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Acoustic Characterization of a Krannert Center Dance Studio

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4/30/2024

Outline

- Introduction
- Acoustics Background
- Instrumentation
- Methods
- Conclusion

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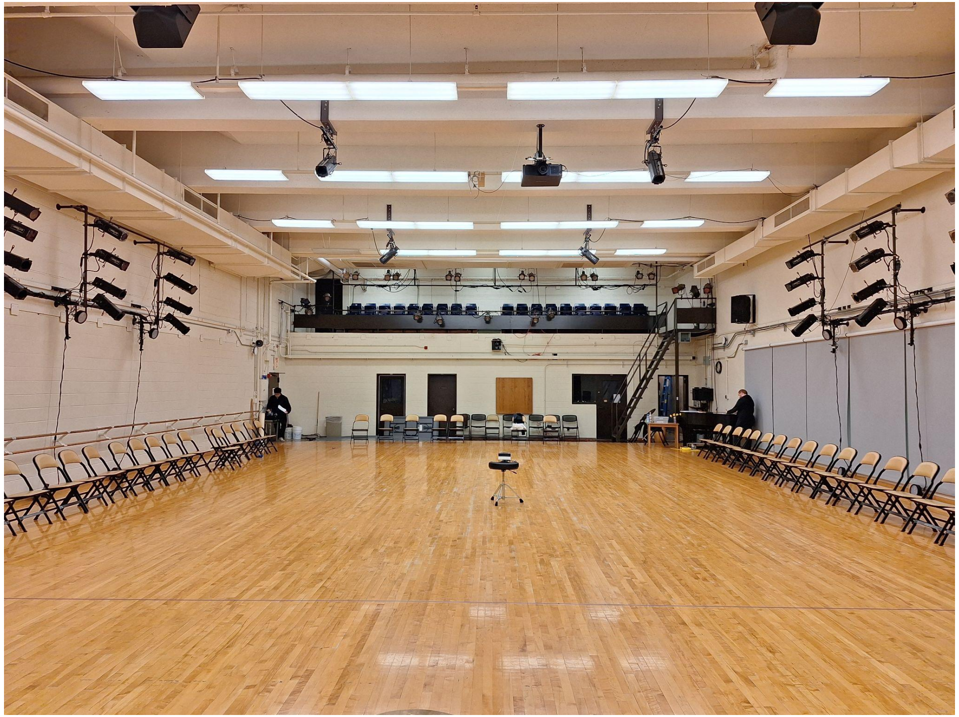
Introduction

The Problem

- Current acoustics of the dance studio are in desperate need of fixing.
- Room is too live for any speaking while rehearsing.
- Also not ideal for live performances.



The Problem

- Acoustic absorption panels are available for use.
- Need to know if they are effective, and if so, how many are necessary

The Goal

1. Find an accurate method to determine RT60 using instruments developed in-house.
    a. Tested two methods.

2. Reduce the RT60 to ≈1.8 s using available materials.

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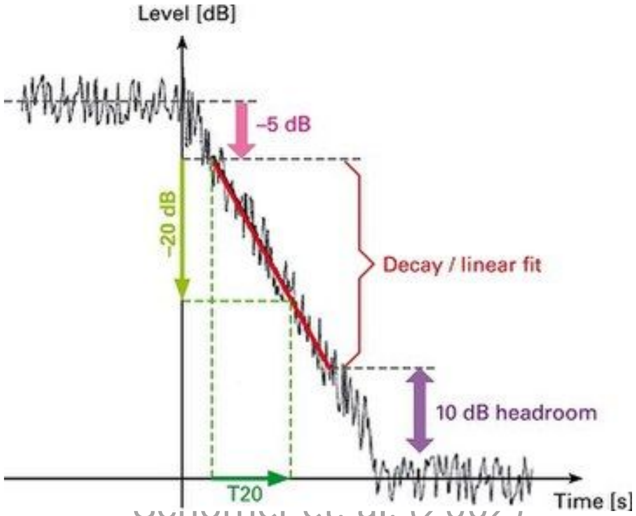
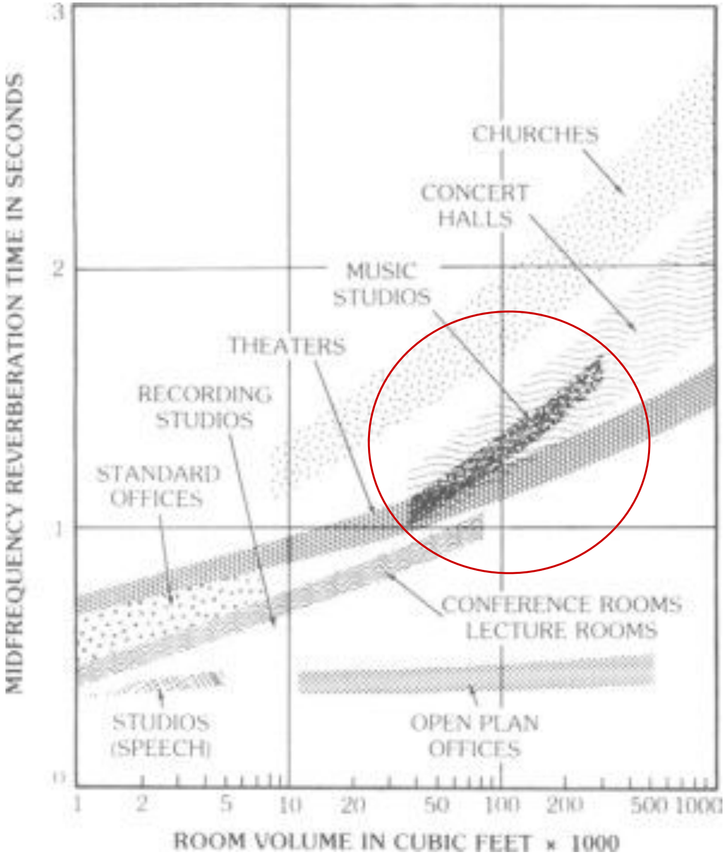
Acoustics Background

Measuring Room Reverberation

- Reverberation Time
  - RT60
  - Measured at 1/3 - 1 octave frequency bands
  - Ideally 1.0 - 1.8 s





Rakerd et. al. (2019)

Schomer et. al. (2002)

Decibels (dB) and Sound Pressure Level (SPL)

- The “loudness” of sound is quantified by its sound pressure level (SPL)

$$SPL = 20\log_{10}(\frac{p}{p_{ref}}), \quad p_{ref} = 20\,\mu Pa$$

$$\Delta SPL = 20\log_{10}(\frac{p}{p_0})$$

Source	Sound Pressure Level (dB)
Threshold of Hearing	0
Rustling leaves	20
Quiet whisper (1 m)	30
Quiet office	40
Normal conversation at 1 m	60
Inside a car	65-80
Loud singing	70
Vacuum cleaner (3 m)	75
Buses, diesel trucks, motorcycles (15 m)	80
Jackhammer (15 m)	90
Subway (inside)	94
Lawn mower (1 m)	107
Deafening, human pain limit	120
Jet plane (30 m)	130
Threshold of pain	140
Military Jet Take-off (30 m)	150
Large military weapons	180

Svantek - Sound Pressure Level (SPL)

RT60 Calculation

Assuming an exponential decay, RT60 can calculated as:

$$-60 = 20\log_{10} e^{kt}$$

Solving for t:

$$RT60 = \ln(\frac{0.001}{k}) \qquad \sigma_{\mathrm{RT60}} = \left|\frac{\ln(0.001)}{k^2}\right|\sqrt{\sigma_k^2}$$

Sabine's Equation and RT60 Prediction

$$A = S_1\alpha_1 + S_2\alpha_2 + \ldots + S_n\alpha_n = \sum S_i\alpha_i$$

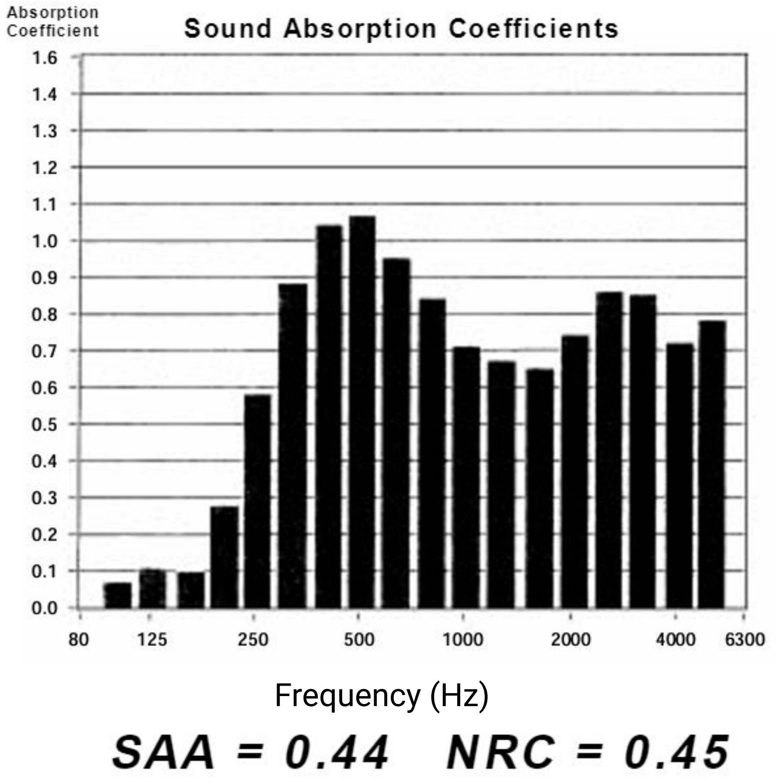
$$RT_{60} = \frac{24\,(\ln 10)\;V}{c_{20}\,S_a}$$

$$RT_{60} \approx 2.3\ s$$

Electroacoustics - Schomer, Swenson. Page 13.

Frequency Dependence

- Mid-range frequencies are absorbed more quickly.
  - Material dependent.

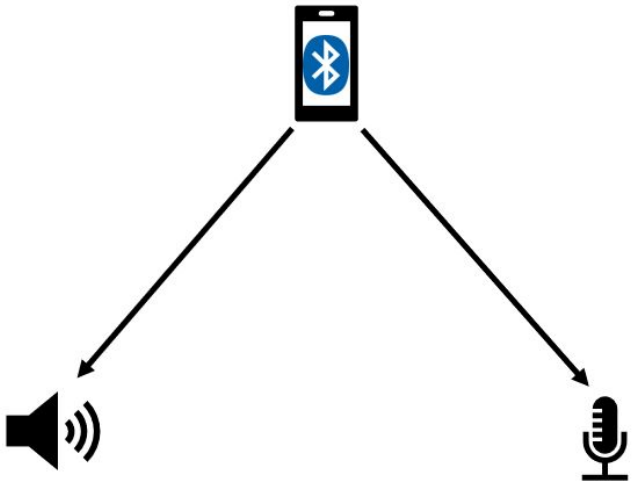


Acoustical Surfaces Inc. Sound Silencer Datasheet

Instrumentation

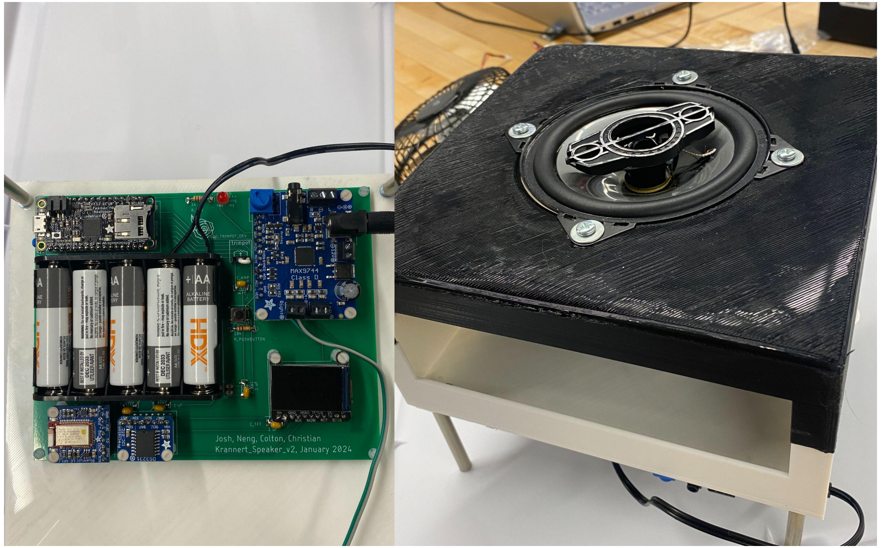
Devices

- 2 Devices in this project.
  - Both controlled via Bluetooth.
- Speaker board (our method).
  - Makes a single frequency tone.
- Microphone board.
  - Electret Microphone converts pressure into voltage.
  - Voltage information recorded in SD card.

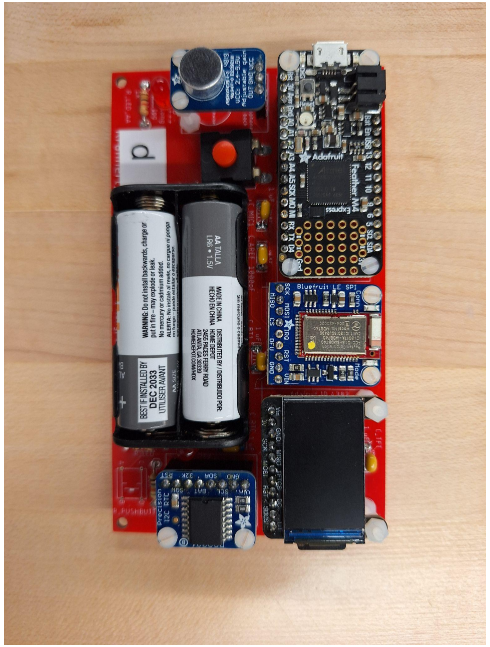


Devices

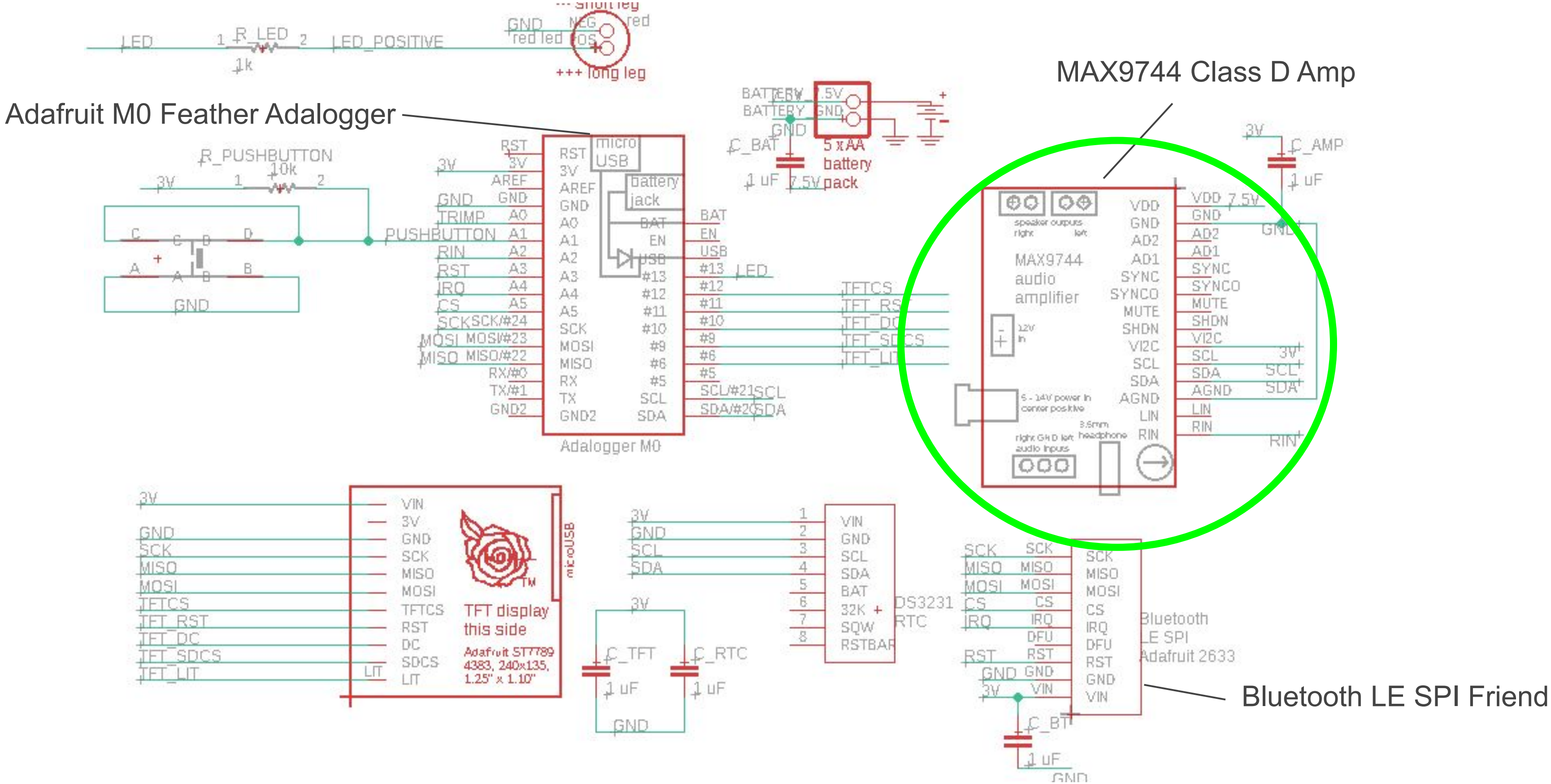
Speaker Board



Microphone Board

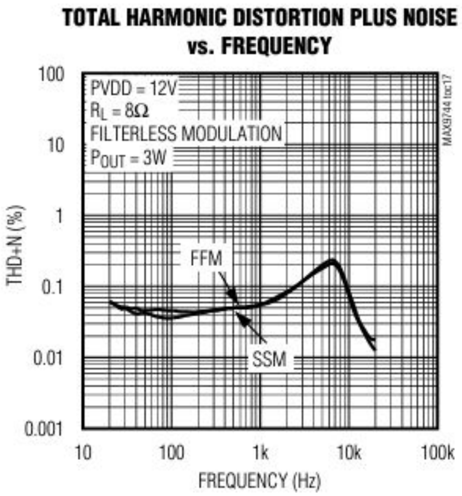


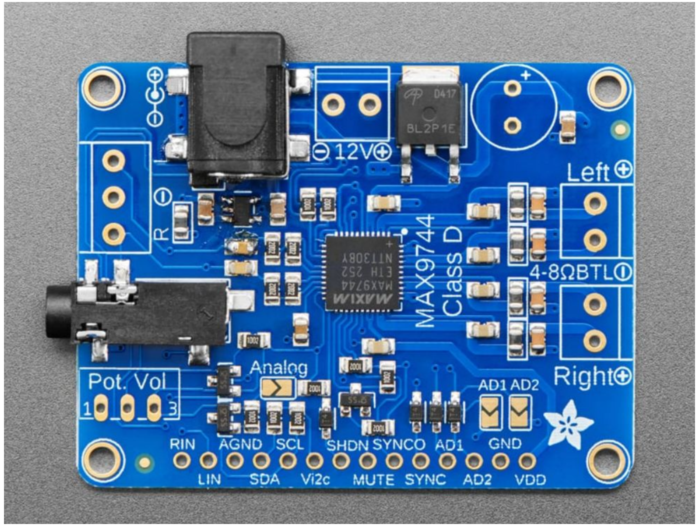
Speaker Board Schematic



MAX9744 Class D Amplifier

- Communicates with Adalogger over I2C protocol.
- Allows digital and analog control.

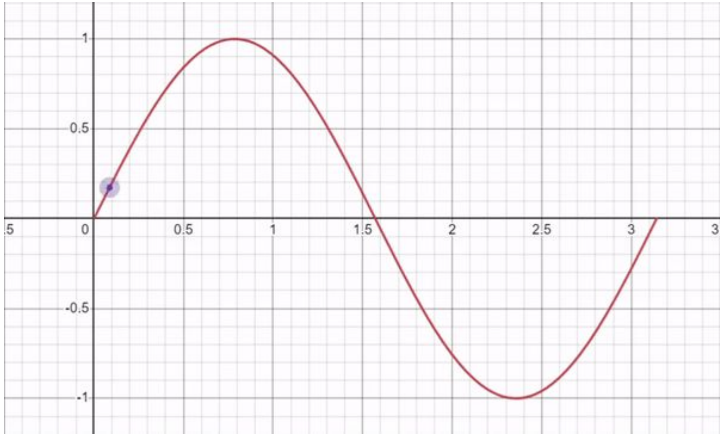


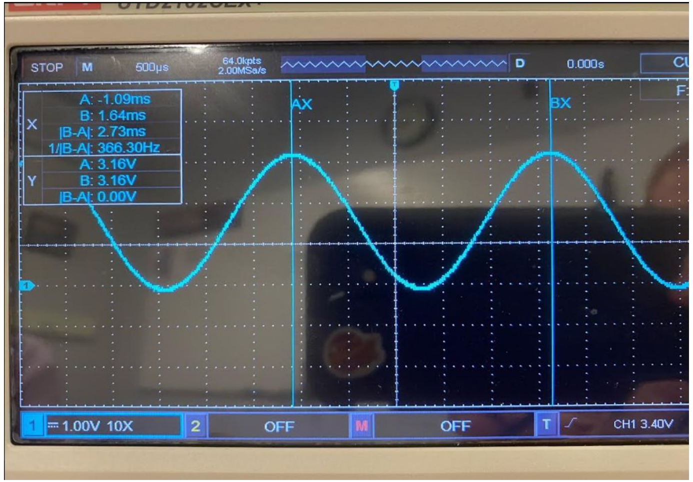


MAX9744 Datasheet

Sound Creation

- Sine wave emulation.
  1. Saves one period at specified frequency to an array.
  2. Reads through array at necessary speed.

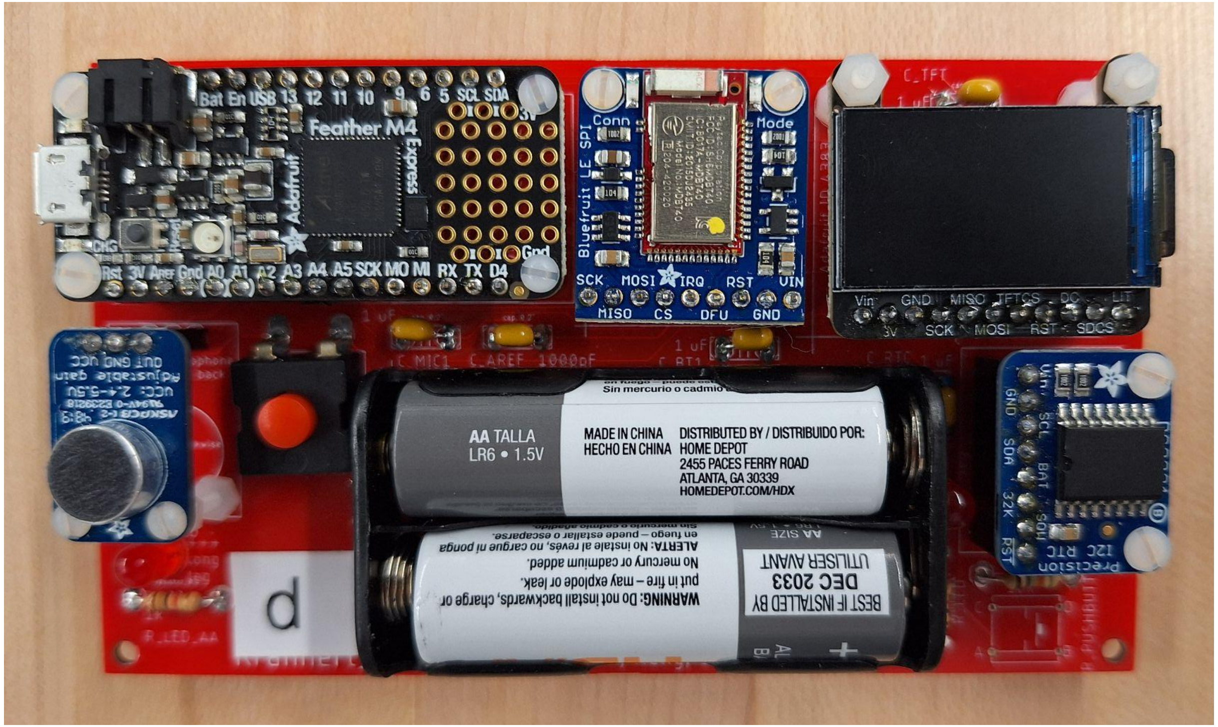




Microphone Board

Adafruit M0 Feather Adalogger

Bluetooth LE SPI Friend

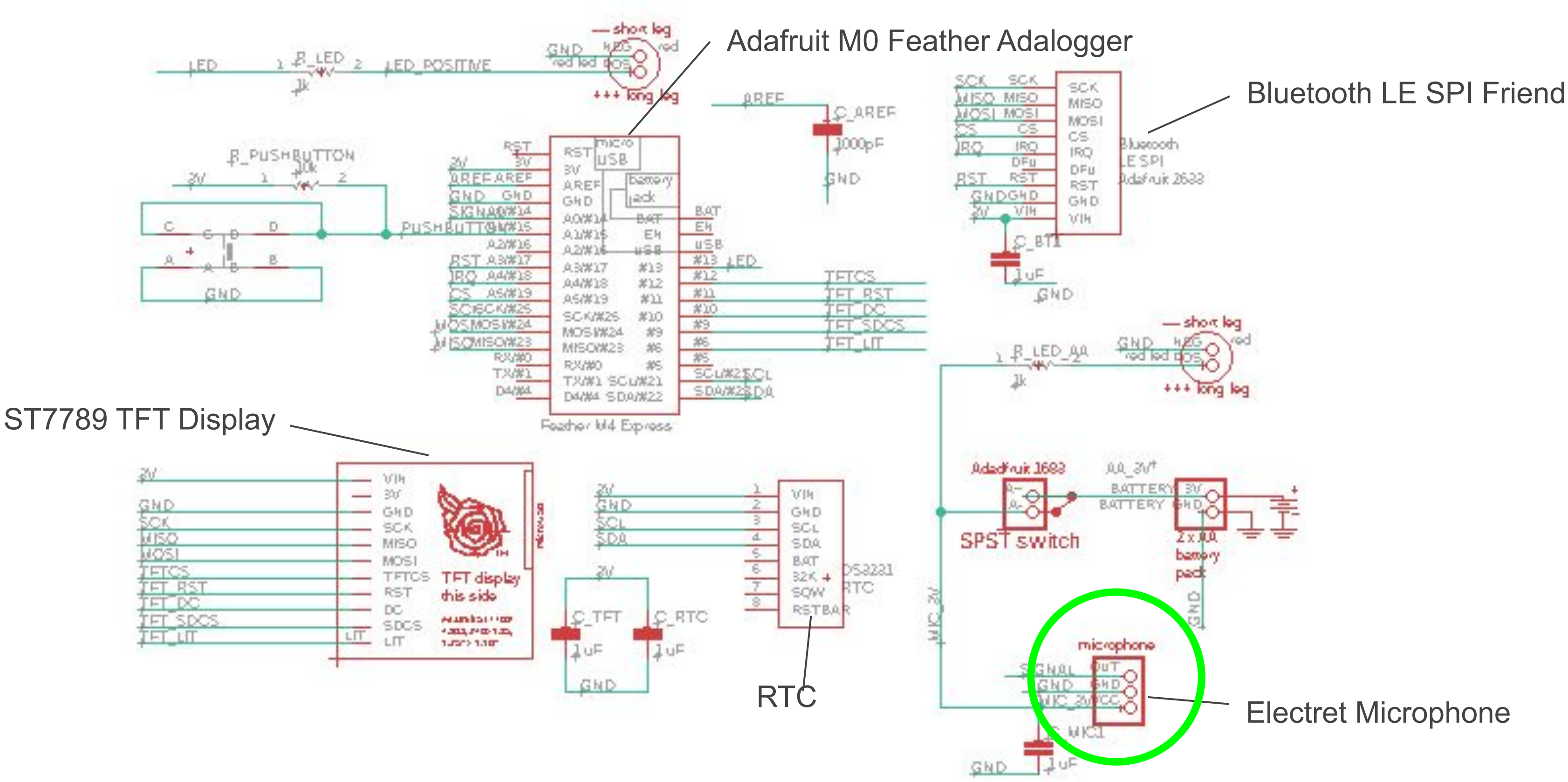


ST7789 TFT Display

Electret Microphone

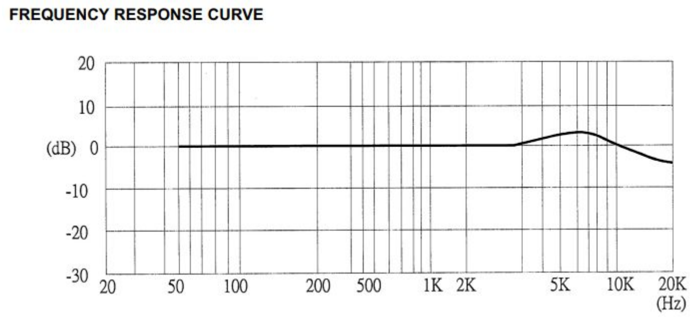
RTC

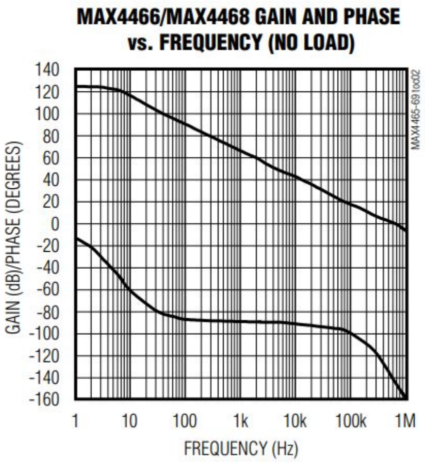
Microphone Board



Microphone

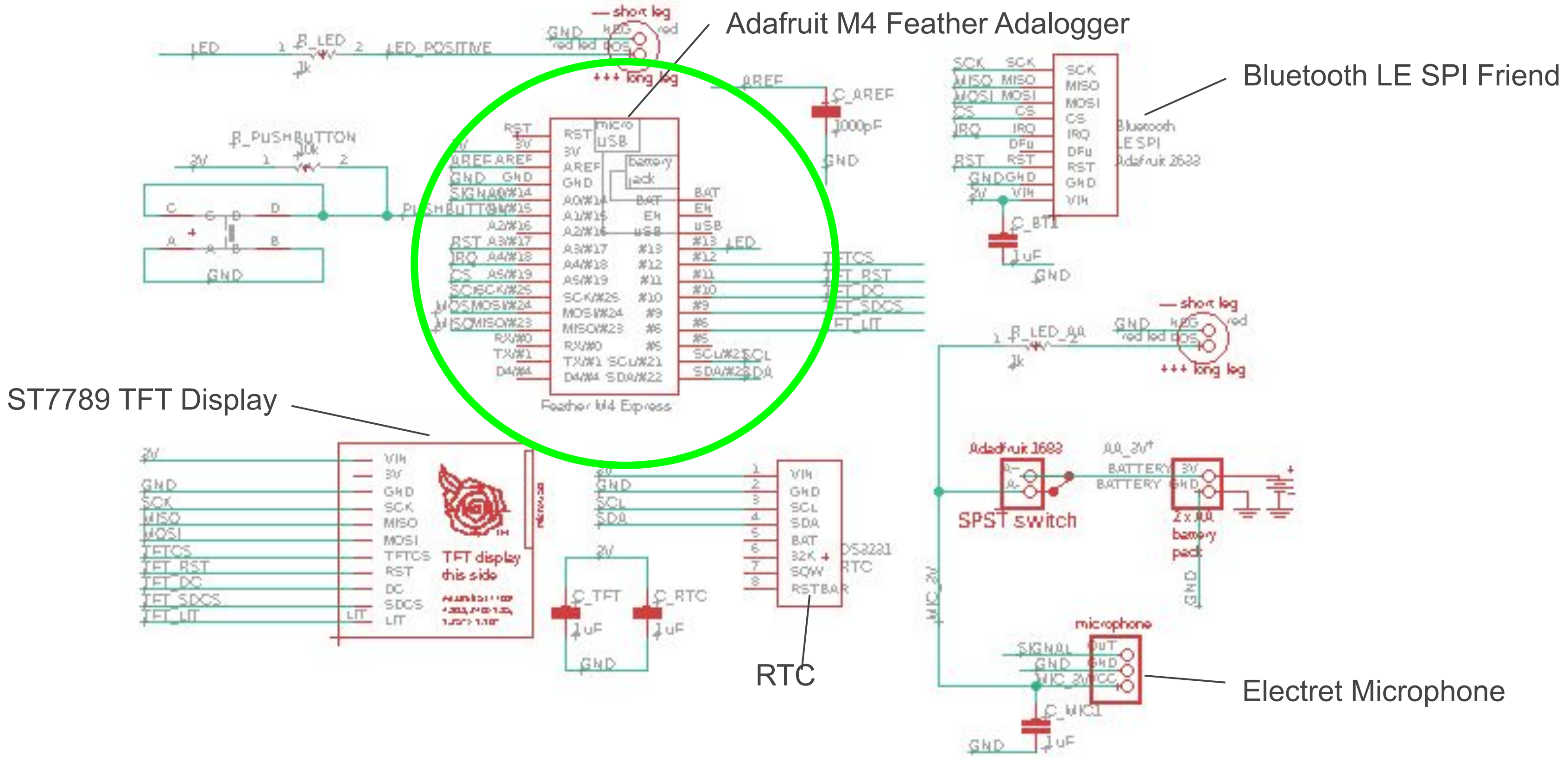
- Electret microphone.
- Built-in MAX4466 amplifier.
- Reliable 20Hz - 20kHz.





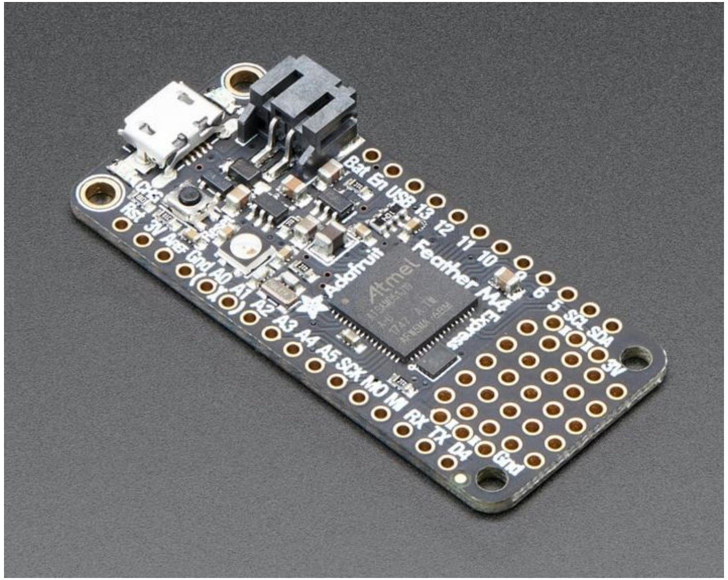
Adafruit Electret Microphone Datasheet

Microphone Board



Analog Inputs

- 12 bit data
- 120 MHz clock: analogRead() - 37 kHz
- Could take faster data - 44.1 kHz (Red Book Audio)
- 512 KB FRAM = 86000 samples = 2.5 s of data

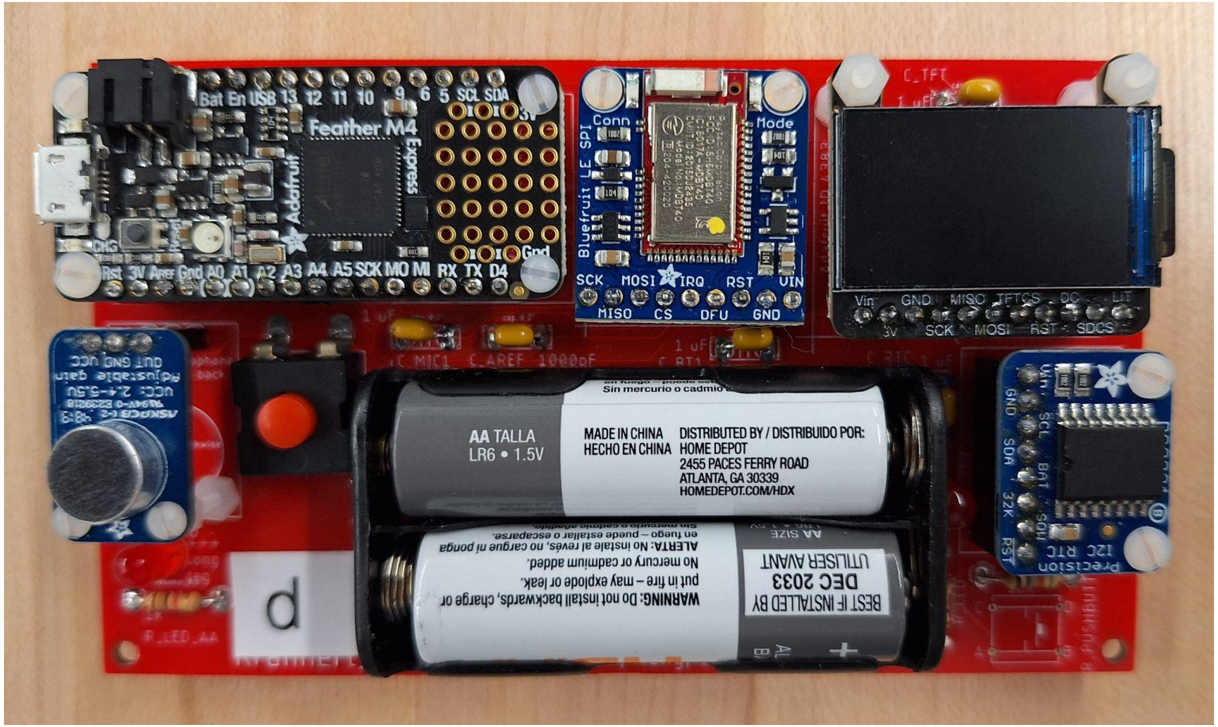


https://www.adafruit.com/product/3857

Microphone Board

Adafruit M0 Feather Adalogger

Bluetooth LE SPI Friend



ST7789 TFT Display

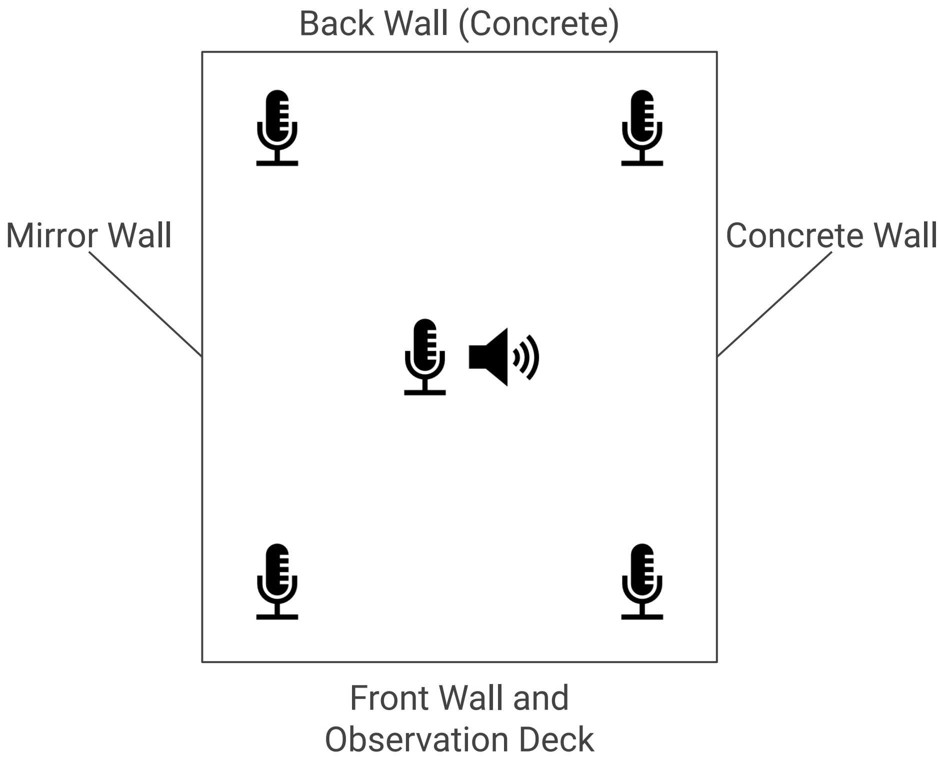
Electret Microphone

RTC

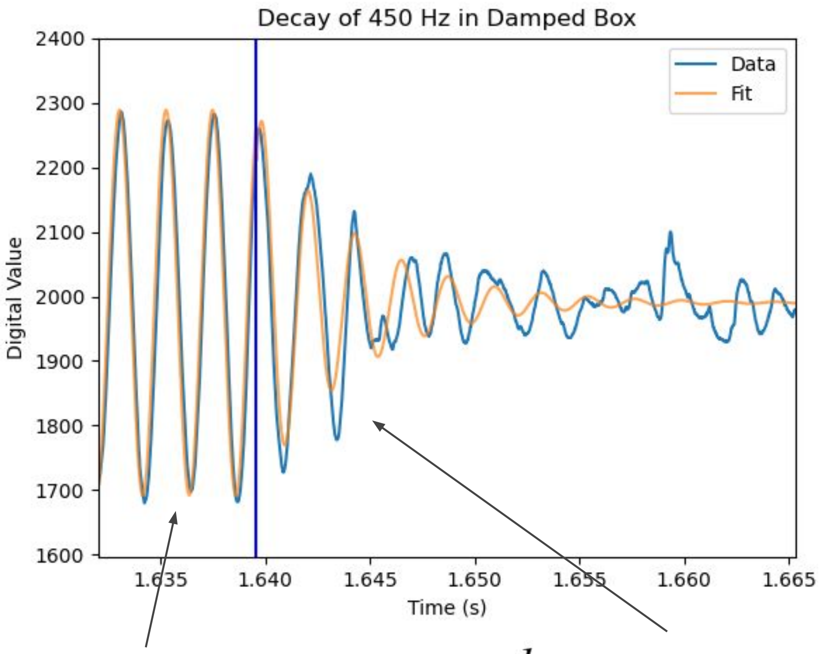
Our Method

Procedure

- Trigger signal sent from smartphone.
- Speaker makes noise for 3 seconds.
- Microphones record data two seconds after speaker starts making noise.
- Trials consisted of two separate tones (220 Hz and 440 Hz).



Box Measurement

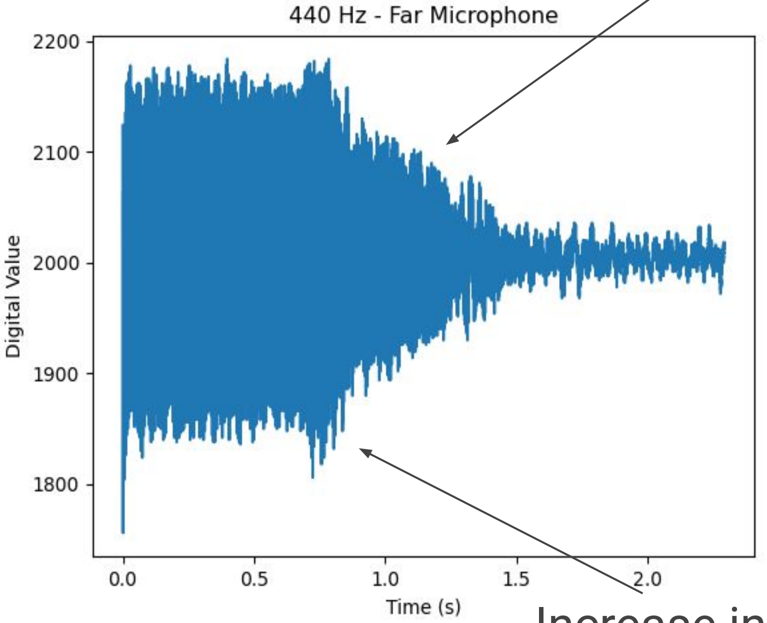


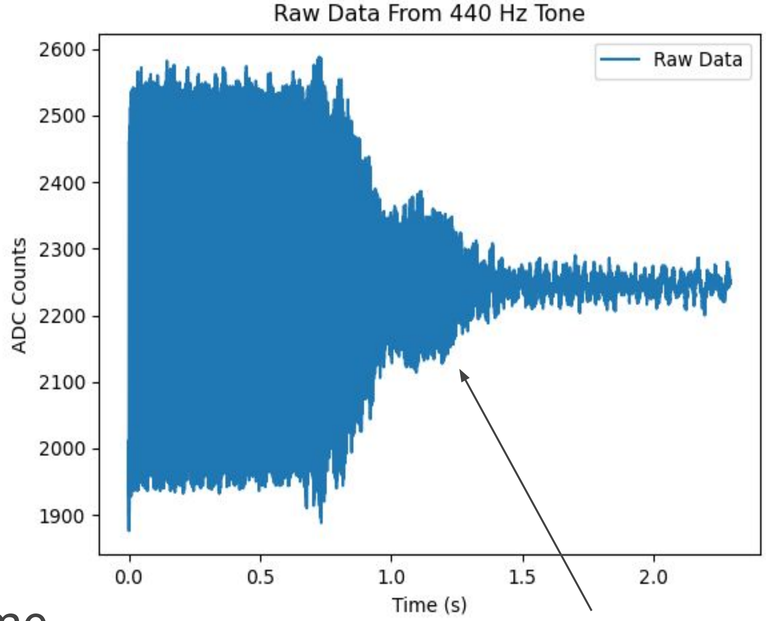
$$\sin\left(fx + \phi_1\right) \qquad e^{-kx}\sin\left(fx + \phi_2\right)$$

- RT60 time is 0.031 ± 0.001 s

Why this does not work in the studio?

Not exponential

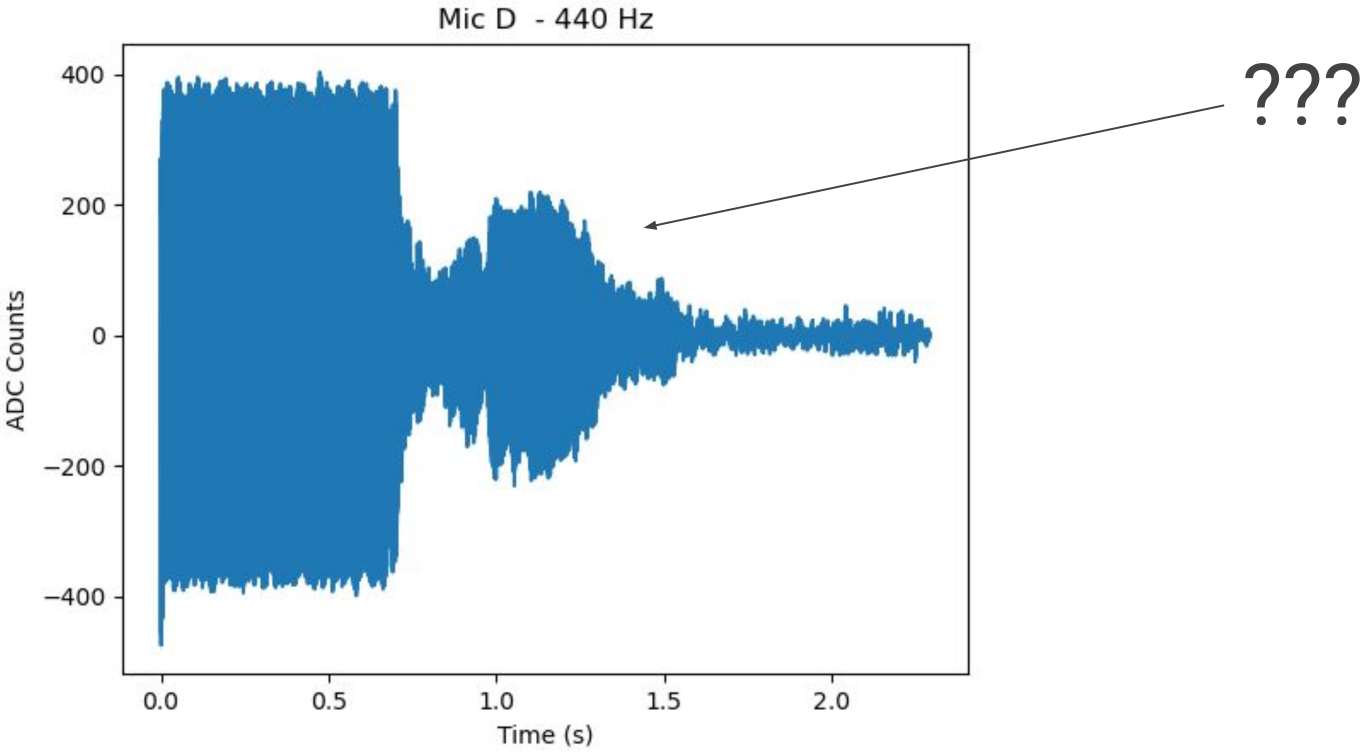




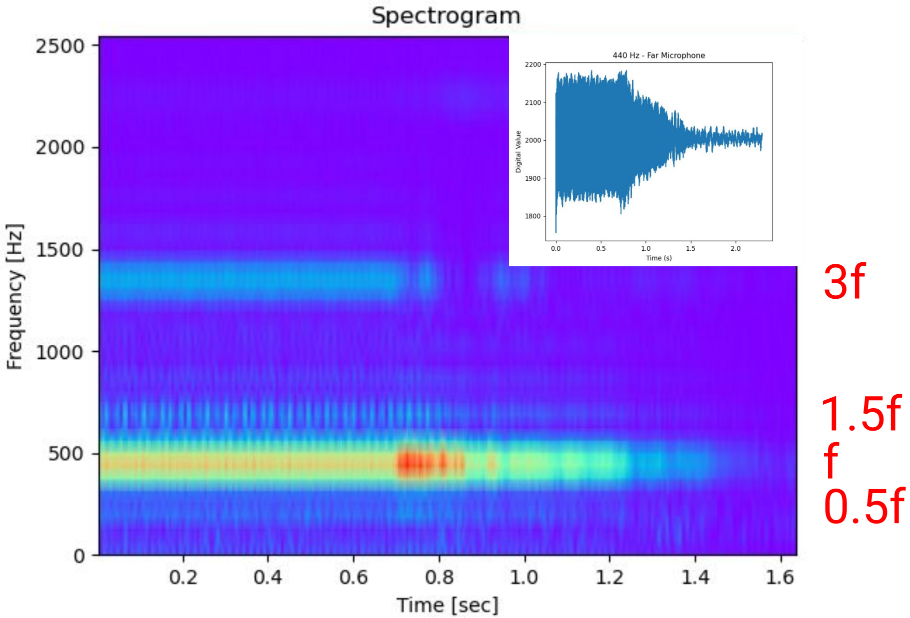
Increase in volume after turning speaker off?

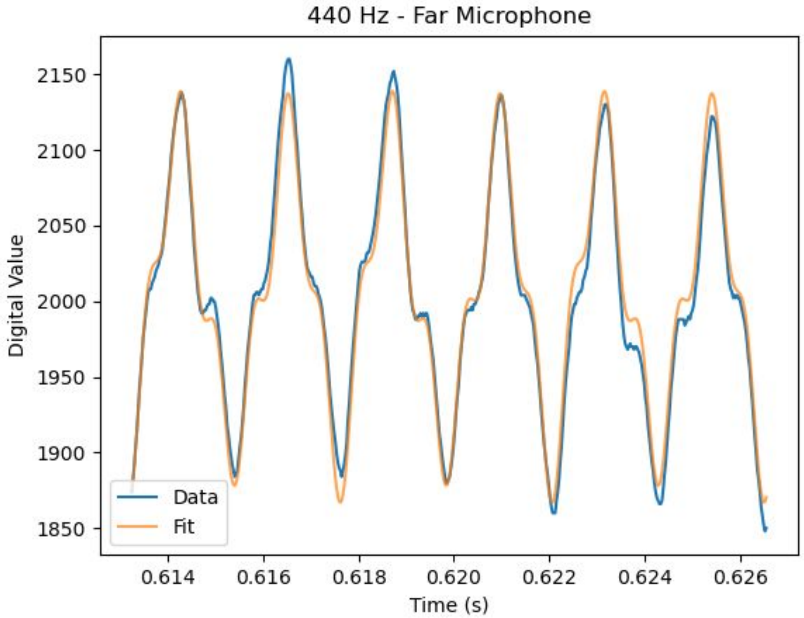
Blip in volume ~ 0.7 s after turning speaker off

Why this does not work in the studio?



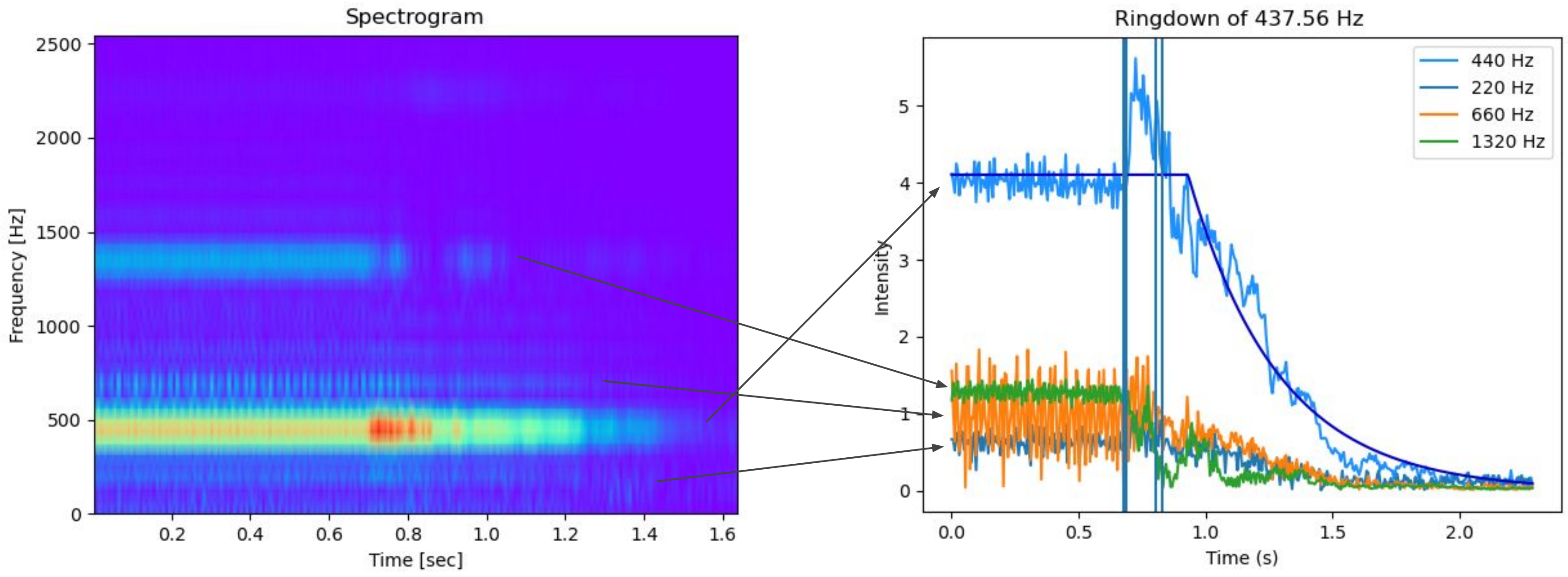
Why this does not work in the studio?





$$e^{-k_1 x} \sin\left(f_1 x + \phi_1\right) + e^{-k_2 x} \sin\left(f_2 x + \phi_2\right) \ldots$$

Why this does not work in the studio?



- RT60 time is 2.45 ± 0.07 s

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Impulse Response Method

Schroeder Method of Reverberation Measurement

- Eliminates the need to take the average of many trials.

- Uses the assumption that any noise is “stationary white noise”.

- Requires an impulse source.
  - Mathematically: Dirac delta.
  - In Practice: Balloon pop, starter gun, etc.

New Method of Measuring Reverberation Time

M. R. Schroeder

Bell Telephone Laboratories, Inc., Murray Hill, New Jersey
(Received 14 December 1964)

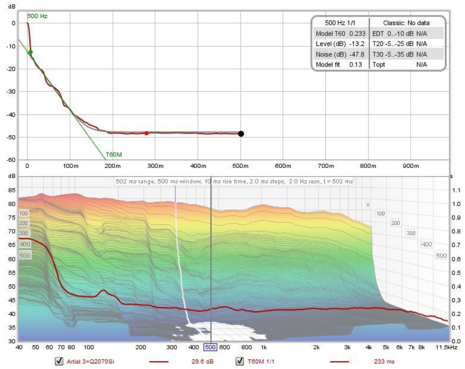
A new method of measuring reverberation time is described. The method uses tone bursts (or filtered pistol shots) to excite the enclosure. A simple integral over the tone-burst response of the enclosure yields, in a single measurement, the *ensemble average* of the decay curves that would be obtained with bandpass-filtered noise as an excitation signal. The smooth decay curves resulting from the new method improve the accuracy of reverberation-time measurements and facilitate the detection of nonexponential decays.

Industry Standard Procedure

- An omnidirectional speaker and a sound level meter with octave filters is used
- Sound source must be capable of producing sound 35-45 dB above the floor noise and should be placed about 1.5 m above the floor
- Data is taken with source in several locations

REW 5.0

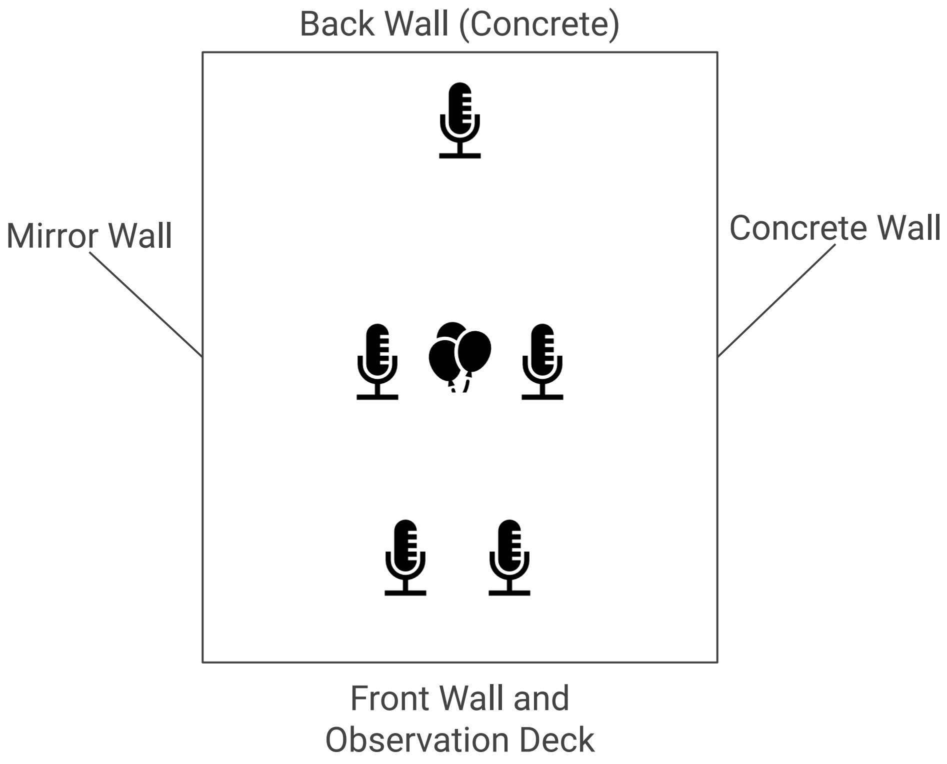
www.roomeqwizard.com



Svantek - RT60 Reverberation Time

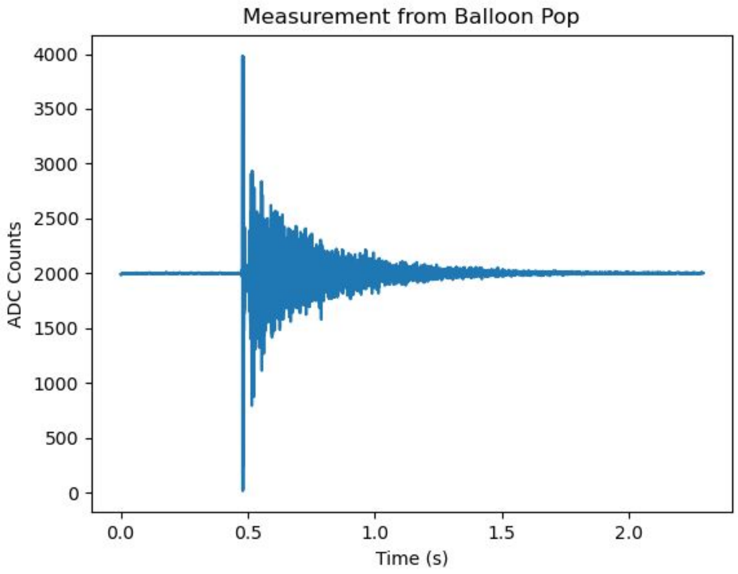
Procedure

- Microphones lined up at different distances from center of the room.
- Trigger signal sent from smartphone.
- Impulse created as soon as LED indicated mics were recording.
- Acoustic foam added for subsequent runs.



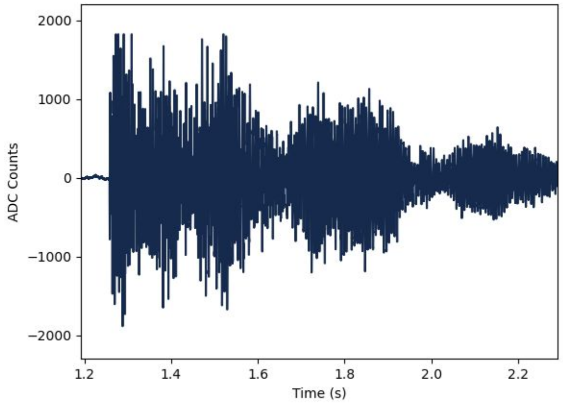
Impulse Measurements

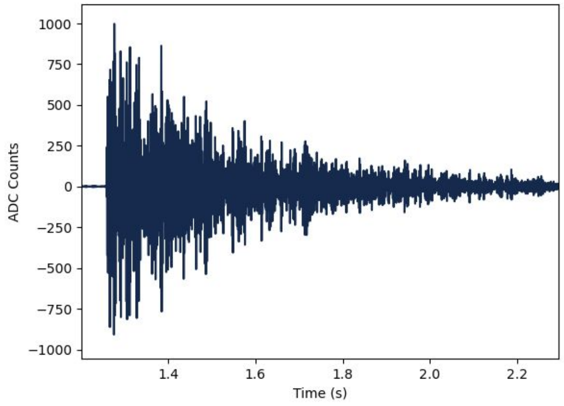
- We chose to pop balloons for our impulse.
- Pros: simple, cost effective, impulse and reverberation are easily visible.
- Cons: inconsistent balloon pressures can throw off measurements, saturates microphone signal unless gain is minimized.

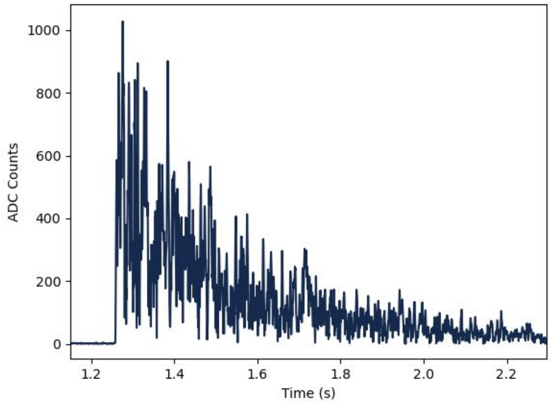


Data Analysis

Raw Data → Band Pass Filter → Hilbert Transform →

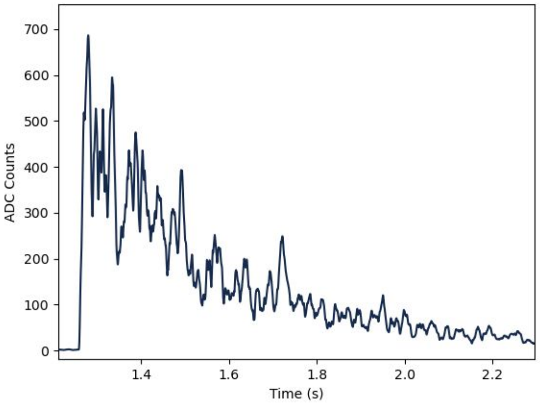


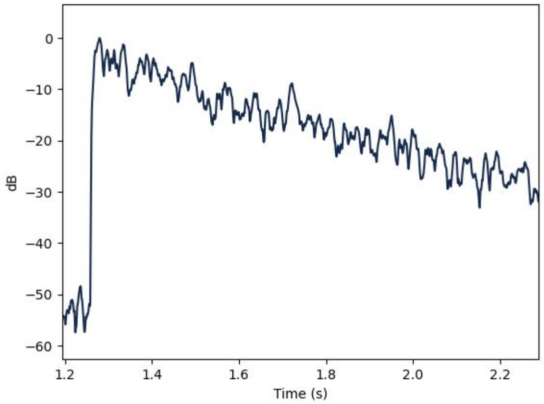


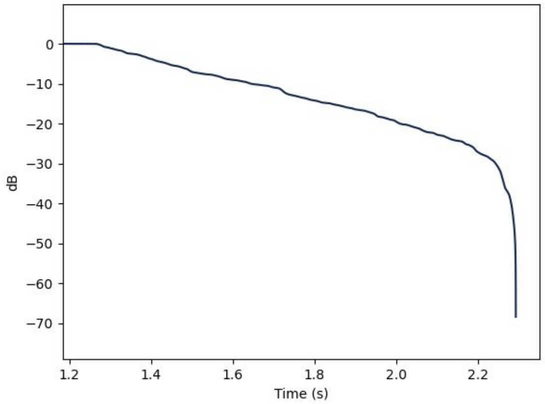


Data Analysis

Filter → Convert to dB → Schroeder Integration

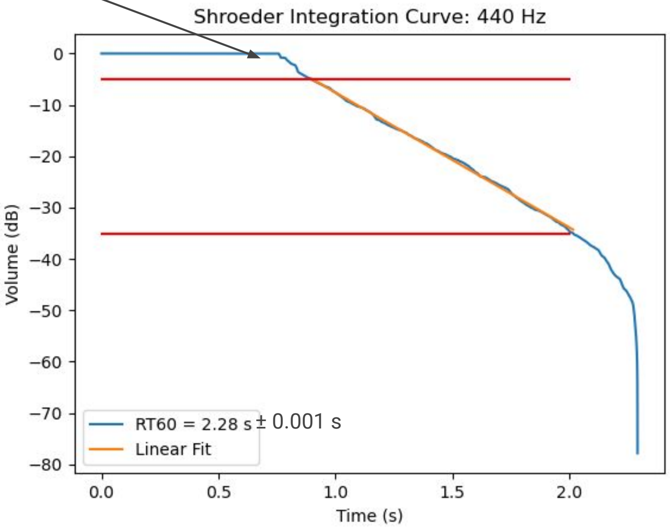


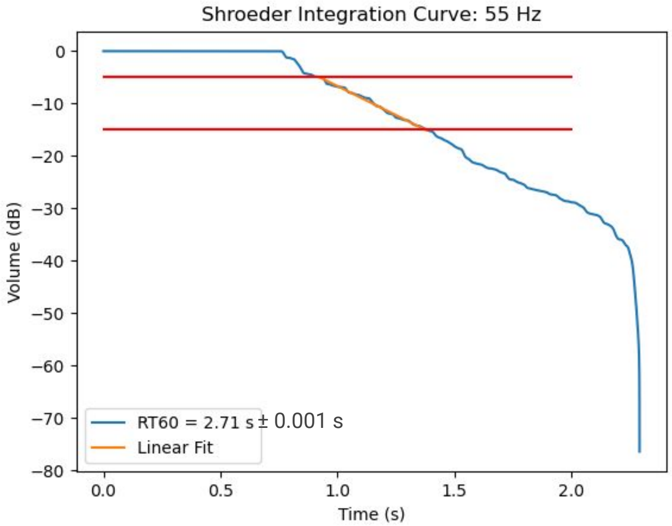




Results

Early Decay Time (EDT)

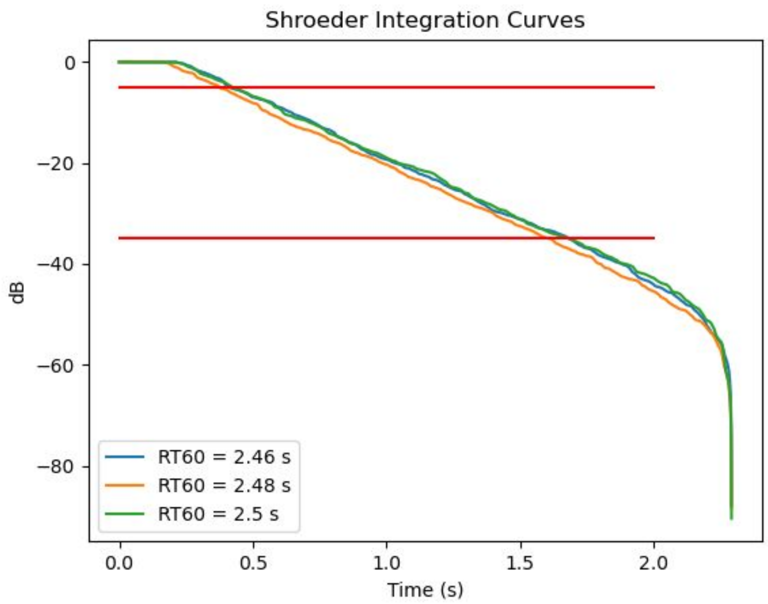




440 - 880 Hz band typically analyzed over 30 dB of decay

Lower and higher frequencies analyzed over 10 dB of decay

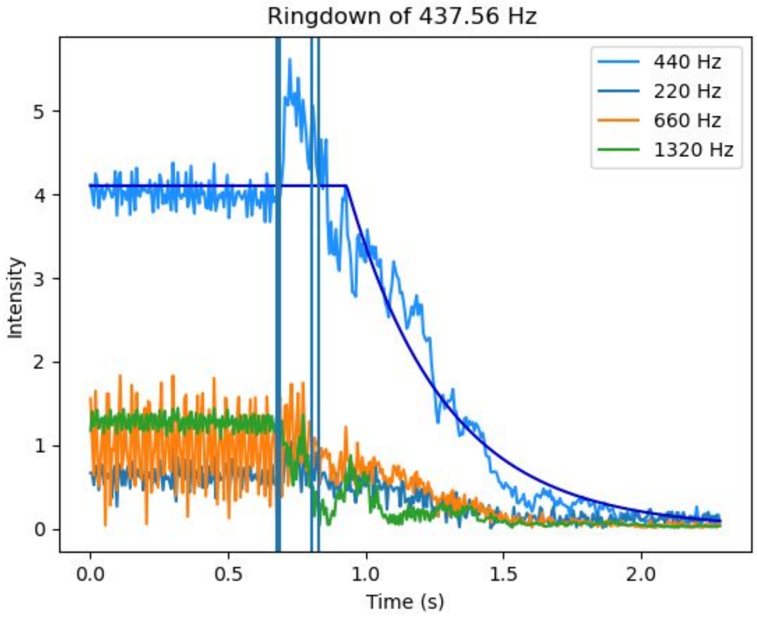
Results



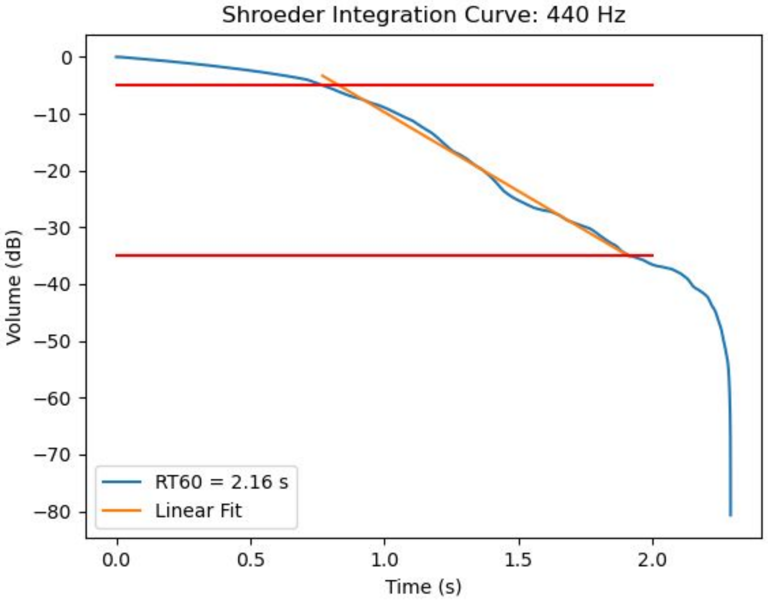
440 - 880 Hz band

Balloon popped in middle of room

Results - Comparison to Our Method

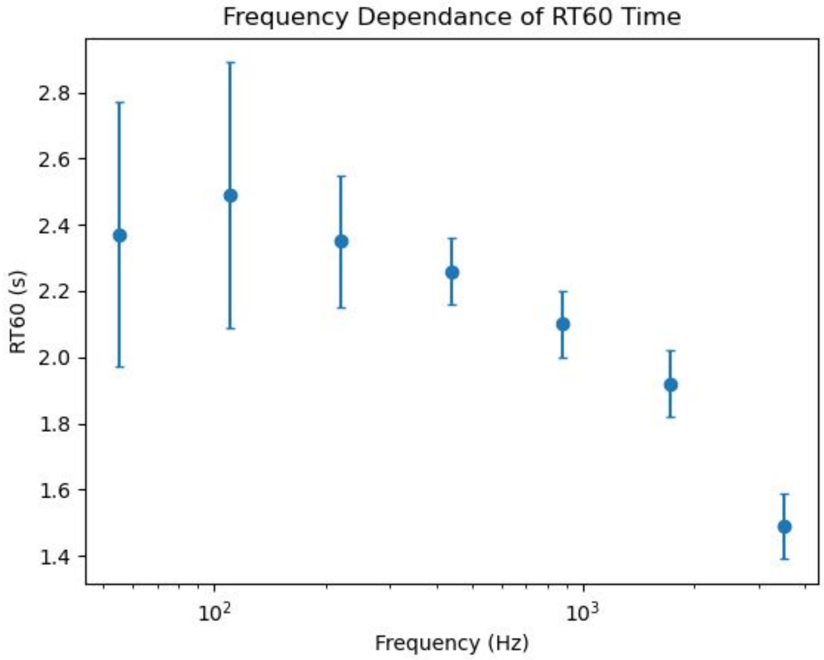


- RT60 time is 2.45 ± 0.07 s



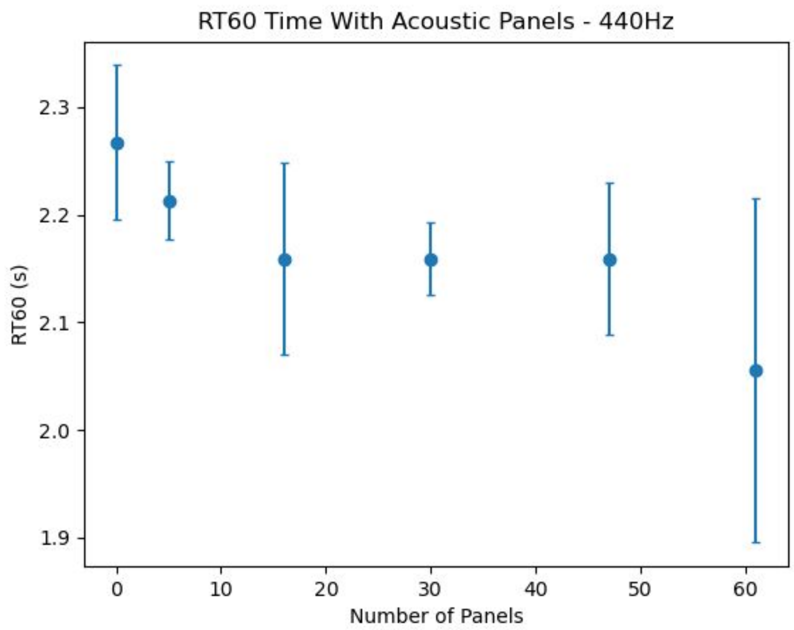
- RT60 time is 2.159 ± 0.001 s

Results - Frequency Dependance



Data from 2 trials of 5 devices

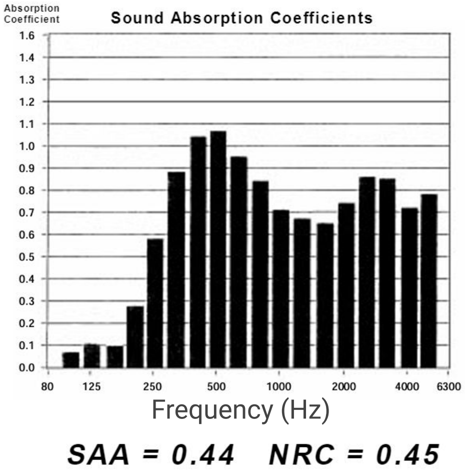
Results - Acoustic Panels

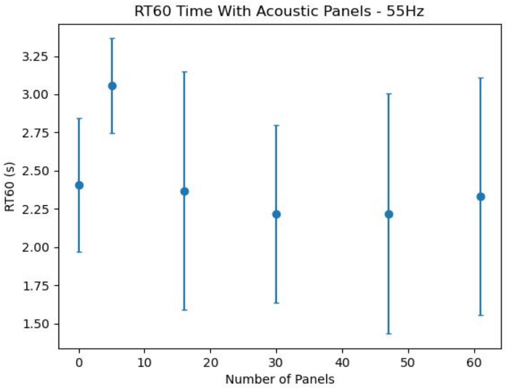


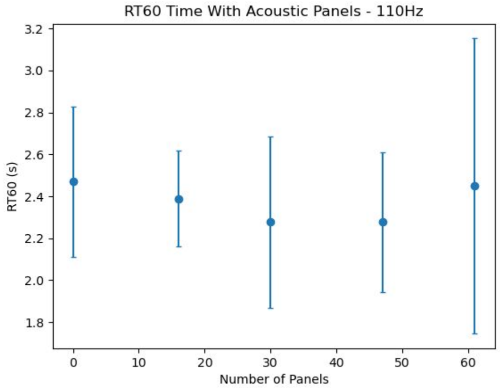
The room with 61 acoustic panels

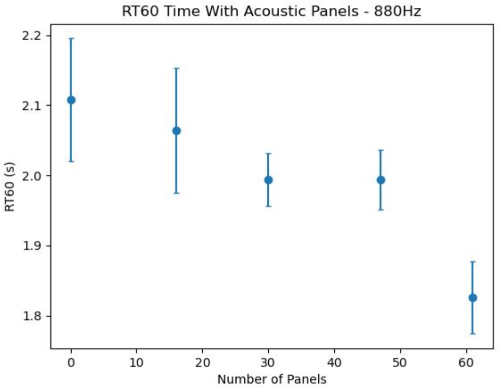
Results - Acoustic Panels

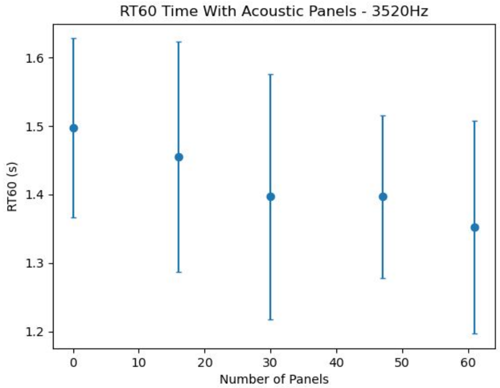
Even less conclusive results at other frequency bands:











Conclusions

Conclusions

- RT60 times measured more accurately using Schroeder's method.
  - Fitting directly to raw data impractical because of anomalies in data.

- Reverberations at high frequencies easier to dampen out.
  - Still not near to 1.8 s goal, even with significant numbers of panels

- Tests with more acoustic foam needed to see difference in RT60 times for lower frequencies.

Acknowledgements

We would like to thank Professor George Gollin and Professor Yuk Tung Liu for their contributions, support, and guidance throughout the semester

We would like to thank Professor Ricardo Longo and Matthew Hoppesch for their help reviewing our final paper and presentation

We would also like to thank Professor Rick Scholwin for giving us access to and reserving time slots on our behalf for the dance center.

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Questions?

References

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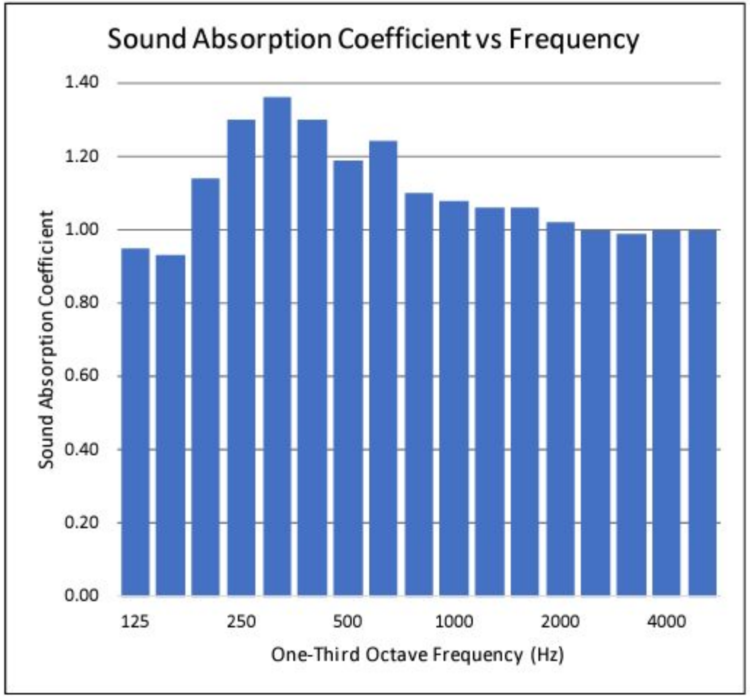
2. Rakerd, B., Hunter, E. J., Berardi, M., & Bottalico, P. (2018). Assessing the Acoustic Characteristics of Rooms: A Tutorial with Examples. *Perspectives of the ASHA special interest groups*, *3*(19), 8–24. https://doi.org/10.1044/persp3.SIG19.8
3. Schomer, P. D., & Swenson, G. W. (2002). Electroacoustics. *Reference Data for Engineers*. https://doi.org/10.1016/b978-075067291-7/50042-x
4. Adafruit, “MAX9744”, 19-4078; Rev 1; 9/08
5. Adafruit, “MAX4466 Low-Noise Microphone Amp Datasheet”, 19-1950; Rev 1, 4/01
6. Feather M4 Datasheet

Backup Slides

Recommended Material

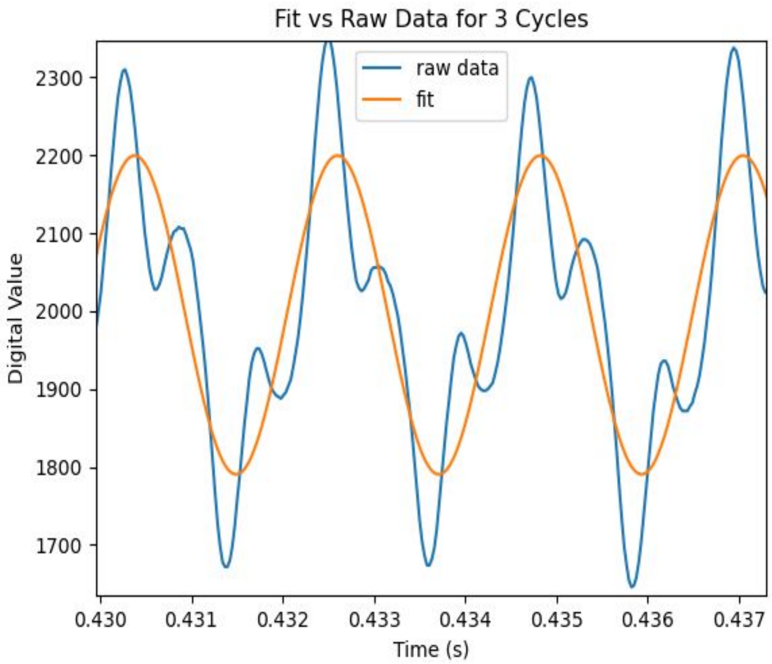
NRC	SAA
1.15	1.10

Frequency (Hz)	Absorption Coefficient
125	0.95
160	0.93
200	1.14
250	1.30
315	1.36
400	1.30
500	1.19
630	1.24
800	1.10
1000	1.08
1250	1.06
1600	1.06
2000	1.02
2500	1.00
3150	0.99
4000	1.00
5000	1.00



https://www.acousticalsurfaces.com/echo-eliminator/bass-buster

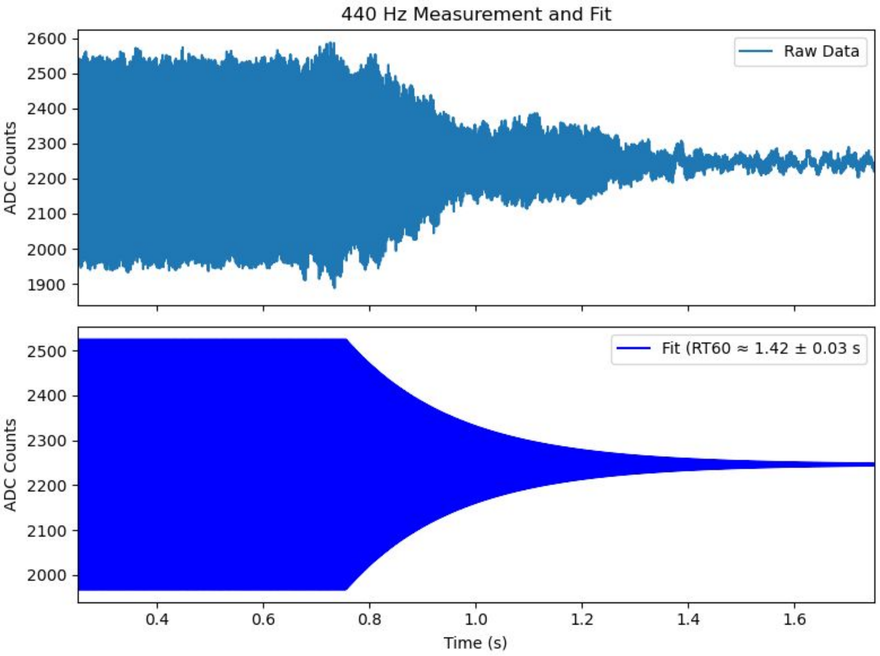
Direct Fit Problems



Recorded in KCPA

- Presence of higher order frequencies makes direct fit impractical.
- Artifacts in data (echoes) add difficulties to RT60 calculation.
- Different approach necessary.

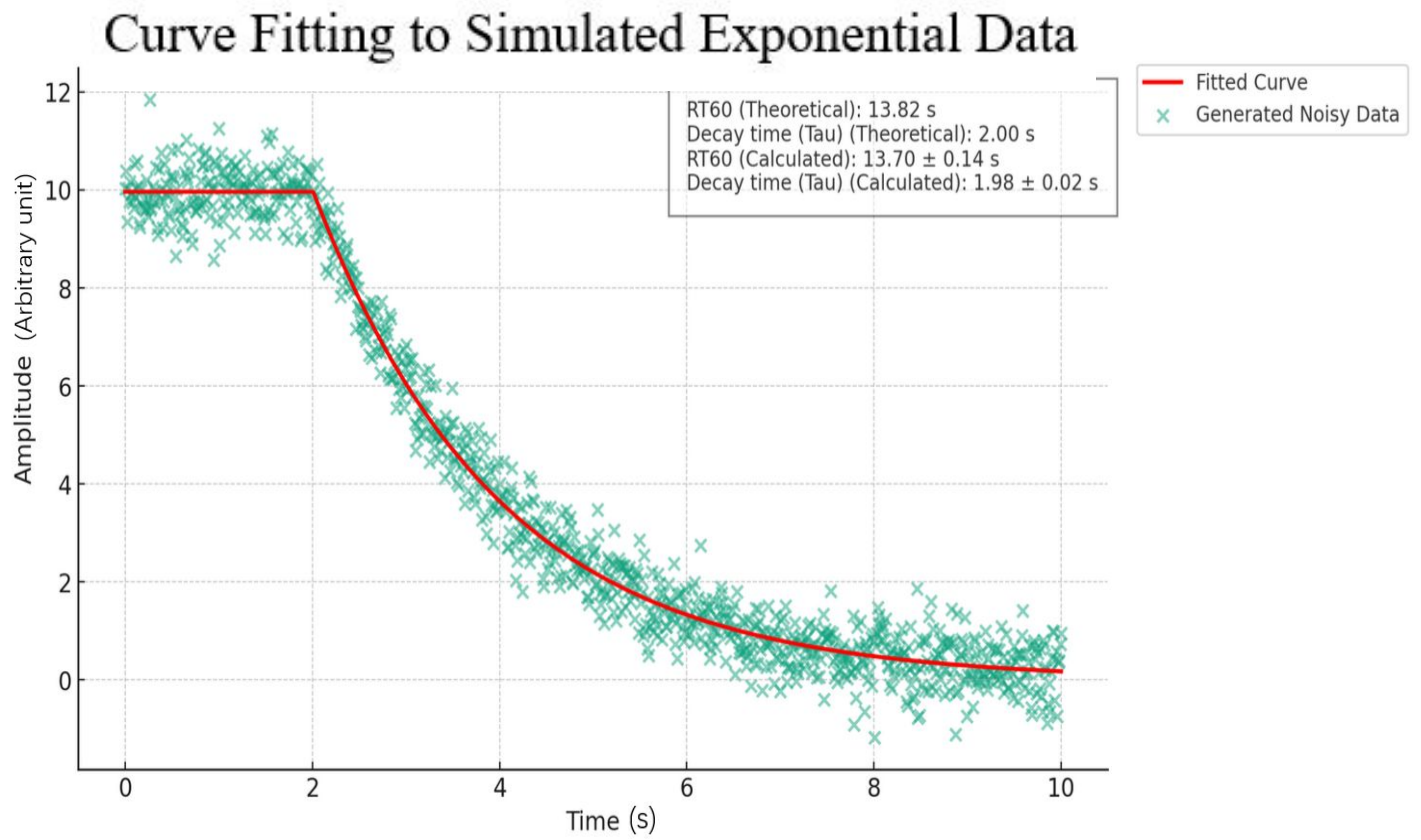
440 Hz Measurement



- Fits work well for 440 Hz but generally poor for 220 Hz.
- Artifacts in data make RT60 calculation difficult.

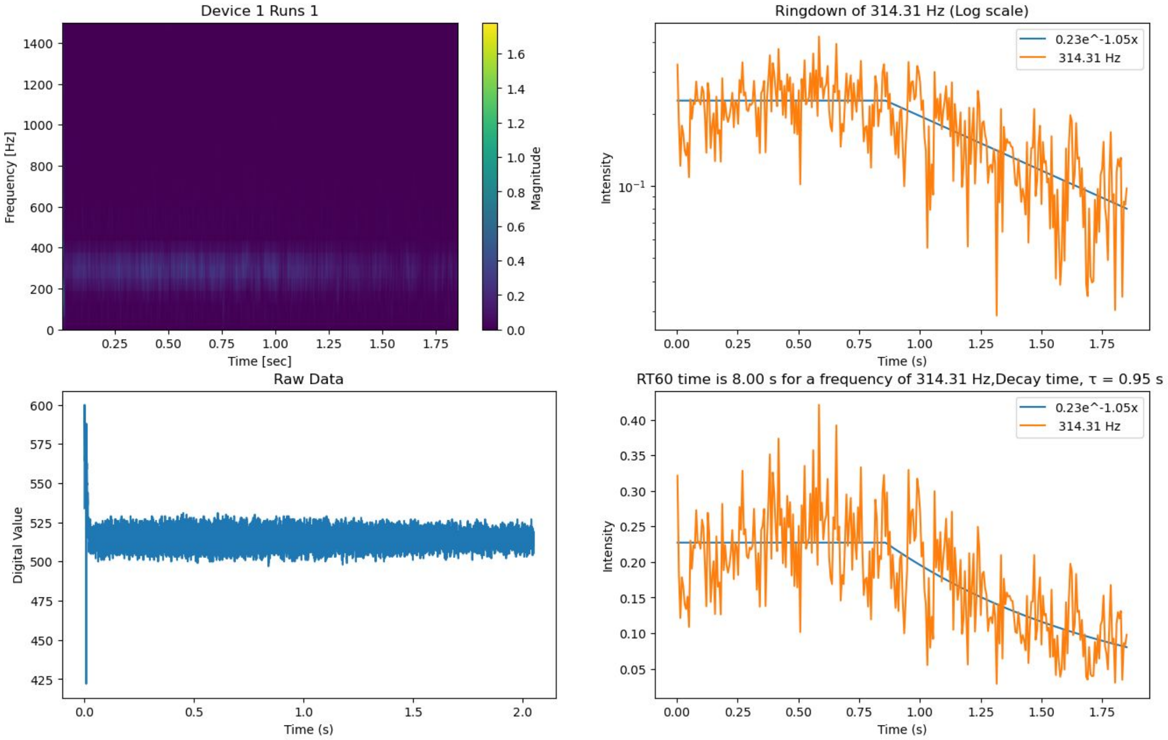
$$f(x) = \begin{cases} A * \sin(ft + \phi_0) & \text{if } t < t_0 \\ A * \sin(ft + \phi_1) * \exp(kt - t_0) & \text{if } t \geq t_0 \end{cases}$$

Testing the code



Testing With Known Decay Time

- Tested over five trials.
- RT60 = 0.95 ± 0.13 s
  - Real decay time: 1 s.



Parameter Derivation

Decibel defined as:

$$SPL = 20\log_{10}(\frac{P}{P_0})$$

Where P_0 is reference pressure value and P is actual pressure value

Equation for Decaying to -60 dB:

$$-60\ dB = 20\log_{10}(\frac{Ae^{(x-p)*k}}{A})$$

Definition of exponential decay

$$a(t) = Ae^{-t/\tau}, \quad t \geq 0$$

Simplified:

$$\text{RT60} = \frac{\ln(0.001)}{k} \qquad \tau = -\frac{1}{k}$$

Error Derivation

Apply Propagation of uncertainty:

$$\sigma_{\text{RT60}} = \sqrt{\left(\frac{\partial \text{RT60}}{\partial k}\right)^2 \sigma_k^2}$$

By applying the partial derivative, we get:

$$\frac{\partial \text{RT60}}{\partial k} = -\frac{\ln(0.001)}{k^2}$$

Thus, the error in RT60 is:

$$\sigma_{\text{RT60}} = \left|\frac{\ln(0.001)}{k^2}\right| \sqrt{\sigma_k^2}$$

The error in τ, σ_τ, is derived as follows:

$$\sigma_\tau = \sqrt{\left(\frac{\partial \tau}{\partial k}\right)^2 \sigma_k^2}$$

Taking the partial derivative of τ with respect to k, we find:

$$\frac{\partial \tau}{\partial k} = -\frac{1}{k^2}$$

Thus, the error in τ is:

$$\sigma_\tau = \sqrt{\sigma_k^2}\left(\frac{1}{k^2}\right)$$

Code description

```
from scipy.optimize import curve_fit
```

$$\mathrm{RT60} = \frac{\ln(0.001)}{k}$$

$$\sigma_{\mathrm{RT60}} = \left|\frac{\ln(0.001)}{k^2}\right|\sqrt{\sigma_k^2}$$

```
print('RT60 time is {:0.2f} +- {:0.2f} s for a frequency of {:0.2f} Hz'.format(np.log(0.001)/popt[1],np.abs(np.log(0.001) / popt[1]**2) * np.sqrt(pcov[1, 1])
print('Decay time, \u03C4 = {:0.2f} +- {:0.2f} s'.format(-1/popt[1],np.sqrt(pcov[1, 1])*(1/ popt[1]**2)))
```

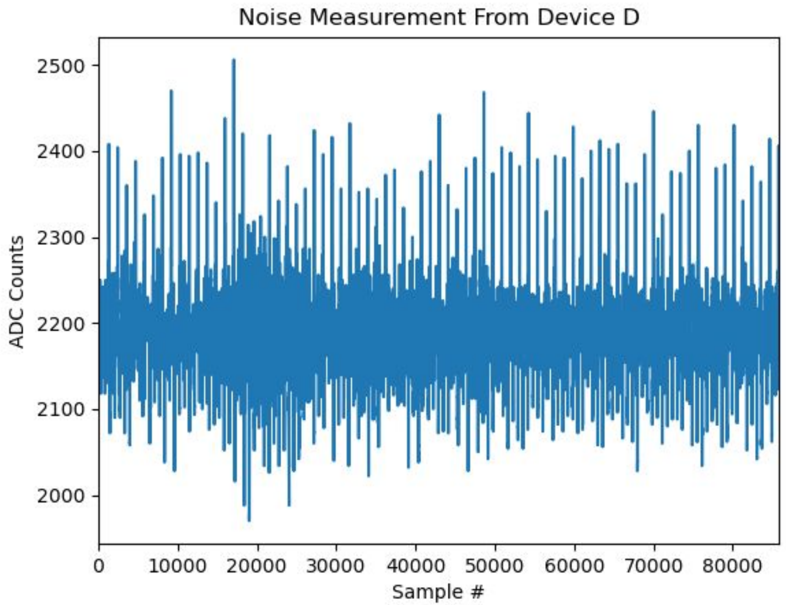
$$\tau = -\frac{1}{k}$$

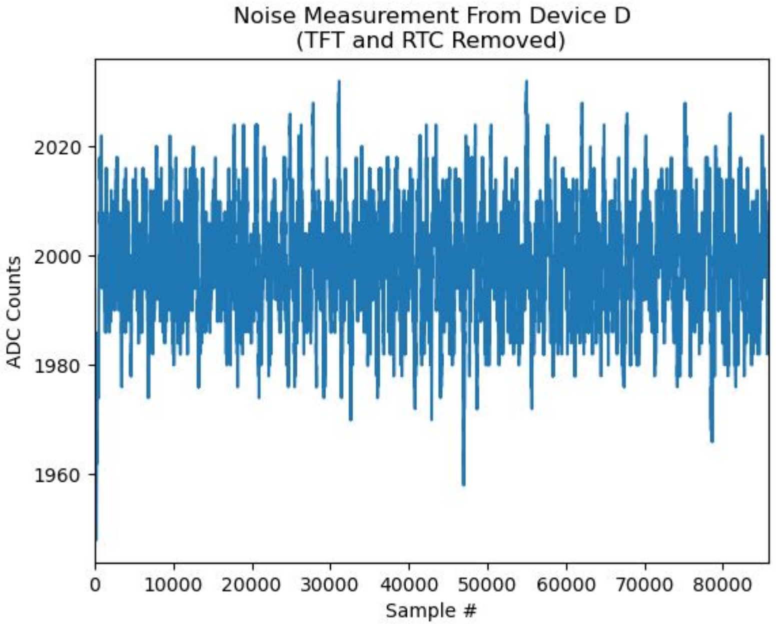
$$\sigma_\tau = \sqrt{\sigma_k^2}\left(\frac{1}{k^2}\right)$$

Parameter k given by pop[1]

Error given by covariance matrix (pcov[1,1])

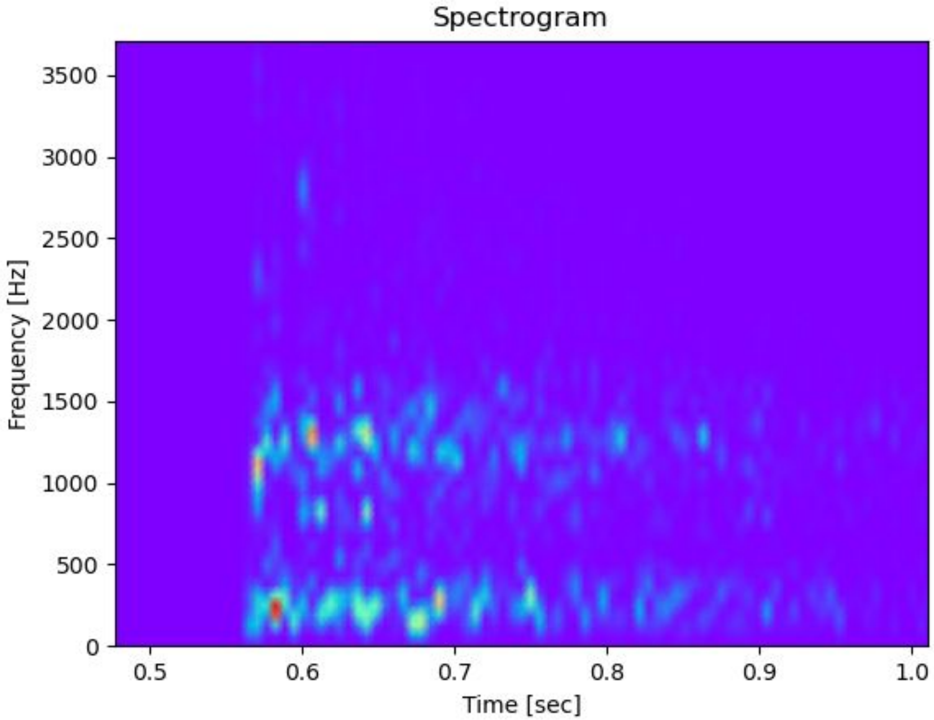
Noise From TFT and RTC





Recorded in KCPA

Balloon Spectrogram



Results - Curtain