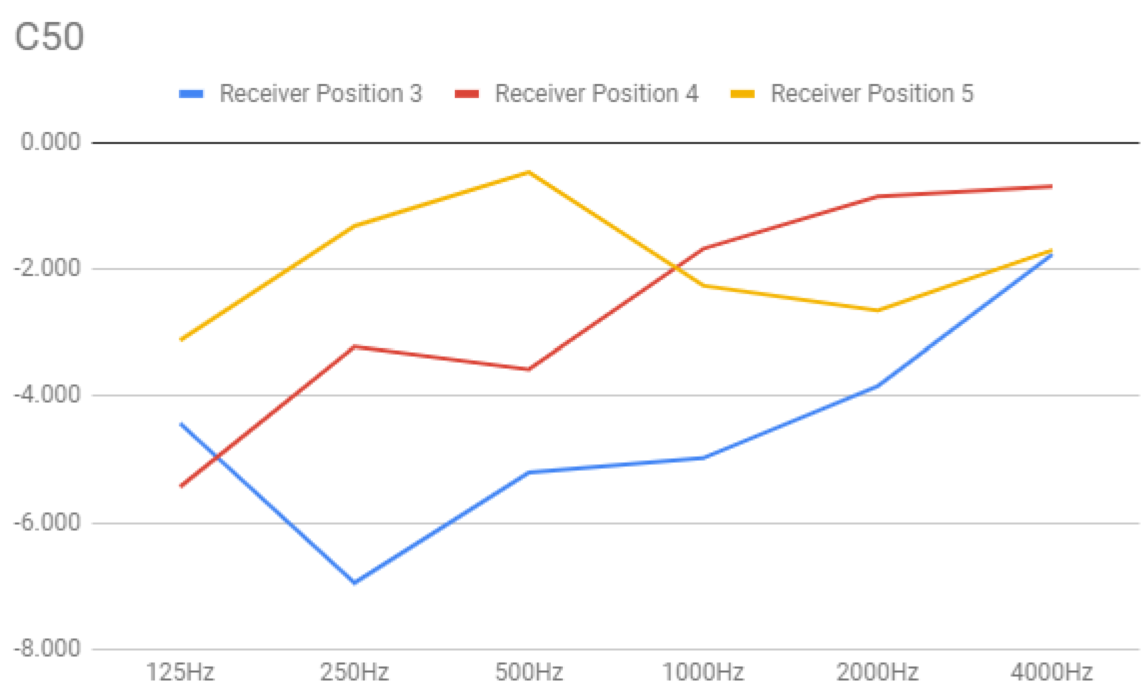
EDT (s)	Receiver Position 3	Receiver Position 4	Receiver Position 5
125Hz	2.076	2.444	2.398
250Hz	2.111	2.232	2.496
500Hz	2.028	2.054	1.884
1000Hz	1.764	1.774	1.755
2000Hz	1.724	1.425	1.618
4000Hz	1.193	1.091	1.381



C80 (dB)	Receiver Position 3	Receiver Position 4	Receiver Position 5
125Hz	-2.147	-0.295	-1.628
250Hz	-0.262	-0.096	0.012
500Hz	-1.709	-0.932	1.155
1000Hz	-2.411	0.774	0.224
2000Hz	-0.830	1.488	0.211
4000Hz	1.178	2.617	1.350



C50 (dB)	Receiver Position 3	Receiver Position 4	Receiver Position 5
125Hz	-4.428	-5.431	-3.122
250Hz	-6.950	-3.221	-1.317
500Hz	-5.208	-3.575	-0.470
1000Hz	-4.979	-1.677	-2.262
2000Hz	-3.840	-0.849	-2.651
4000Hz	-1.770	-0.692	-1.700



Model Creation and Calibration

In the first part of the Nest+m auditorium assessment, we experimentally determined the reverberation time, clarity index, and early decay time using sine sweep noise input and analyzing the auditorium's acoustic response. Here, we develop a CATT-Acoustics model and calibrate model parameters to match experimental results.

We begin by creating a 3D model of the Nest+m auditorium in Sketchup.

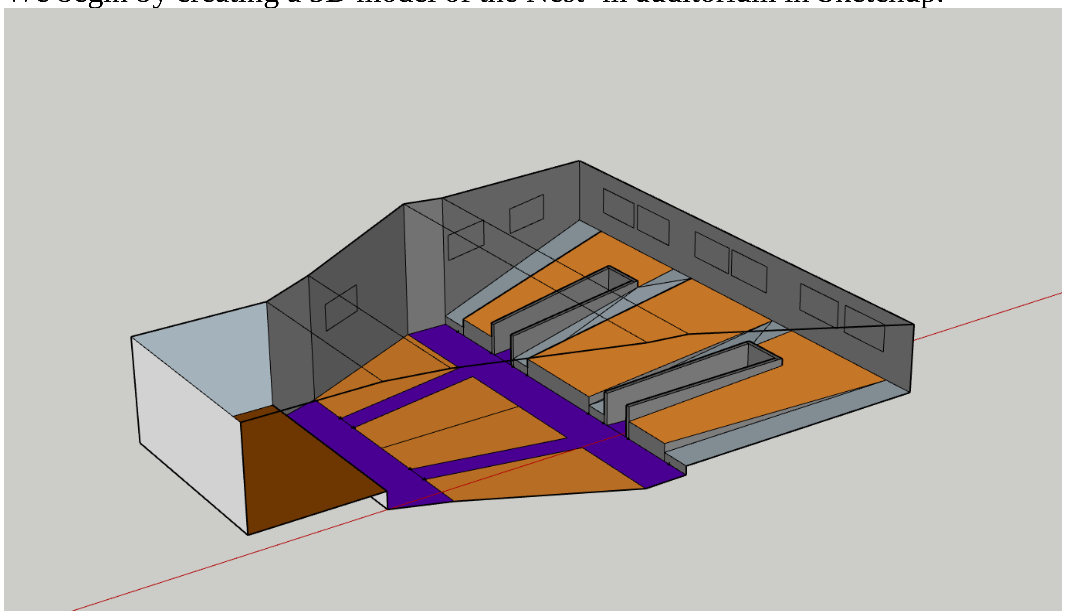


Figure 1. 3D model of the Nest+m auditorium.

The auditorium model is then imported into CATT-Acoustics software.

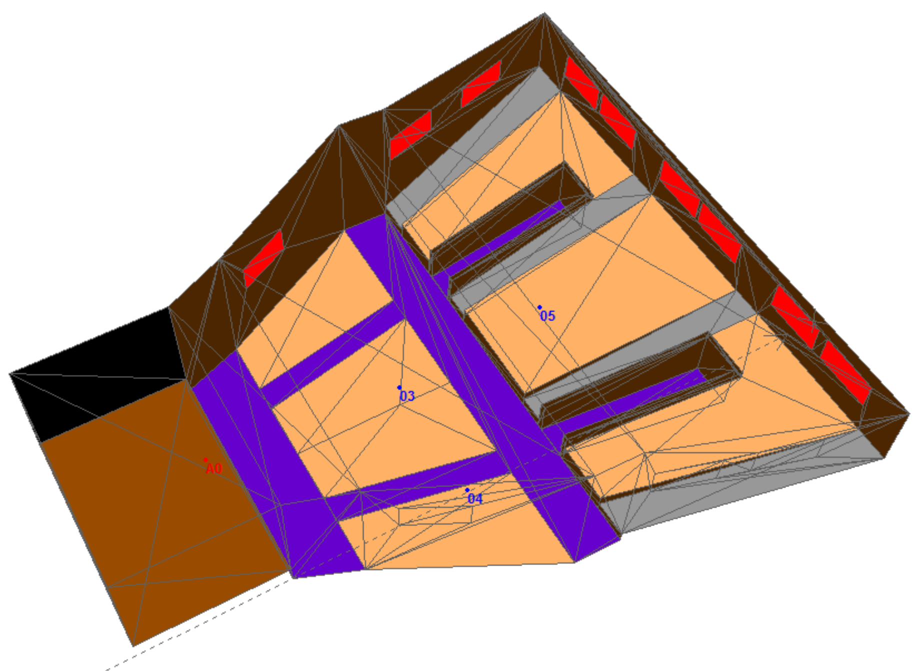


Figure 2. Auditorium model shown in CATT-Acoustics window, with different colors shown for walls, curtains, panels, and seats in the room. The source omnidirectional speaker is located at the center of the stage, and three receivers are located at the center and left seats.

Based on the materials of wall, curtain, panels, and seats, we assigned appropriate absorption and scattering coefficients using provided Material Data sheets.

Initial Assigned Material Absorption Coefficient								
Absorption Coefficients (%)	PANEL	STAIR	AUDIENCE	WALL	STAGE FLOOR	CARPET	CEILING	CURTAIN
125 Hz	2	1	5	2	1	2	2	36
250 Hz	2	1	8	2	7	4	2	26
500 Hz	3	2	10	3	6	8	3	51
1000 Hz	4	2	12	4	6	20	4	45
2000 Hz	5	2	12	5	6	35	5	62
4000 Hz	5	2	12	5	6	40	5	76

Table 1. Absorption and Scatter Coefficients for materials Nest + m auditorium for each Octave Band.

Assigned Material Scattering Coefficient			
Scattering Coefficient (%)	STAIR	AUDIENCE	WALL
125 Hz	5	30	10
250 Hz	5	50	60
500 Hz	2	60	50
1000 Hz	3	60	40
2000 Hz	4	70	30
4000 Hz	45	70	40

Table 2. Material scattering coefficients for Nest + m auditorium.

We ran the first simulation on CATT-Acoustics with the default absorption and scattering coefficients in Table 1, and compared the modeling calculations to experimental results.

Initial Comparison

Comparison between initial simulated T30 and measured T30 results (s)						
	Receiver Position 3		Receiver Position 4		Receiver Position 5	
Octave Band	Simulation	Measured	Simulation	Measured	Simulation	Measured
125 Hz	4.7	2.002	4.91	2.529	4.79	2.386
250 Hz	3.73	1.941	3.72	2.097	3.8	1.985
500 Hz	2.35	1.775	2.45	1.893	2.39	1.851
1000 Hz	1.89	1.652	1.88	1.741	1.98	1.745
2000 Hz	1.44	1.524	1.52	1.491	1.46	1.51
4000 Hz	1.18	1.322	1.22	1.312	1.19	1.354

Table 3. First simulation T30 result compared to measured data.

Comparison between initial simulated EDT and measured EDT results (s)						
	Receiver Position 3		Receiver Position 4		Receiver Position 5	
Octave Band	Simulation	Measured	Simulation	Measured	Simulation	Measured
125 Hz	5.25	2.076	4.26	2.444	4.19	2.398
250 Hz	3.84	2.111	3.36	2.232	3.63	2.496
500 Hz	2.3	2.028	2.18	2.054	2.05	1.884
1000 Hz	1.79	1.764	1.85	1.774	1.72	1.755
2000 Hz	1.44	1.724	1.53	1.425	1.39	1.618
4000 Hz	1.25	1.193	1.23	1.091	0.99	1.381

Table 4. First simulation EDT result compared to measured data.

Comparison between initial simulated C80 and measured C80 results (dB)						
	Receiver Position 3		Receiver Position 4		Receiver Position 5	
Octave Band	Simulation	Measured	Simulation	Measured	Simulation	Measured
125 Hz	-2.51	-2.147	-6.12	-0.295	-2.78	-1.628
250 Hz	-3.65	-0.262	-4.38	-0.096	-1.59	0.012
500 Hz	-0.42	-1.709	-1.84	-0.932	0.14	1.155
1000 Hz	1.89	-2.411	0.65	0.774	1.08	0.224
2000 Hz	2.52	-0.83	2.14	1.488	2.94	0.211
4000 Hz	4.02	1.178	3.61	2.617	4.76	1.35

Table 5. First simulation C80 result compared to measured data.

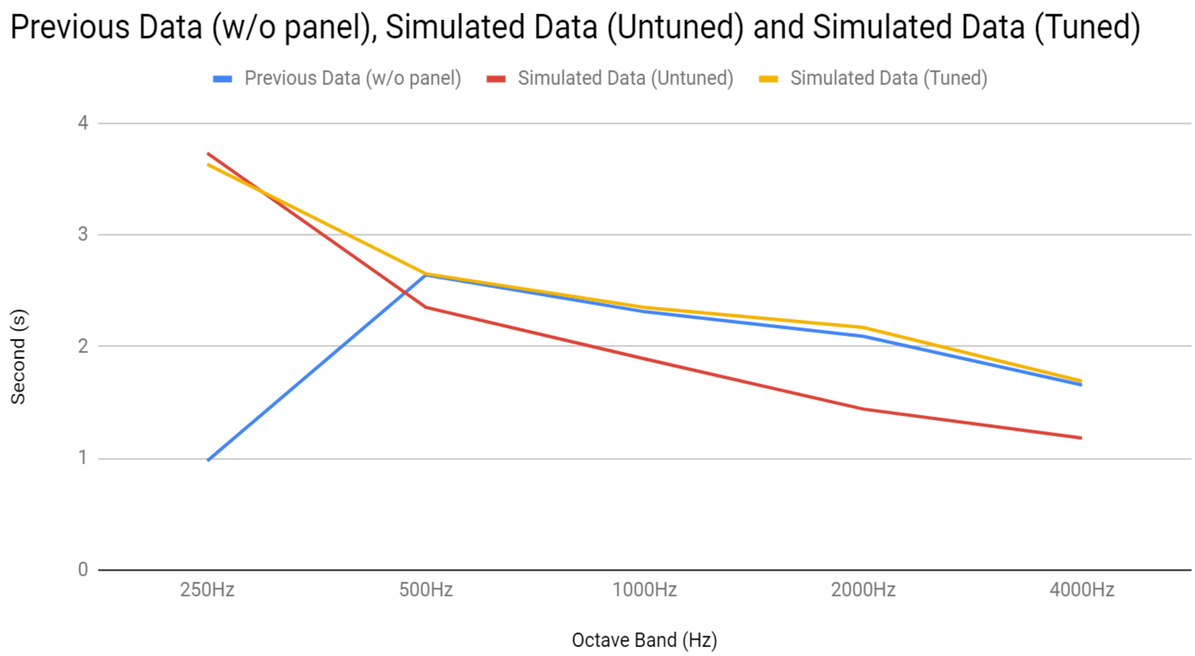
Comparison between initial simulated C50 and measured C50 results (dB)						
	Receiver Position 3		Receiver Position 4		Receiver Position 5	
Octave Band	Simulation	Measured	Simulation	Measured	Simulatio n	Measured
125 Hz	-3.46	-4.428	-7.64	-5.431	-6.98	-3.122
250 Hz	-4.82	-6.950	-5.76	-3.221	-4.54	-1.317
500 Hz	-2.75	-5.208	-3.26	-3.575	-1.22	-0.470
1000 Hz	0.85	-4.979	-0.76	-1.677	-2.25	-2.262
2000 Hz	-0.17	-3.840	0.71	-0.849	0.81	-2.651
4000 Hz	2.67	-1.770	1.47	-0.692	1.26	-1.700

Table 6. First simulation C80 result compared to measured data.

Then we iterated by changing absorption coefficients for walls, acoustic panels, and seats. We set the acoustics panels' absorption rate the same as the wall. Thus, we can tune other materials' absorption coefficient in order to match up previous measured T30 result of the auditorium without the acoustical panels. The iteration stops when we closely match (i.e. within 5% of actual experiment) the model results to experimental results.

Tuning the absorption coefficient for the T30 (s)			
	Previous Data (w/o panel)	Simulated Data (Untuned)	Simulated Data (Tuned)
250Hz	0.976	3.73	3.63
500Hz	2.64	2.35	2.65
1000Hz	2.311	1.89	2.35
2000Hz	2.091	1.44	2.17
4000Hz	1.656	1.18	1.69

Table 7. Comparison between previous measured data and simulated data before and after tuning



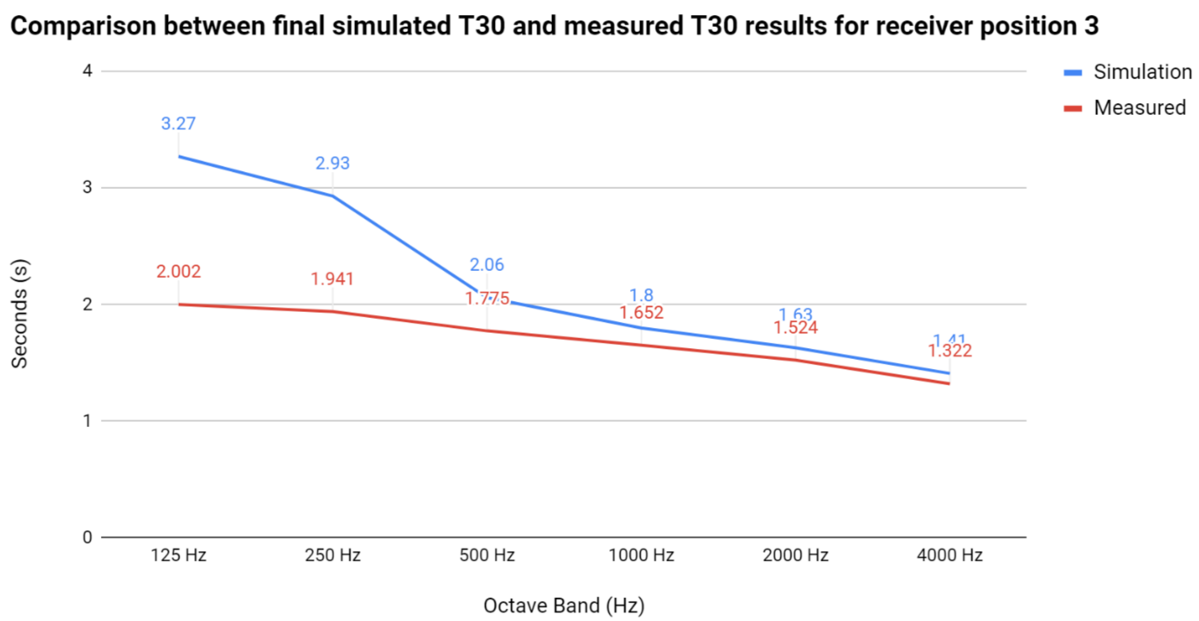
Final Assigned Material Absorption Coefficient								
Absorption Coefficients (%)	PANEL	STAIR	AUDIENCE	WALL	STAGE FLOOR	CARPET	CEILING	CURTAIN
125 Hz	33	1	5	4	1	2	4	36
250 Hz	67	1	8	5	8	3	5	26
500 Hz	100	2	8	7	7	6	7	45
1000 Hz	100	2	9	7	7	10	7	50
2000 Hz	100	2	9	7	7	10	7	50
4000 Hz	100	2	9	7	7	15	6	50

Table 8. Calibrated absorption and scattering coefficients for Nest + m auditorium materials for each Octave Band.

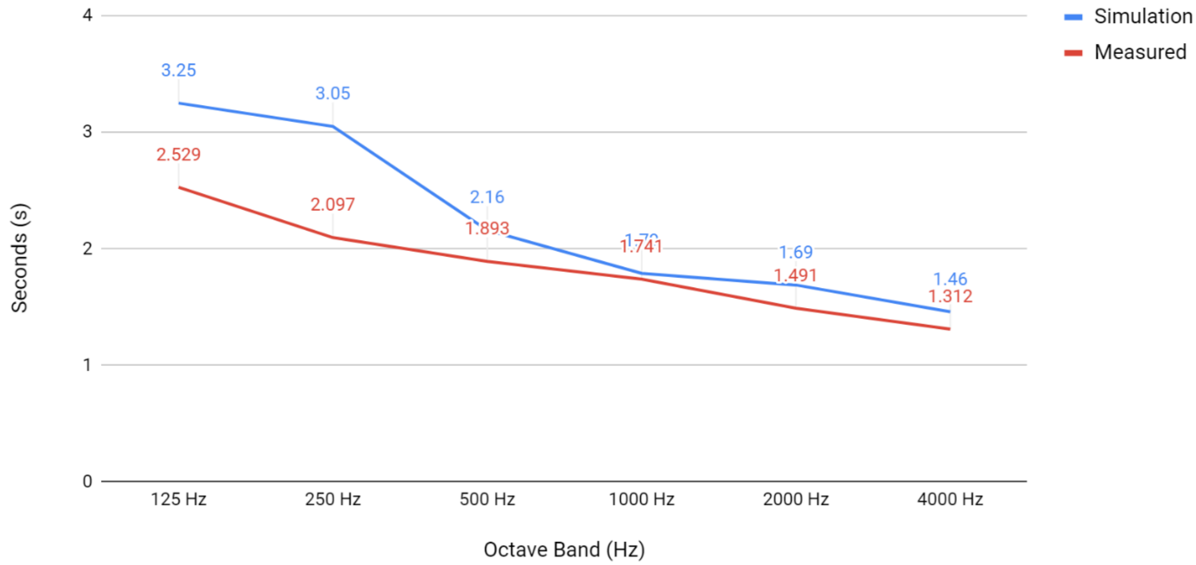
Final Comparison

Comparison between final simulated T30 and measured T30 results						
	Receiver Position 3		Receiver Position 4		Receiver Position 5	
Octave Band	Simulation	Measured	Simulation	Measured	Simulation	Measured
125 Hz	3.27	2.002	3.25	2.529	3.31	2.386
250 Hz	2.93	1.941	3.05	2.097	2.96	1.985
500 Hz	2.06	1.775	2.16	1.893	1.93	1.851
1000 Hz	1.8	1.652	1.79	1.741	1.75	1.745
2000 Hz	1.63	1.524	1.69	1.491	1.7	1.51
4000 Hz	1.41	1.322	1.46	1.312	1.44	1.354

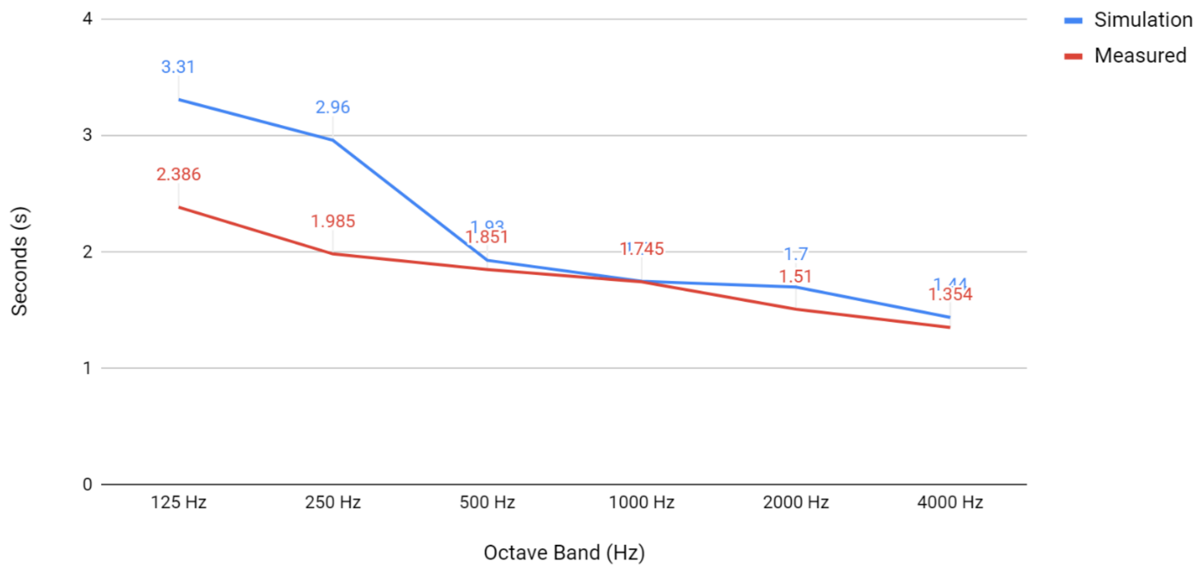
Table 9. Final simulation T30 result compared to measured data.



Comparison between final simulated T30 and measured T30 results for receiver position 4

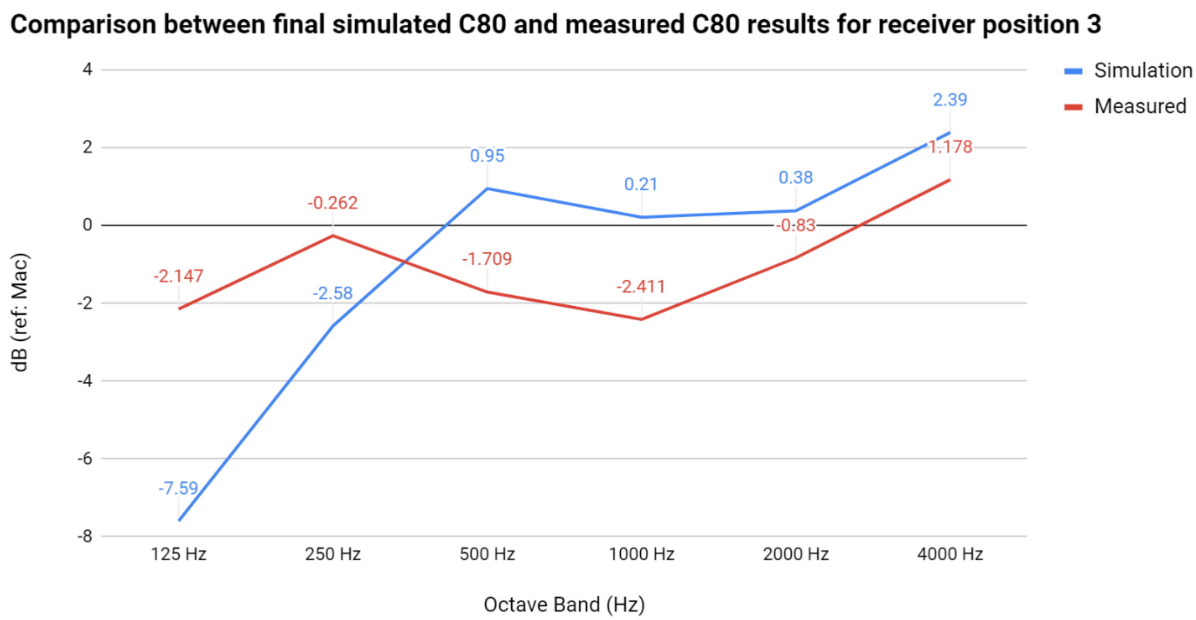


Comparison between final simulated T30 and measured T30 results for receiver position 5

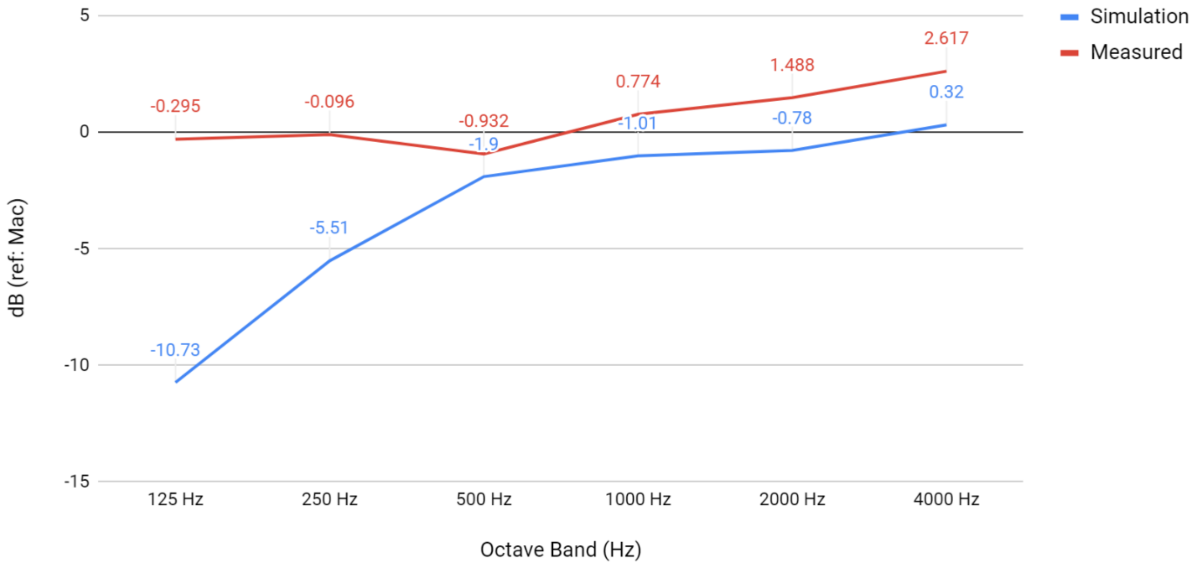


Comparison between final simulated C80 and measured C80 results						
	Receiver Position 3		Receiver Position 4		Receiver Position 5	
Octave Band	Simulation	Measured	Simulation	Measured	Simulation	Measured
125 Hz	-7.59	-2.147	-10.73	-0.295	-9.2	-1.628
250 Hz	-2.58	-0.262	-5.51	-0.096	-4.95	0.012
500 Hz	0.95	-1.709	-1.9	-0.932	0.25	1.155
1000 Hz	0.21	-2.411	-1.01	0.774	0.05	0.224
2000 Hz	0.38	-0.83	-0.78	1.488	0.3	0.211
4000 Hz	2.39	1.178	0.32	2.617	1	1.35

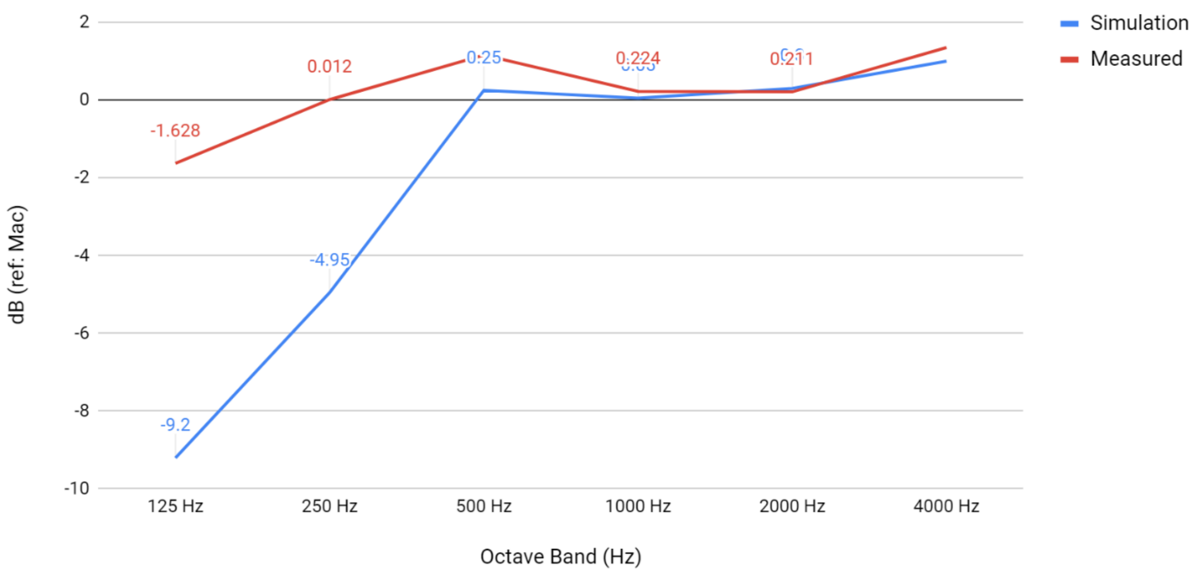
Table 10. Final simulation C80 result compared to measured data.



Comparison between final simulated C80 and measured C80 results for receiver position 4

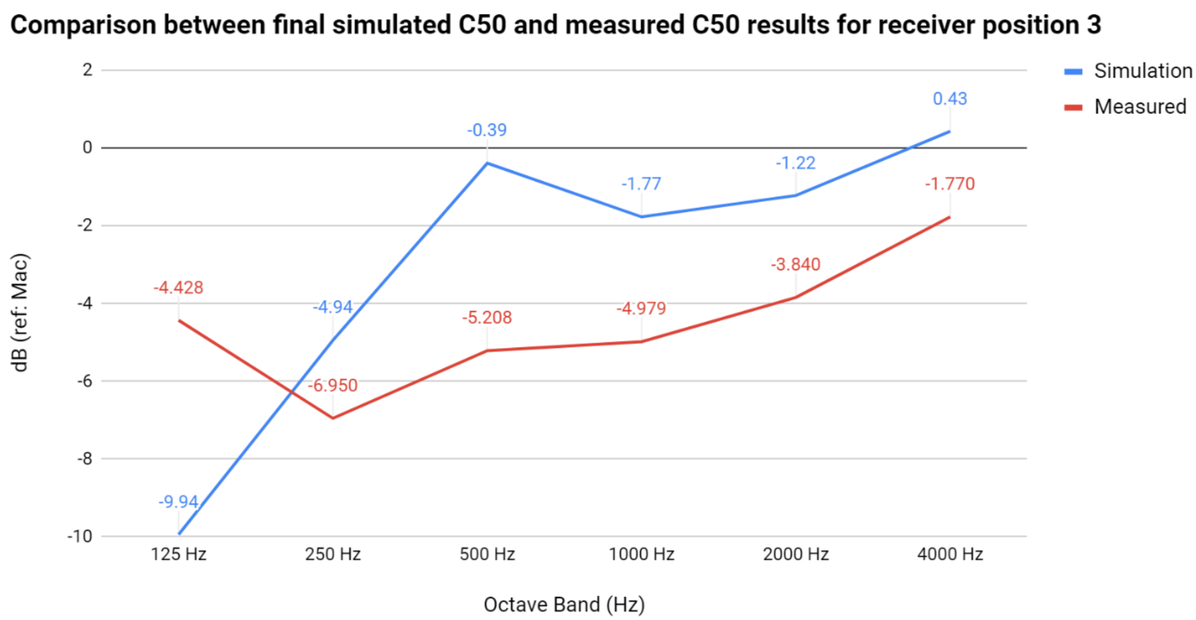


Comparison between final simulated C80 and measured C80 results for receiver position 5

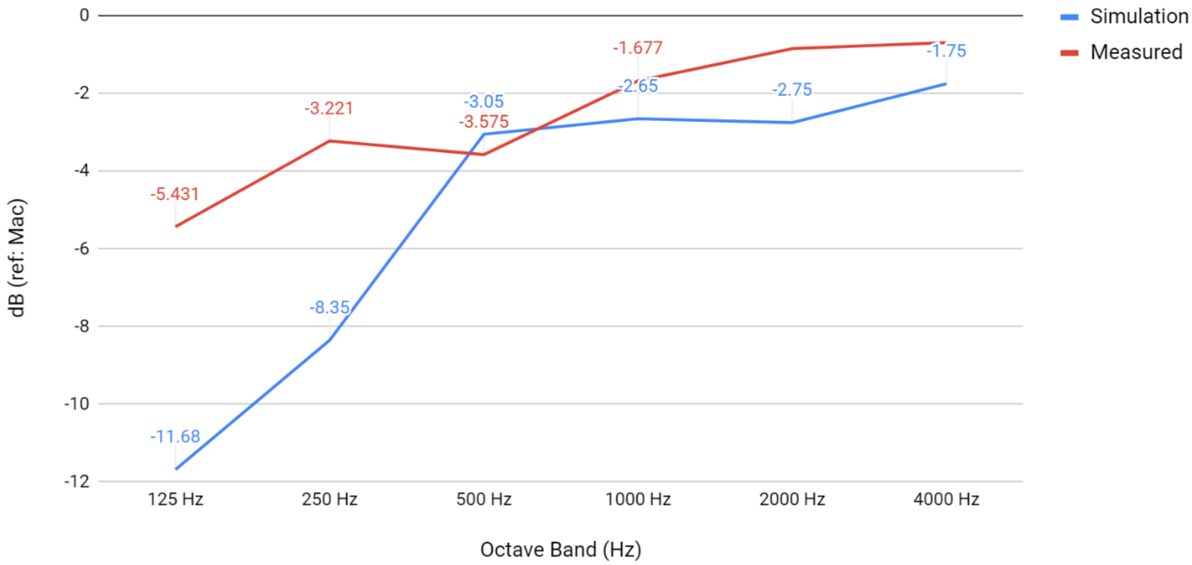


Comparison between final simulated C50 and measured C50 results						
	Receiver Position 3		Receiver Position 4		Receiver Position 5	
Octave Band	Simulation	Measured	Simulation	Measured	Simulation	Measured
125 Hz	-9.94	-4.428	-11.68	-5.431	-10.76	-3.122
250 Hz	-4.94	-6.950	-8.35	-3.221	-6.28	-1.317
500 Hz	-0.39	-5.208	-3.05	-3.575	-2.36	-0.470
1000 Hz	-1.77	-4.979	-2.65	-1.677	-2.53	-2.262
2000 Hz	-1.22	-3.840	-2.75	-0.849	-1.75	-2.651
4000 Hz	0.43	-1.770	-1.75	-0.692	-1.22	-1.700

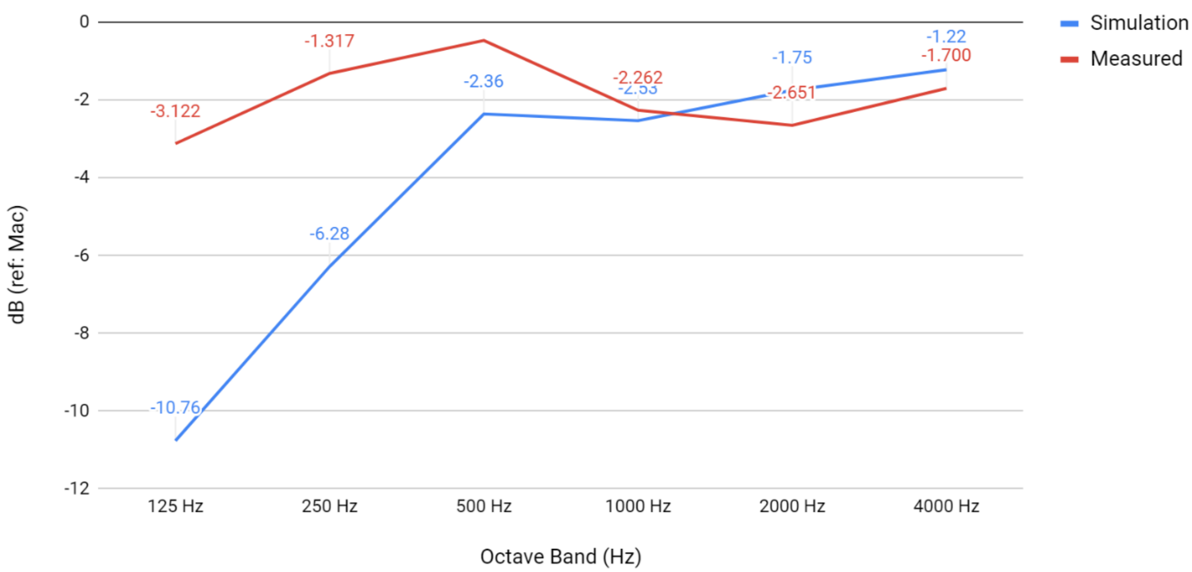
Table 11. Final simulation C50 result compared to measured data.



Comparison between final simulated C50 and measured C50 results for receiver position 4

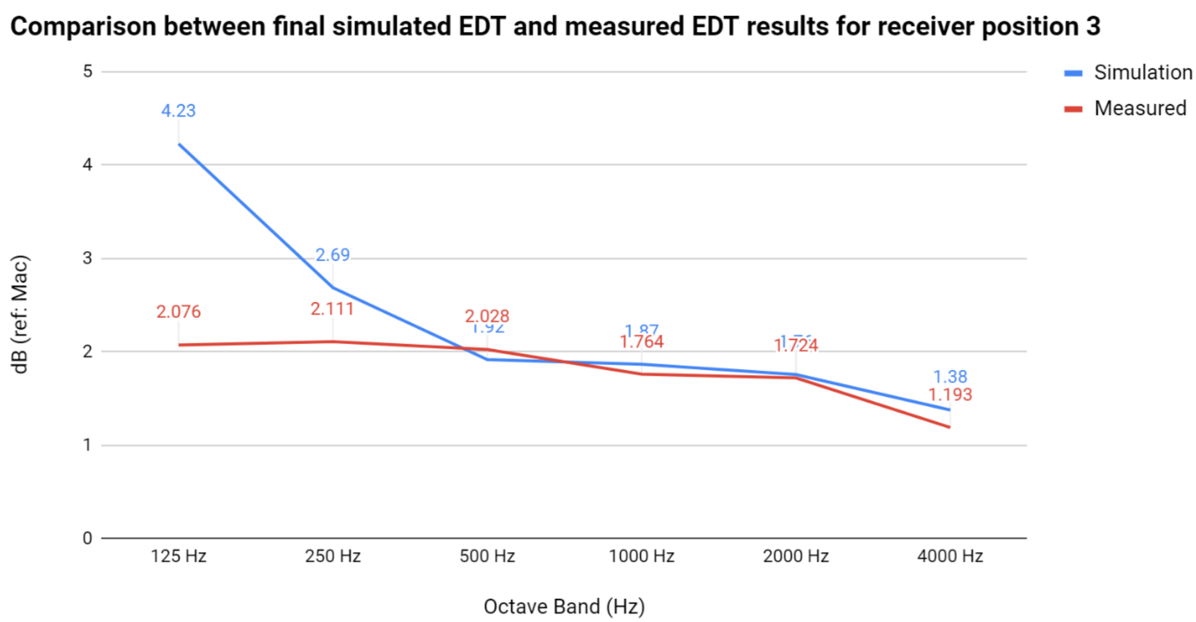


Comparison between final simulated C50 and measured C50 results for receiver position 5

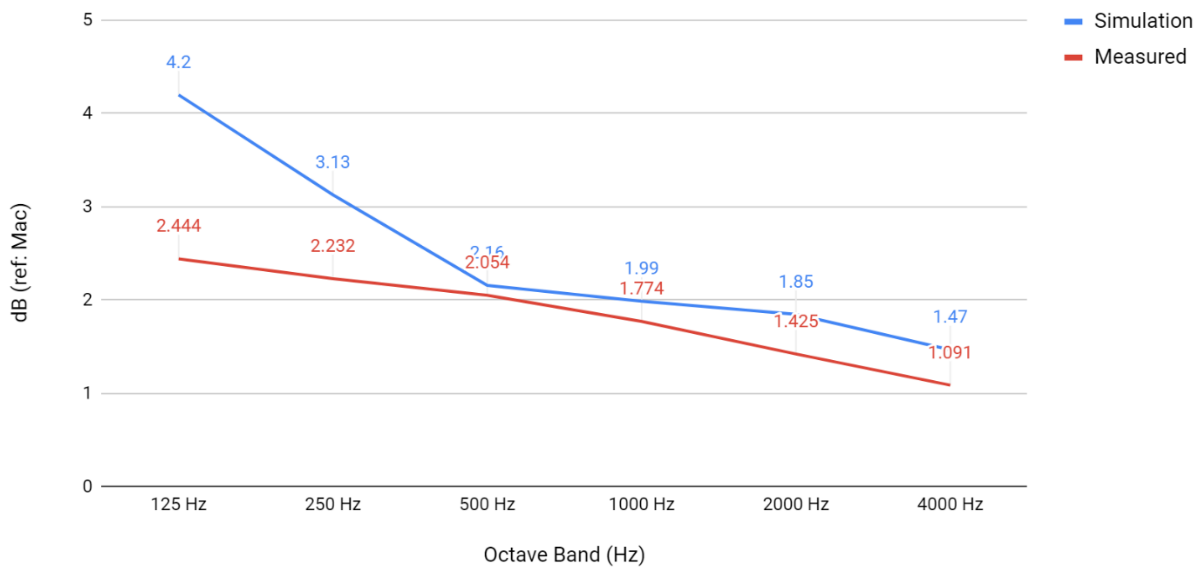


Comparison between final simulated EDT and measured EDT results						
	Receiver Position 3		Receiver Position 4		Receiver Position 5	
Octave Band	Simulation	Measured	Simulation	Measured	Simulation	Measured
125 Hz	4.23	2.076	4.2	2.444	4.12	2.398
250 Hz	2.69	2.111	3.13	2.232	2.96	2.496
500 Hz	1.92	2.028	2.16	2.054	1.93	1.884
1000 Hz	1.87	1.764	1.99	1.774	1.77	1.755
2000 Hz	1.76	1.724	1.85	1.425	1.77	1.618
4000 Hz	1.38	1.193	1.47	1.091	1.43	1.381

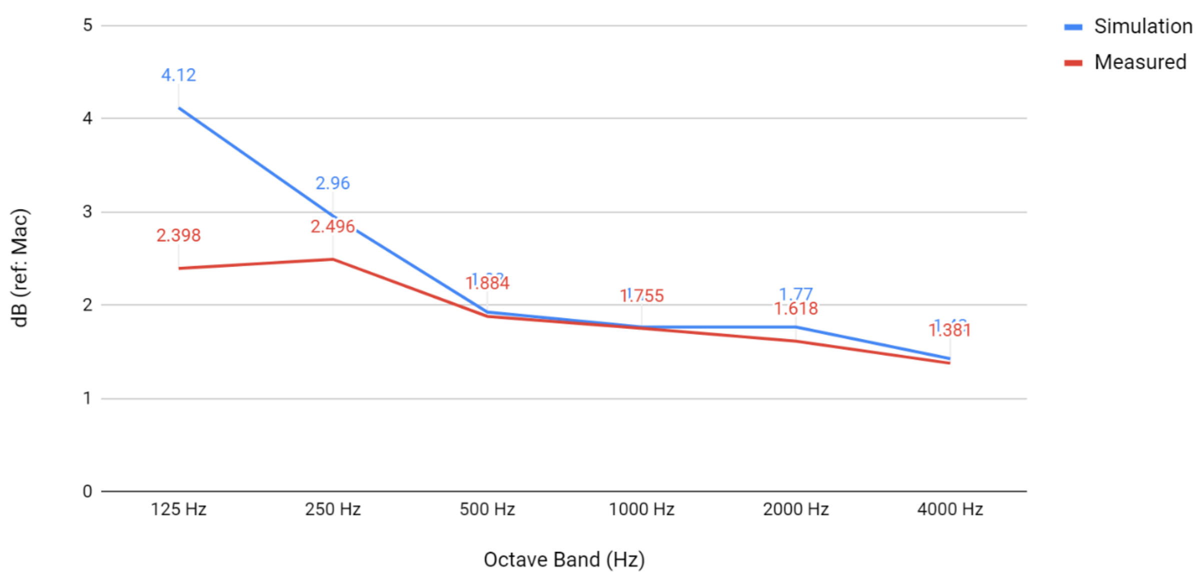
Table 12. Final simulation EDT result compared to measured data.



Comparison between final simulated EDT and measured EDT results for receiver position 4



Comparison between final simulated EDT and measured EDT results for receiver position 5



Acoustics Performance Improvement For the Auditorium using Model

The Nest+m auditorium is multi-purposed; the room is used for both concert music and speech/lecture sessions. To satisfy the school's need, we come up with the following solution: installing two additional absorber panels and acoustics sound blocks. These installations are made removable so that they could be taken down to increase reverberation time for concert band playing and could be installed back on to increase reverberation time for speech lectures.

The sound blocks used are Colinwell EchoCheck EC100 and EC215. The location of the panel/sound block installation, and their absorption coefficients are shown below.

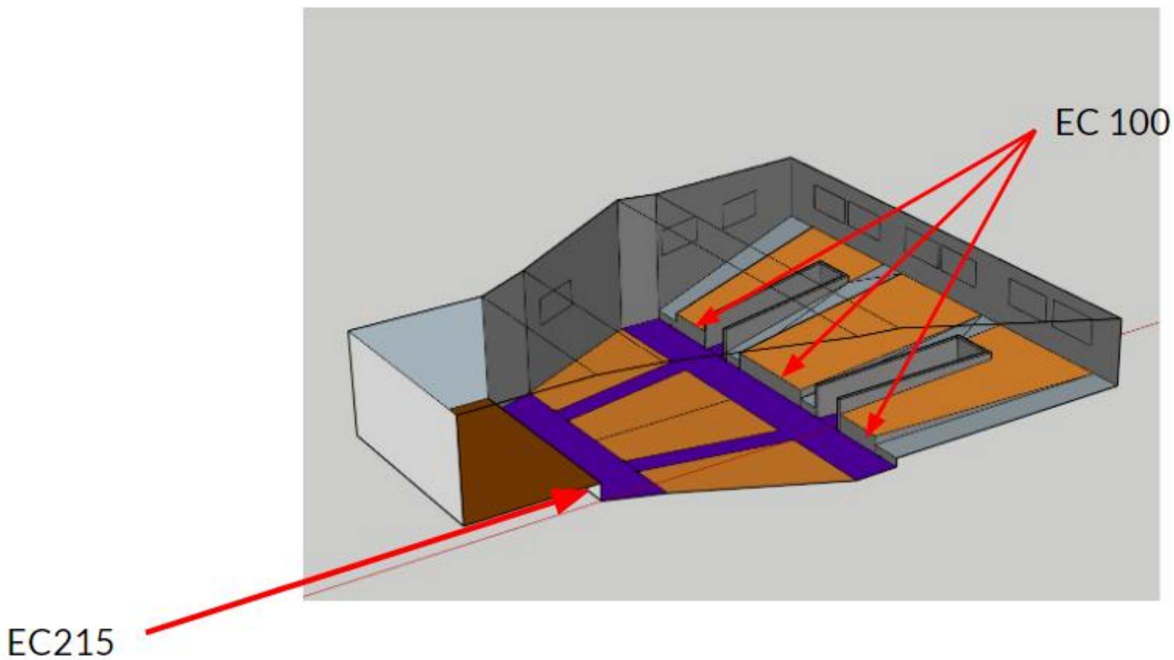


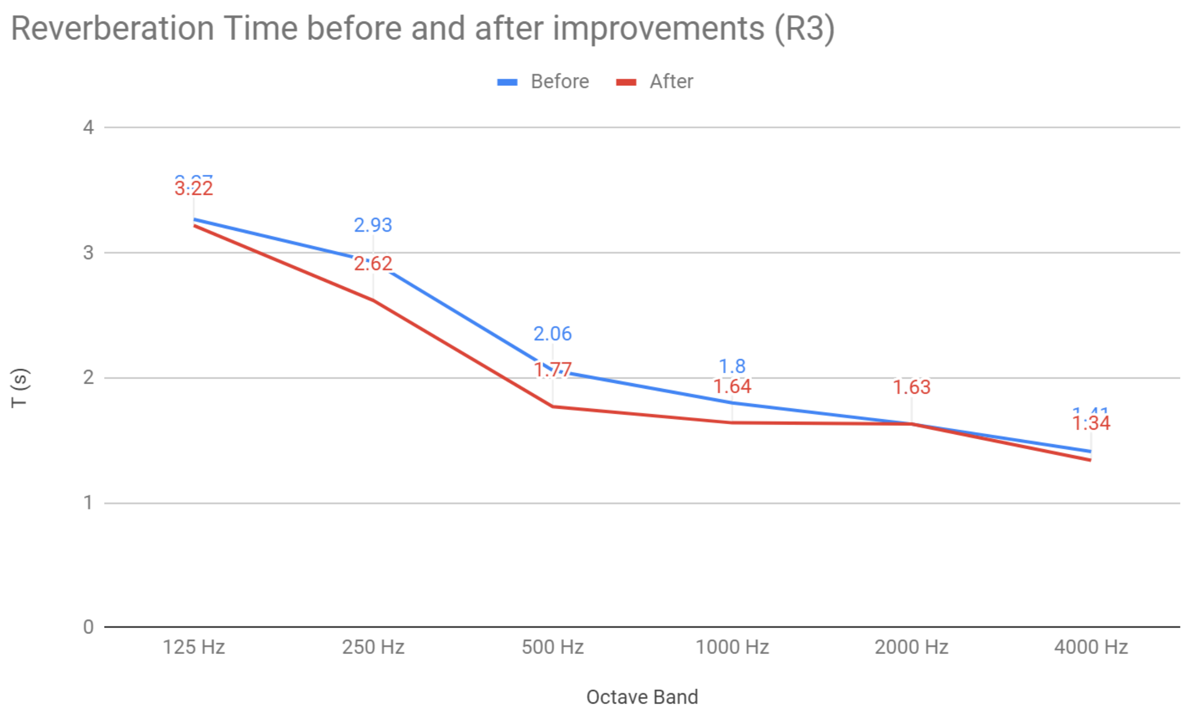
Figure 3. Location of the sound blocks installation.

Soundblock Absorption Coefficients		
Absorption Coefficients (%)	EC215	EC100
125 Hz	75	23
250 Hz	75	80
500 Hz	60	70
1000 Hz	65	44
2000 Hz	55	42
4000 Hz	50	39

Table 13. Absorption Coefficients of Colinwell EchoCheck EC100 and EC215 for each Octave Band.

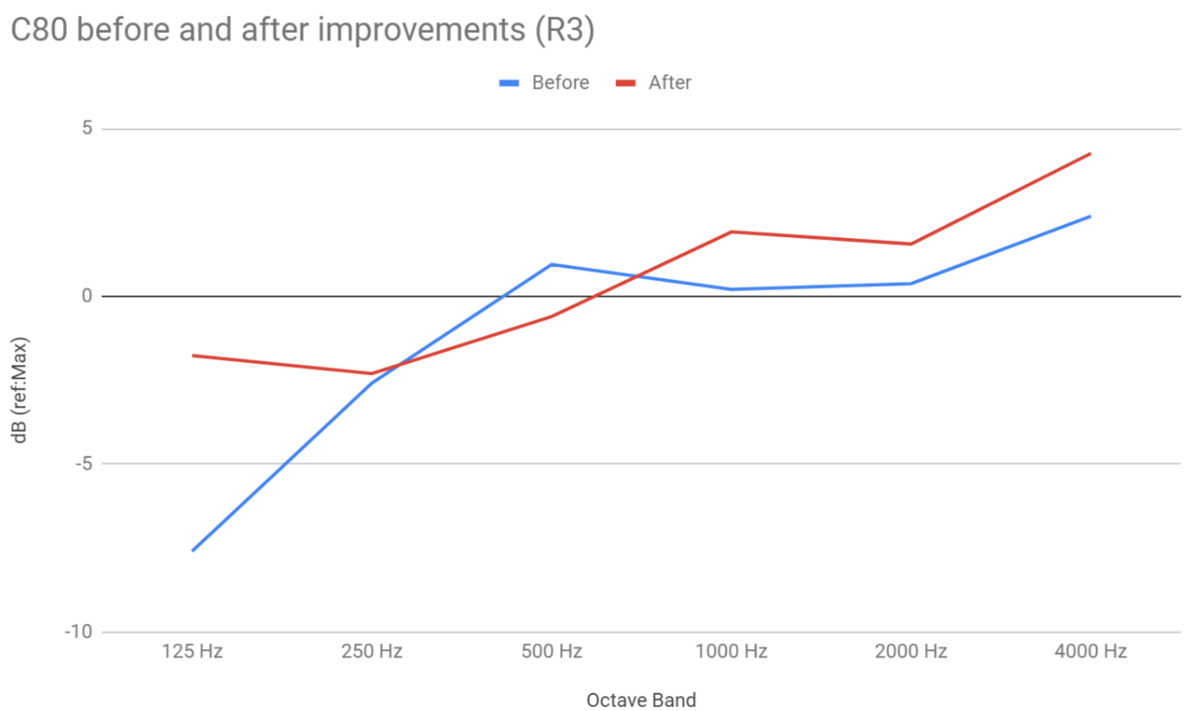
With the addition of panels and sound blocks, we run the same simulation in CATT-Acoustics, and determined the new T30, C80, C50, EDT. The result comparisons are shown for receiver position 3.

Comparison between final simulated T30 and improved T30 results		
	Receiver Position 3	
Octave Band	Before	After
125 Hz	3.27	3.22
250 Hz	2.93	2.62
500 Hz	2.06	1.77
1000 Hz	1.8	1.64
2000 Hz	1.63	1.63
4000 Hz	1.41	1.34

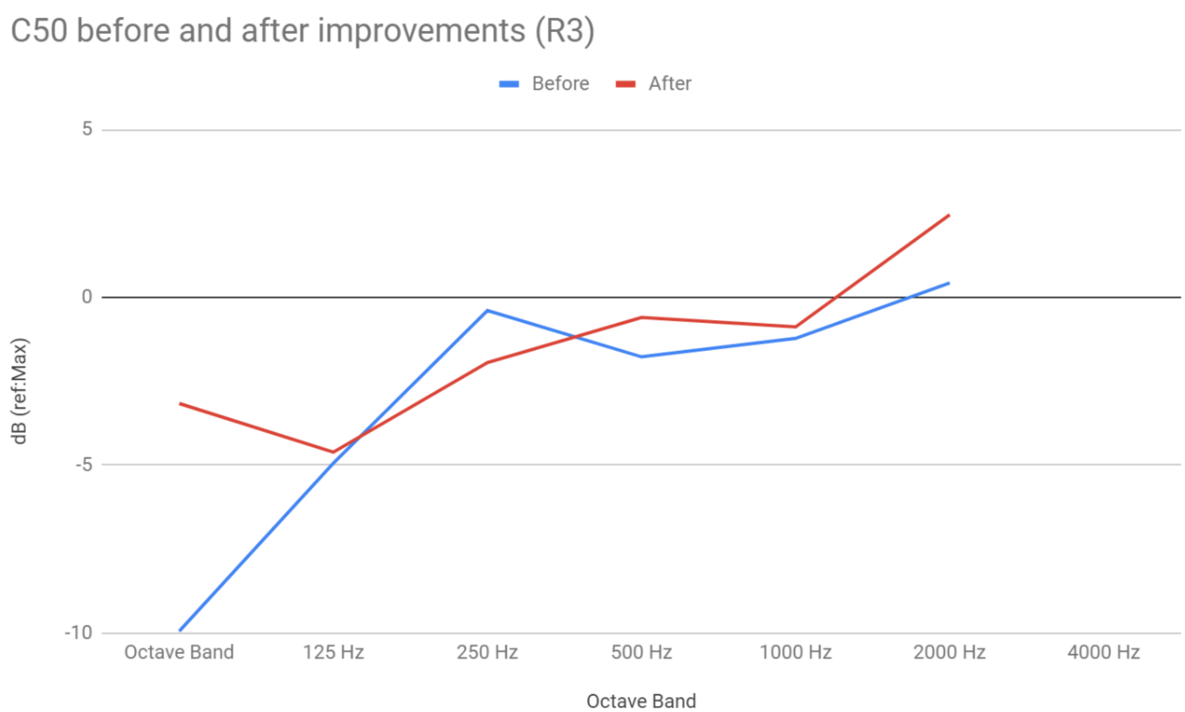


The addition of panels and sound blocks does not significantly lower the reverberation time T30, especially in the 125 Hz, 2000 Hz, and 4000 Hz frequency. The T30 at other frequencies showed a more significant increase. Overall, the T30 does not change much.

Comparison between final simulated C80 and improved C80 results		
	Receiver Position 3	
Octave Band	Before	After
125 Hz	-7.59	-1.76
250 Hz	-2.58	-2.3
500 Hz	0.95	-0.6
1000 Hz	0.21	1.92
2000 Hz	0.38	1.56
4000 Hz	2.39	4.26

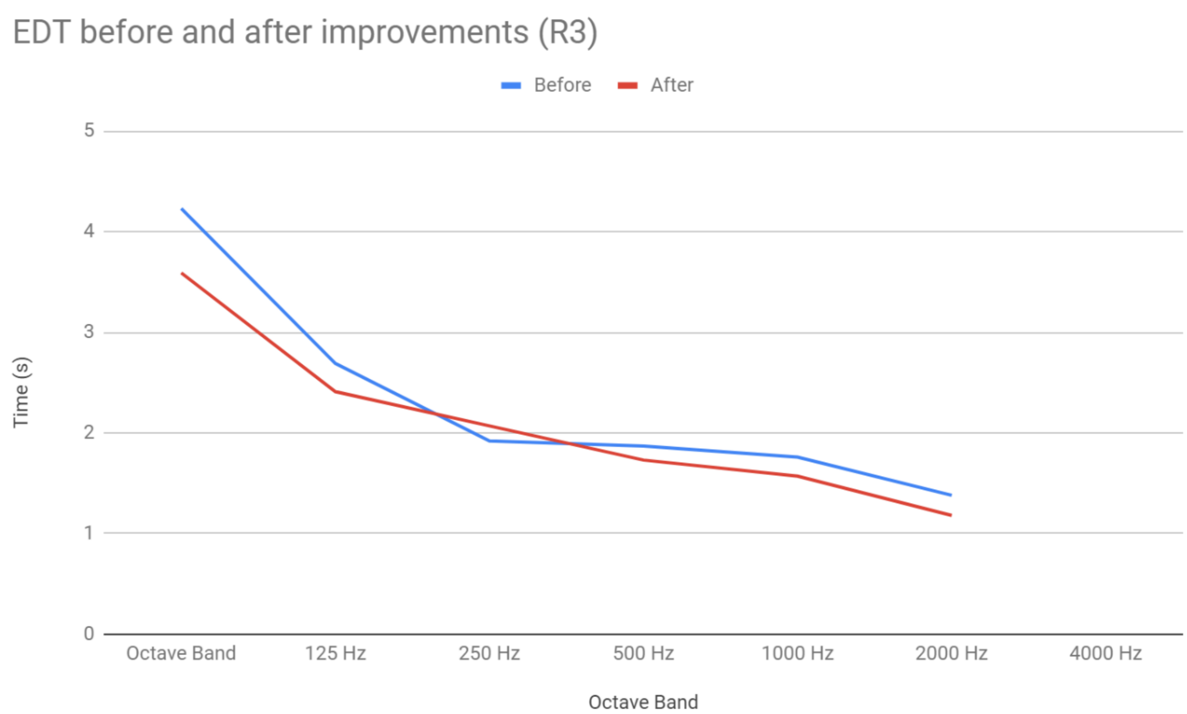


Comparison between final simulated C50 and improved C50 results		
	Receiver Position 3	
Octave Band	Before	After
125 Hz	-9.94	-3.160
250 Hz	-4.94	-4.610
500 Hz	-0.39	-1.940
1000 Hz	-1.77	-0.600
2000 Hz	-1.22	-0.880
4000 Hz	0.43	2.460



Both C80 and C50 showed a significant raise except for 500 Hz where it decreased.

Comparison between final simulated EDT and improved EDT results		
	Receiver Position 3	
Octave Band	Before	After
125 Hz	4.23	3.590
250 Hz	2.69	2.410
500 Hz	1.92	2.070
1000 Hz	1.87	1.730
2000 Hz	1.76	1.570
4000 Hz	1.38	1.180



Conclusion/Recommendation

The addition of the sound blocks and absorber panels decreased reverberation time and increased C80 and C50 clarity indices. Although these results are obtained with no audience present, we expect to have a high improvement on the clarity for both music and speech based on the clarity indices.

Appendix A. MATLAB Measurement Analysis Code

```
clc;
clear all;
close all;

%% SET UP THE DAQ DEVICE
% Interface with the ni USB 4431
% Set up a Mic with IEPE power
% Set up an output channel for the
speaker devices = daq.getDevices
s = daq.createSession('ni'); s.Rate = 44100;

addAnalogOutputChannel(s,'Dev2',0,'Voltage');

addAnalogInputChannel(s,'Dev2',0,'IEPE');



%% SET UP
SIGNAL % Set fs,
N
% Create your sine sweep and
averaging fs = 44100;
dt = 1/fs;
T = 2; % legth of the sweep
N = T*fs; % sample number of one
signal t = (0:N-1)*dt; t=t';
f_1 = 20;
f_2 = 22000;

phi = 2*pi*f_1*((f_2/f _1).^(t./T)-1)*(T/log(f_2/f_1));
sin_sweep = sin(phi);
plot(sin_sweep)
%[C, f] = my_Spect(sin_sweep, 44100, 0.1, 0.4)

z = zeros(N,1); % concate zeros at the end for time
decay signal_clip = vertcat(sin_sweep, z); signal_f =
[];
m_num = 10; %number of averaging

for i = 1:1:m_num
    signal_f = vertcat(signal_f, signal_clip);
end
t_f = (0:length(signal_f)-1)*dt;
plot(t_f, signal_f)

%% DO THE MEASUREMENT
% Interfacing with the 4431
output_data = signal_f;
queueOutputData(s,output_data
) disp('measuring')
[captured_data,time] =
s.startForeground(); disp('done')

%% PLOT (MAKING SURE THAT YOU ARE COLLECTING
DATA) figure(1)
plot(time, captured_data);
```

```
audiowrite('R9_capture.wav', captured_data,fs)
% soundsc(captured_data, fs)


%% ANALYSIS
% Get the average measurement and the resulting IR and FRF
% signal and response
[captured_data,~] = audioread('R9_capture.wav');
% synchronous averaging of the response,
 response_avg N = length(captured_data);
 N2 = length(signal_clip);
 n_avg = floor(N/N2); %how amny actual audio clip in one averaging
 clip bin_size = N2;

for i = 1:1:n_avg
    data_clip(:,i) = captured_data((i-1)*bin_size+1:i*bin_size, :);
end
data_avg = mean(data_clip, 2);
plot(data_avg)
%audiowrite('R9_avg.wav', data_avg, fs);

response_fft = my_fft(data_avg, 44100);
signal_fft = my_fft(signal_clip,
44100); FRF = response_fft./signal_fft;
plot(abs(FRF));

% Calculate the Impulse Response
(IR) IR = my_ifft(FRF, 44100);
plot(10*log10(IR.^2))
save('R9_IR.mat','IR');

%% Octaveband Filtered IR and
FRF % Plot the Octave Band
Filtered IR load('R5_IR.mat',
'IR')
fc = [125, 250, 500, 1000, 2000,
4000] fs = 44100;
IR_filt = []
for i=1:1:6
    [b, a] = butter(3, [1*fc(i)/sqrt(2)/(fs/2)
    1*fc(i)*sqrt(2)/(fs/2)]); IR_filt(:, i) = filter(b, a, IR);
end
dt=1/fs;
t = (0:length(IR_filt)-1)*dt; t=t';
plot(t, 10*log10(IR_filt.^2))
save('R5_filt.mat', 'IR_filt')



%% EDC for filtered IR
load('R4_ filt.mat', 'IR_filt')
fs=44100
dt=1/fs;
t = (0:length(IR_filt)-1)*dt; t=t';
[EDC_curve,EDC_max] = EDC(IR_filt,fs);
Decay = 10*log10(EDC_curve./EDC_max);
```

```
plot(t, 10*log10(EDC_curve./EDC_max))
legend('125', '250', '500', '1000', '2000', '4000')

%% Find RT, EDT &C80

for i = 1:1:6
    index = i
    sample_1 = find(Decay(:,index)>-0.01 & Decay(:,index)<0.01);
    sample_2 = find(Decay(:,index)>-10.001 & Decay(:,index)<-9.99);
    sample_3 = find(Decay(:,index)>-5.001 & Decay(:,index)<-4.99);
    sample_4 = find(Decay(:,index)>-25.001 & Decay(:,index)<-24.99);
    sample_5 = find(Decay(:,index)>-35.001 & Decay(:,index)<-34.99);
    time(i, 1) = sample_1(1)*dt;
    time(i, 2) = sample_2(1)*dt;
    time(i, 3) = sample_3(1)*dt;
    time(i, 4) = sample_4(1)*dt;
    time(i, 5) = sample_5(1)*dt;
end
p = IR_filt.^2;
[~, idx] = max(p)
E_1 = sum(p(idx:idx+3528,:));
E_2 = sum(p(idx+3528:end,:));
C_80 = 10*log10(E_1./E_2);

%% C80
load('R5_filt.mat', 'IR_filt')
fs = 44100;
dt = 1/fs;
[~, EDC_max_1] = EDC(IR_filt(1:0.08*44100,:));
[~, EDC_max_2] = EDC(IR_filt(0.08*44100:end,:));
C_80 = 10*log10(EDC_max_1./EDC_max_2);
```

Energy Decay Curve function code

```
function [energy_remain,total_energy] = EDC(x,fs)
% EDC - Energy Decay Curve. Inputs are time series x and sampling frequency
% fs. outputs are time vector t, remaining energy vector, and total energy
% from the sound. EDC is also known as Schroeder Curve. When plotting. Take
% 10log10 of energy_remain/total_energy for dB.

dt = 1/fs; % time increments.

p = x.^2; % amplitude squared power.

energy_remain = cumsum(p*dt,'reverse'); % backwards integration for
EDC total_energy = sum(p*dt); % total energy.
```

Appendix B. Reverberation Time Calculation

Reverberation time RT60 is calculated by locating the time it takes for EDC to drop 60 dB from -5 dB level. If the EDC does not drop 60 dB, locate the time of 30 dB drop, and multiply the time by 2 to obtain equivalent reverberation time T30. If EDC does not reach 30 dB drop, locate time of 20 dB drop, and multiply time by 3 to get T20. If EDC does not reach 20 dB drop, locate time of 15 dB drop, and multiply time by 4 to get T15. In our case, there is no 60 dB drop for any of the receiver positions so the reverberation time RT60 is approximated using T15, T20, T30. The approximated RT60 uses the time with greatest dB drop. For example, 30 dB drop time is preferred to the 20 dB drop time.

Note: tXY (X and Y are digits) represents the time at -XY dB on the Schroeder EDC. E.g. t25 is time at -25 dB on EDC. Chart entries are time in seconds corresponding to the frequency at the associated dB levels.

Receiver Position R3 data

Frequency (Hz)	-5 dB	-25 dB	-35 dB
125	0.2488	1.3408	
250	0.1952	0.8795	
500	0.1866	0.7832	
1000	0.1778	0.7343	1.1088
2000	0.1732	0.6649	0.9442
4000	0.1035	0.5081	

R3 Calculation

Frequency (Hz)	T20 = 3*(t25-t5)	T30 = 2*(t35-t5)
125	3.276	
250	2.0529	
500	1.7898	
1000	1.6695	1.862
2000	1.4751	1.542
4000	1.2138	

Receiver Position R4

Frequency (Hz)	-5 dB	-20 dB	-25 dB	-35 dB
125	0.2222	0.8482		
250	0.2095		0.9913	
500	0.1742		0.8272	
1000	0.1601		0.7049	1.1373
2000	0.1292		0.6177	0.9025
4000	0.091		0.4819	

R4 Calculation

Frequency (Hz)	T15 = 4*(t20-t5)	T20 = 3*(t25-t5)	T30 = 2*(t35-t5)
125	2.504		
250		2.3454	
500		1.959	
1000		1.6344	1.9544
2000		1.4655	1.5466
4000		1.1727	

Receiver Position R5

Frequency (Hz)	-5 dB	-20 dB	-25 dB	-35 dB
125	0.2316	0.8183		
250	0.1935		0.9486	
500	0.1481		0.8068	
1000	0.1582		0.732	1.1406
2000	0.145		0.6429	0.9127
4000	0.1355		0.5274	

R5 Calculation

Frequency (Hz)	T15 = 4*(t20-t5)	T20 = 3*(t25-t5)	T30 = 2*(t35-t5)
125	2.3468		
250		2.2653	
500		1.9761	
1000		1.7214	1.9648
2000		1.4937	1.5354
4000		1.1757	

Appendix C. Photos of NEST+m Auditorium

Some photos of NEST+m Auditorium taken during measurement