

ECE 445 Final Project Proposal

Cost-Effective Signal Processing Solution for Bat-Call Detection and Hearing

Authors: Theo Xiong, Michael McNally, Liwei Koh

9/18/2026

I. Introduction

a. Problem

Reliable heterodyne bat-call detectors are difficult to obtain for under \$150 in the United States. Affordable options such as the Magenta Electronics Bat4 (approximately £80)¹ generally require international purchasing and shipping, which often prove inaccessible for US-based customers. Comparable devices available in the US, such as the Elekon Batscanner (approximately \$395)², are significantly more expensive. This limits researchers, students, and bat enthusiasts who want an affordable and accessible way to detect and listen to ultrasonic bat calls.

b. Solution

To address the cost and accessibility issue of obtaining a quality batscanner as a US consumer, we propose building a portable heterodyne bat detector with a 3D-printed housing that is able to detect ultrasonic bat calls and convert them into frequencies that can be heard by the user. The device will aim to provide similar core functionality to the Magenta Bat4, minus the flashlight, while also using signal processing to recommend a frequency range for the user to tune to. A MEMS ultrasonic microphone feeds two paths in parallel:

1. An analog heterodyne chain (bandpass filter, amplifier, mixer, and audio amplifier) that converts bat calls (20kHz-100kHz) to audible frequency.
2. An ESP-WROOM-32E that samples the signal (ADC), runs a FFT, and displays the dominant frequency on an LCD to inform the user of the optimal range to tune the device to.

c. Visual Aid

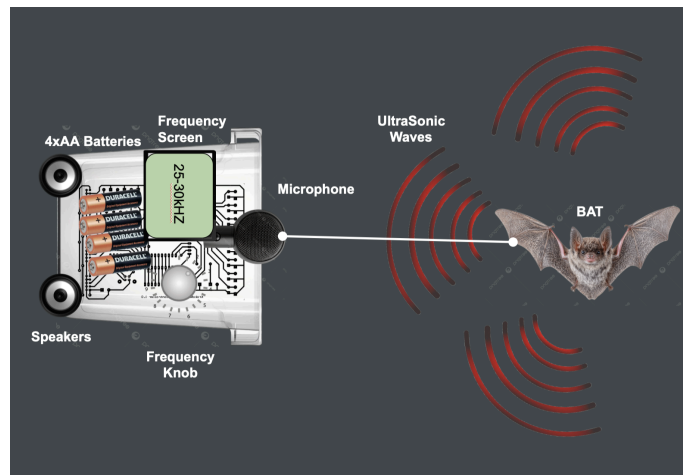


Figure 1. Representation of Bat Device with Bat

¹ <https://magenta2000.co.uk/product/bat4-bat-detector/> (Magenta 4)

² https://batmanagement.com/products/elekon-batscanner?srsId=AfmBOorURSgGKEMDTNNw0QPtuJM5woCWdNZA0H0KJlpBsd1_JF4idCff (Elekon)

- d. **High-level requirements list: A list of three quantitative characteristics that this project must exhibit in order to solve the problem. Each high-level requirement must be stated in complete sentences and displayed as a bulleted list. Avoid mentioning "cost" as a high level requirement.**

We formulated three quantitative objectives to determine the success of our proposed solution.

1. **Cost:**

- The cost of all components ordered should be no more than \$75.

2. **Frequency Range Detection Accuracy:**

- For a continuous ultrasonic test tone (20–80 kHz) presented 1m away from the device, it must display the dominant frequency to within ± 1 kHz of the true frequency.

3. **Heterodyne Output Quality Under Different Operating Conditions:**

- With the local oscillator tuned to within 5 kHz of a 20–80 kHz test tone, the speaker output must contain a tone at the intermediate frequency.

II. Design

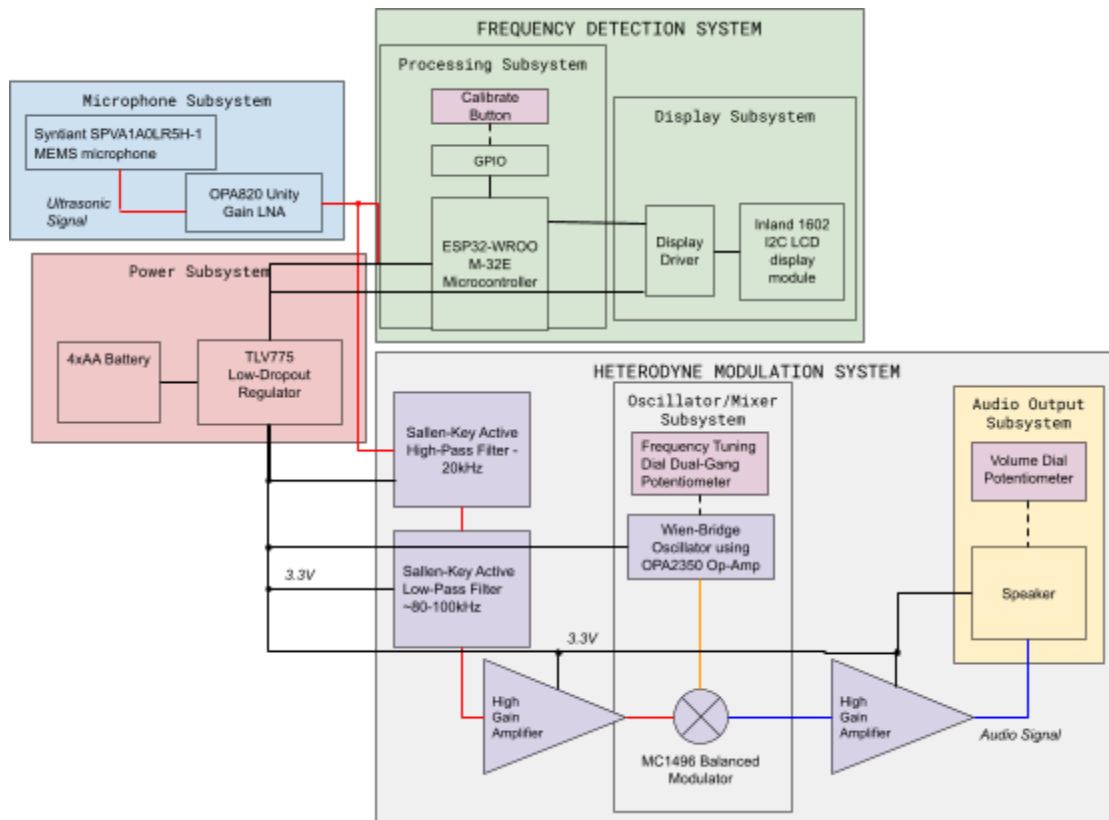


Figure 2. High-Level Block Diagram

- **Subsystem Overview:** A brief description of the function of each subsystem in the block diagram and explain how it connects with the other subsystems. Every subsystem in the block diagram should have its own paragraph. - **all**

i. **Processing Subsystem:**

1. Processes the microphone signal and performs an FFT to determine the most prominent frequency range being detected.
2. Sends the detected frequency range to the display subsystem to recommend where the user should tune the detector.
3. Example below in *Figure 3* is what we would be using to choose our calibration ranges as Professor O'Keefe has a repository of these frequency charts.

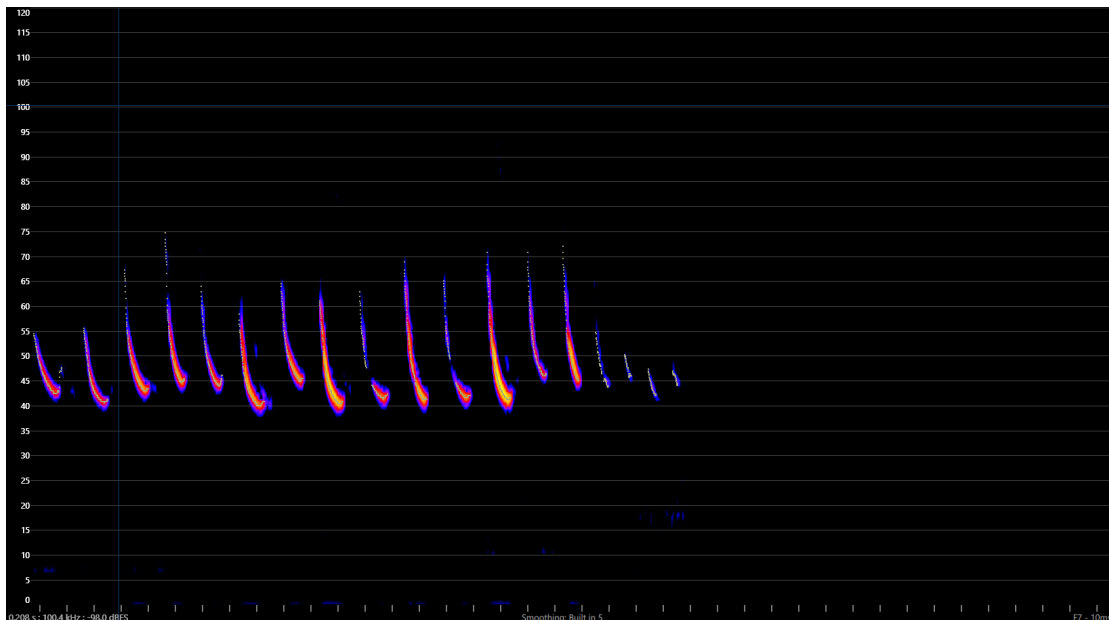


Figure 3. Example of Eastern Red Bat Call

- Power Subsystem:** provides stable power to all active components within the detector. This includes amplifiers, filters, oscillators, and the microcontroller/display system
- Microphone Subsystem:** uses Micro-Electro-Mechanical-Systems (MEMS) ultrasonic microphone, paired with low-noise unity gain buffer, to take in signal for processing in the analog and digital systems of the detector.
- Display Subsystem:** receives frequency values from microcontroller from FFT algorithm, then relays signals to LED display module for display to the user.
- Heterodyne Modulation System:** includes audio subsystem and oscillator/mixer subsystem, responsible for taking input directly from microphone subsystem, filtering for the ultrasonic range, and amplifying the signal before and after mixing to preserve signal to noise ratio.

- vi. **Audio subsystem:** includes manual input from volume dial, tied to speaker unit, for user to manually adjust volume of bat call output
 - vii. **Oscillator/mixer subsystem:** starting from 555 timer and necessary duty cycle/frequency determining circuitry, then through 3 stage low-pass RC filter to remove odd harmonics from square wave, for clean sine wave signal to mix. Then, the signal is mixed with previously amplified microphone signals to modulate to human sonic range.
- **Subsystem Requirements:** For each subsystem in your block diagram, you should include a highly detailed block description. Each description must include a statement indicating how the block contributes to the overall design dictated by the high-level requirements. Any interfaces with other blocks must be defined clearly and quantitatively. Include a list of requirements where if any of these requirements were removed, the subsystem would fail to function. Good example: Power Subsystem must be able to supply at least 500mA to the rest of the system continuously at 5V +/- 0.1V.

Processing Subsystem

- **Part(s):** ELEGOO 3PCS ESP-32 Dev Boards, ESP-WROOM-32E, USB-C, WiFi Bluetooth 4.2
- The processing subsystem receives the buffered ultrasonic signal from the Microphone subsystem on an ESP32-WROOM-32E ADC input, samples it continuously at 240 kSa/s using the ADC's DMA mode. The Nyquist frequency is: $f_{Nyquist} = \frac{f_s}{2} = \frac{240 \text{ kSa/s}}{2} = 120 \text{ kHz}$. Samples are buffered into blocks of 1024 samples. ($\frac{1024 \text{ samples}}{240 \text{ kSa/s}} = 4.267 \text{ ms}$)
- The resolution is $\Delta f = \frac{f_s}{N} = \frac{240 \text{ kHz}}{1024 \text{ samples}} = 234 \text{ Hz}$
- The MCU runs a 1024-point FFT on each 4.3 ms block using the ESP-DSP library and outputs a magnitude spectrum with a bin every 234 Hz. The dominant frequency is calculated by finding the bin with the largest magnitude.

$$k_{peak} = \text{argmax}(X[k])$$

$$f_{out} = k_{peak} \times \Delta f \quad 20 \text{ kHz} \leq f_{out} \leq 80 \text{ kHz}$$

- When the calibration button is pressed, the MCU sends the following strings to the display subsystem every 250ms over I2C clocked at 100kHz..
 - Frequency Range: f_{out} rounded down and up to the nearest 5kHz, forming the following string: [RNG low-high kHz] (ex. [RNG 040-045 kHz])

- Bat Species: The MCU looks up f_{out} against a table mapped to *Figure 4* stored as a constant array of pairs (frequency, bat name), selects the closest value, and writes the bat name characters padded to 16 chars.
- Requirements:
 - Sample rate has to be larger than 200kSa/S so the 20-80kHz signal doesn't alias.
 - Does not write to Display Subsystem when f_{out} is not within 20-80kHz.

Microphone Subsystem

- **Parts:** Syntiant SPVA1A0LR5H-1 MEMS microphone to receive ultrasonic signals up to 80kHz, with peak signal sensitivity at 40kHz, paired with OPA3250 Low-Noise Amplifier
- Requirements
 - Microphone must receive signals up to a minimum of 80kHz for wide access to the ultrasonic spectrum at which bats echolocate
 - Unity Gain Buffer ensures low output impedance for ideal signal receipt for digital and analog systems

Heterodyne System and Mixer/Oscillator Subsystem

- **Parts:** 5 OPA3250 Single-Supply Op-Amps: 2 for Sallen-Key Filters, 1 for Wien-Bridge Oscillator, 2 for higher-gain signal amplifiers; MC1496 Balanced Modulator for signal modulation; RK09L12D0A1W (logarithmic) or **RK09L1240015 (linear)** dual-gang potentiometer for Wien-Bridge Tuning
- **Requirements:**
 - Passes the microphone signal through high-pass (>20kHz) and low pass (<100kHz) Sallen-Key Active filters using op-amps to attenuate non-bat call range signals, then pass through high-gain op-amp
 - Mixes the signal with tunable sine wave constructed from Wien-Bridge Oscillator, using simple op-amp and RC bandpass filter loop configuration. Since frequency tuning will need precise resistance matching between low-pass and high pass filter components, a high-quality dual-gang potentiometer is needed for clean sinusoidal output
 - Mixing the signal with the local oscillator wave modulates the signal down to audible range, filters/amplifies the resulting signal optimized at 1.5-4kHz (optimal human hearing range) for audio output, shedding LO feedthrough and other unwanted frequencies

Power Subsystem

- **Parts:** 4xAA battery and enclosure, TLV775 LDO
- **Requirements:** Will use 4×AA battery pack as the main power source for the device. A Low-Dropout Regulator will be used to step 6V down to 3.3V to provide a stable supply voltage to the microphone, processing, heterodyne, display, and audio subsystems. Basic filtering and an on/off switch are included to

help provide clean and controllable power throughout the system. 4xAA configuration is chosen to maintain longer battery life, with more tolerance between needed 3.3V and nominal 6V supply

Display Subsystem

- Uses an Inland 1602 I2C LCD display module.
 - Displays the recommended frequency range on the first line determined by the processing subsystem (32 Characters on display, 2 lines of 16 characters per line). Template of [RNG 000-080 KHz] 15 Characters
 - Also displays potential species detected on the second line based on the microcontroller logic that we implement and the frequency ranges below. Template of longest ex [Nathus. Pipist.] 15 Characters
 - Helps the user determine where to tune the detector by showing the frequency range where the best signal is read. For our purposes we will only have to consider frequencies up to 80KHz as it covers most common bat species in North America pictured in *Figure 4*.

Frequency (kHz)	Bat species
20–25	Noctule
25	Leisler's
27	Serotine
32	Barbastelle
39	Nathusius's Pipistrelle
45	Pipistrelle (45)
45	Whiskered
45	Brandt's
45	Daubenton's
45–50	Brown Long-eared
45–50	Grey Long-eared
50	Natterer's
50	Bechstein's
55	Pipistrelle (55)
80	Greater Horseshoe

Figure 4. Bat call frequencies from magenta graph provided by Professor O'Keefe

Buttons/Dials Subsystem

- RK09L12D0A1W (logarithmic) or **RK09L1240015 (linear)**
 - If finer tuning is required we can add a 3:1 gear ratio which would require 3 rotations to go from 0 to 80 KHz.
 - Might add LED to the side of the dial in order to let the user see the value better at night.



Figure 5. Example LED on the Magenta Bat 4

- R-VS-1MA-SS - Volume Dial / Power Button: Switched Potentiometer
 - The integrated power switch in the volume button is used to mimic the design of the Magenta bat call device.
 - 300±5 degrees which gives the user enough freedom to control however they want their volume to be.
- SW414-ND - Calibration Button -12x12mm through hole tactile switch. Deliberate pressing feel from 2.55 N pressing force requirement.
 - Going to have to add some sort of membrane over the button to make sure that moisture doesn't get in.
- 3D printed volume dials to go on the side of the device.



Figure 6. Volume Dial Embedded in the Housing

- 3D printed frequency dial that is front facing for the user to manually tune the device.



Figure 7. Example of Frequency Dial on the Magenta Bat 4

Tolerance Analysis: Identify an aspect of your design that poses a risk to successful completion of the project. Demonstrate the feasibility of this component through mathematical analysis or simulation.

In the heterodyne bat-call detector, the local Wien-bridge oscillator generates the tuning frequency (20 kHz to 80 kHz) required to modulate the incoming ultrasonic microphone signal down to the audible range. The dual-gang potentiometer controls the variable resistive elements (R_1 and R_2) of the RC feedback network.

A critical risk to the successful completion of this design is the channel-to-channel tracking error of the dual-gang potentiometer. If the two gangs do not maintain an identical resistance as the shaft is rotated, the phase and attenuation of the positive feedback network shift. This mismatch can cause the OPA2350 op-amp to either fall out of oscillation entirely or produce severe harmonic distortion, which would compromise the clarity of the audio output subsystem.

The frequency-selective feedback network of this oscillator consists of a series RC branch (R_1 , C_1) and parallel branch (R_2 , C_2). Assuming tightly toleranced fixed capacitors are used ($C_1=C_2=C$), the feedback fraction β at the resonant frequency $\omega = \frac{1}{C\sqrt{R_1R_2}}$ is determined by the

ratio of the resistors: $\beta = \frac{R_2}{R_1+2R_2}$.

In an ideal system with matched resistance values, the feedback fraction is exactly $\frac{1}{3}$. This requires the op-amp to supply a constant closed-loop gain of $A_v = 3$ to maintain sustained oscillation. To model the risk of tracking error, let $R_1 = R$ and $R_2 = R(1 + \delta)$, where δ is the

percentage mismatch between the two tracks of the potentiometer at a given dial position. The feedback fraction β becomes $\beta = \frac{R(1+\delta)}{R+2R(1+\delta)} = \frac{1+\delta}{3+2\delta}$.

Using a high-quality linear dual-gang potentiometer restricts the maximum channel tracking error to approximately 10%. Applying this tolerance bound to the transfer function yields the worst-case attenuation scenarios during a frequency sweep. For a positive 10% mismatch, $\beta_{min} = \frac{1+0.1}{3+2(0.1)} \approx 0.344$. For a negative 10% mismatch, $\beta_{min} = \frac{1-0.1}{3-2(0.1)} \approx 0.321$. So, to compensate for these values, the gain of the op-amp must dynamically shift between 2.91 and 3.11 to sustain a pure sine wave without clipping.

III. Ethics, safety and societal impact

- The primary environmental concern with the detector is whether it would be able to interfere with the bats or other wildlife. The parts that make up the device are all passive receivers and do not transmit ultrasonic waves which would stop it from interfering with the bats' echolocation.
- The device however does have a speaker output that could possibly violate ACM Code of Ethics (1.2) if played loudly to intentionally disturb wildlife. However, this will be combated by the fact that the volume button is integrated with the power on button to start at the lowest volume.
- Moisture entering the device could cause PCB corrosion, short circuits and battery overheating. The device should be designed to be resistant to light rain but not full underwater submersion since it will be used primarily outdoors.
- To adhere to the ACM Code of Ethics (1.3) honesty and trustworthiness clause we will accurately communicate the fact that the bat detector is to be used to listen to bat calls and make an educated guess on the bat that it is detecting. However, this should not be used as a means to definitively identify species as overlapping calls and environmental noise can skew results. This is not as much of a concern as O'Keefe has a primary recording device she uses.