**Spatial Wave Accumulator**

**Group Number Seventy Three**

**Oliver Foley, Mohammad Abd-Elmoniem, & Cassandra Zent**

**ENEE408J: Capstone Design Project; Audio Electronics Engineering**

**Section 0102**

**Professor Brian L. Beaudoin**

**May 16, 2025**

**Table of Contents**

## 1: Executive Summary

The Spatial Wave Accumulator is an electronic device designed to detect and convert ambient, everyday electromagnetic (EM) radiation originating from sources such as transformers, lighting systems, and appliances into audio signals. Unlike traditional radios, which are tuned to specific broadcast frequencies, the Spatial Wave Accumulator captures non-broadcasting EM emissions. The Spatial Wave Accumulator not only functions as a technical proof-of-concept but also as a tool for performers, composers, and sound designers. These emissions can then be repurposed into drone-like soundscapes.

Since the primary goal was to create an artistic tool, a combination of practical and creative goals were applied to the overall design process. The most substantive part of the project, which was allotted a large amount of time to experiment with and perfect, was the EM sensing and demodulation circuits forming the primary functional basis of the device. This was accomplished through studying basic AM radio construction and then applying that to non-standard inputs. In order to facilitate the creation of more complex and tonal audio signals, we designed audio processing circuitry to modulate the demodulated interference with an audio-rate oscillator.

Due to the hard-to-define parameters of the input signals, the primary goal of the design was to allow for flexibility both in use and in the design and testing process. Simulation was only used for some submodules due to the difficulties of modeling EM emissions in spice software. Circuits were tested on breadboards for their basic function using test inputs from a wave generator and monitored using an oscilloscope. As each module was completed they were soldered to perfboards. These sub-modules were then combined and additional phases of alteration took place after a full prototype of working sub-modules was assembled. The majority of testing in the post-assembly phase was done by connecting the output to an audio interface and measuring the signal level of various inputs and amplification levels.

Upon completion of a working circuit, testing was performed on various shapes and types of small antennas by using the same interference source for varying antenna types. To reflect the artistic theme of the device, a vintage intercom box was repurposed as an enclosure and modified with 3D printed components.

## 2: Signature Approval

**Oliver Foley:**

Demodulator design, oscillator design, ring modulator design. Build stage soldering. Signal level testing. Antenna testing.

**Cassandra Zent:**

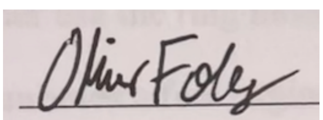
Amplifier design. Ring modulator assembly, testing, and redesign. Oscillator initial construction and testing. Documentation. Antenna construction and testing.

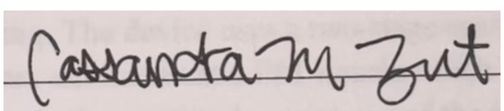
**Mohammad Abd-Elmoniem:**

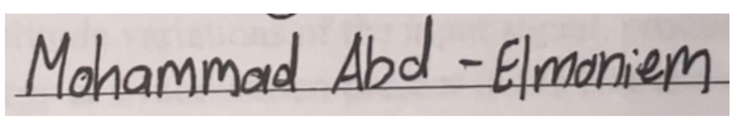
Mixer design (not in final design). Ring modulator assembly and testing, and redesign. Oscillator initial construction and testing. Enclosure modification CAD design. Antenna construction and testing.

---

I pledge on my honor that I have not given or received any unauthorized assistance on this assignment. I approve this report and the summary of my contributions to this report.

**Oliver Foley**: 


**Cassandra Zent:** 

**Mohammad Abd-Elmoniem:** 

## 3a: Introduction

The core concept is to convert electromagnetic (EM) radiation, normally invisible and inaudible, into auditory, recordable signals. This device is intended for both artistic and technical communities, with the overarching aim of engaging with curiosity. We are surrounded by technology and energy infrastructure which emits complex forms of EM interference, such as power adapters, electrical transformers, and lights. Detecting and interpreting this interference is useful from both an educational and creative lens. Educationally, it emphasizes the ubiquity of our technological influence on our environments, even in ways that are invisible. Sensing EM radiation also helps build an intuitive understanding of the types of inefficiencies that electronic devices can have, and encourages curiosity about non-ideality. Creatively, the chaotic and unpredictable nature of EM radiation provides a uniquely expressive musical material akin to an audio field recording of nature. In electronic music, these sounds can be used to create heavily abstractified audio soundscapes or even melodic instruments.

These needs can be met through the design of a device which transforms EM interference into audible-frequency audio at recordable levels. This device is housed in a portable enclosure. This can be done by leveraging analog circuitry and modulation techniques often used in AM radio. The user can choose to either listen to this “demodulated” signal in its pure form, or modulate it with a variable frequency oscillator to add a more defined tonal component. In practical applications, the user would place the antenna on electronic devices and run the output of the Spatial Wave Accumulator into a portable field recording device like an mp3 recorder. While holding the antenna to their subject, the user adjusts the gain of the demodulated interference and chooses to either use the ring modulator or record the direct demodulated audio.

Our project combines a few engineering disciplines, including analog circuit design, EM sensing, and signal processing. The device uses a two-stage sensing and signal transformation process. The antenna captures environmental EM signals which are passed directly into an envelope detector which outputs the amplitude variations of the input signal, producing a low-frequency waveform reflective of the energy and modulation present in the EM environment. This is inspired by basic AM radio demodulation circuits. From the demodulation stage, the signal is amplified. Then, the amplified signal can be routed one of two ways; directly into the audio output for a raw, droning soundscape, or into a ring modulator, where it is multiplied by the output of a variable-frequency oscillator (VFO). The VFO is also amplified to match the envelope signal’s amplitude, ensuring the modulation is balanced. This section of the device is inspired by technology used in synthesizers and effect pedals. The result is a complex, frequency-shifted audio output that introduces harmonically rich and unpredictable textures.

## 3b: Goals & Design Overview

The goals and design specifications of this project morphed throughout the experimentation and building process. Although our overarching goal, which was to create a device which could detect EM radiation and render it audible, stayed the same, the complexity of the device shifted in scope. This overarching goal is twofold: the device should be able to sense and demodulate EM radiation into audible frequencies, and we wanted some sort of additional way to shape or modify the resultant audio to allow greater artistic opportunities for generating complex waveforms. It was also a central goal that the device have a variable gain control to amplify signals to accomodate for varying signal strengths in RF emissions.

Initially, the "audio complexification" goal was intended to be met by allowing mixing of RF demodulated in two different ways. The primary shift in goals was from designing a device with two antennas and demodulators to a device with only one, but an additional form of audio processing post-modulation. This change was spurred by the testing phase of the device which was originally intended to be the demodulator for one of the antennas: the ring modulator. In theory, a ring modulator should be able to reduce the frequency of high-frequency RF signals down to audible frequencies using a high frequency carrier. However, this design was ultimately changed due to the frequency responses of the components we had access to and the variability of the input signal, so we instead opted to incorporate the ring modulator with an audible-range variable frequency oscillator carrier as a form of post-demodulation processing.

Throughout this entire process, the most significant underlying challenge is the specific nature of the input signals we are working with. It wasn't until late in the build process that we were even able to extensively test using real inputs, since it required a fully functioning demodulation circuit to be able to see what types of devices even emit suitable EM radiation. An additional challenge that needed to be addressed was balancing the signal levels of the oscillator and demodulated interference. Another challenge was antenna design due to the broad range of frequencies which we would be dealing with. Finally, it was important that this design be portable, since it would require extensive movement through space to find different devices to sense.

The final design consisted of four main modules: a demodulation module, amplification module, ring modulator, and oscillator.

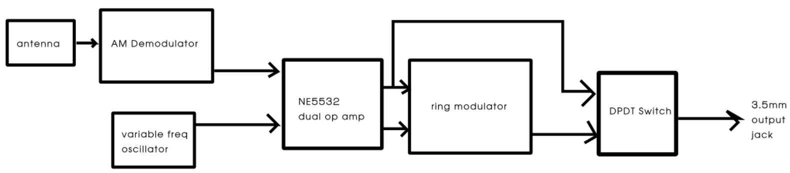



**Fig. 1: Spatial Wave Accumulator Block Diagram, also in Appendix**

1. **Antenna**
    a. A wire terminated with an alligator clip to allow different antennas to be connected.
    b. Connected to an LC tuning circuit with a variable capacitor
2. **AM Demodulator**
    a. An envelope detector comprised of a germanium diode half wave rectifier and an RC filter
3. **Variable Frequency Oscillator**
    a. Audio-rate oscillator to act as the carrier for ring modulation
    b. Potentiometer controlled frequency
4. **NE5532 Dual Amplifier**
    a. Takes both oscillator and demodulated interference as inputs.
    b. Potentiometer-controlled gain for demodulated signal from **1-21x**
        i. Demodulated signal sent to both output selector and ring modulator input
    c. Fixed gain for oscillator of **4.3x**
5. **Ring Modulator**
    a. Takes amplified oscillator output and demodulator output as inputs and multiplies them
6. **DPDT Switch**
    a. Selects between pure demodulated signal and ring modulated demodulated signal.

**Table 1: Quantitative Specifications**

| **Property** | **Specification** |
|---|---|
| Demodulated signal gain | **1-21x** |
| Oscillator gain | **4.3x** |
| Oscillator frequency | **20-1000 Hz** (High C) |
| AM Demodulator cutoff frequency | **3.3 KHz** |
| Antenna resonant frequency | **0.5 - 1MHz** |
| Power supply voltage | **18V** |

## 3c: Realistic Constraints

The following constraints influenced our design and build phases.

1. **Economic Viability**

Since this was a self-funded project, our budget was limited. RF equipment and circuitry can be highly expensive due to its integration into many industries, which is further complicated by the tariffs which have been placed on many imported electronics. As a result, we opted to construct all of our circuits from scratch, rather than purchasing modules. This necessitated a more intense design phase with an emphasis on discrete circuit design.

2. **Input Signal Unpredictability**

The most significant constraint on this project was the unpredictable frequency and amplitude of the signals being picked up by the antenna. This complicated the process by giving unclear necessary frequency responses for various components. As a result, we opted to process the audio almost exclusively after demodulation, when we could have a predictable frequency range of audible frequencies. The only component with a notable frequency response in the RF signal processing stage was a diode with a frequency range extending into the MHz. This unpredictability also influenced antenna design, since we could not design it to be suited for a specific frequency.

3. **Manufacturability**

Despite being a device which is intended to capture EM interference, our design needed to prioritize low noise. Additionally, any noise introduced by the circuitry would make it harder to verify the functionality of the device, since it could appear to be picking up an external noise source but actually not be. In order to avoid internal noise dominating the amplified signal, our design process necessitated planned layout and filtering capacitors. It also influenced our choice of amplifiers, focusing on low-noise op amps.

4. **Health and Safety**

The high-gain amplification of the demodulated signal could potentially drive headphones or audio equipment at unsafe levels if not limited properly. With this in mind, the device was designed to require a final gain stage of an audio interface or field recorder, so that the direct 3.5mm audio output could not damage someone's ears accidentally.

5. **Power Constraints/Portability**

In order to allow flexible use in differing environments, our device had to be portable rather than using a wall power supply. Since the device consists of multiple active and passive circuits, all of these modules needed to be able to be powered by a battery source of some kind. Additionally, the weight and bulk of the device could not be excessive, which relates to battery choice. Circuit designs needed to consider that they must all be able to share the same battery power source. Additionally, these batteries needed to be attached in an accessible way to the portable enclosure so that they can be replaced.

## 3d: Engineering Standards

Our device incorporated many engineering standards into our design and final product.

1. **RoHS**

This engineering standard restricts hazardous materials in electronic components [1]. This standard is important because otherwise the device could contribute to environmental contamination if it ever breaks and is disposed of. From the list of restricted materials, which can be found in the references, the only material which was relevant to our construction was lead. The most significant way in which this guided design choices that were made was that we opted to use **unleaded solder** despite its slightly less favorable melting properties.

2. **IEC 62368-1** (Electrical Safety Standards)

By this standard, we assess the device based on potential electrical hazards and ensure that the power supplies and amplified signals will not be able to shock the user or otherwise cause injury or fire [2]. We ensured that all of our circuit boards were enclosed in a non-conductive housing which could not accidentally bridge any harmful parts of the circuit or shock the user. All metal parts of the potentiometers were grounded to avoid shocking the user. All wires which were connected to each other were shrink-tubed so that no conductive points were accessible.

3. **FCC Part 15**

This standard dictates that our device does not unintentionally radiate harmful RF signals [3]. If this were not followed, it could potentially harm people's medical devices. This guided our amplifier design. Initially, we intended to build a regenerative amplifier which amplified the RF signal from the antenna, however we realized that this could potentially violate FCC Part 15 by amplifying and possibly even re-radiating harmful EM radiation. Instead, we only amplified audio-frequency signals.

## 3e: Alternative Designs & Design Choices

As the central module of the Spatial Wave Accumulator, the Demodulation circuit was the primary component which had multiple different alternative designs to evaluate. Our initial project plan was to develop a device with two different antennas and demodulators, rather than a single antenna and demodulator with optional audio processing. The following demodulator ideas were explored and evaluated.

1. **Ring Modulator**

A ring modulator consists of a transformer-isolated diode ring which multiplies two audio signals. We initially considered it as a **frequency mixer**, since the frequency of the output of the ring modulator is either the sum or the difference of the frequencies of the inputs [4]. Connected to an antenna, the ring modulator would subtract the frequency of a variable frequency oscillator from the input, producing an audible frequency output. The frequencies of the RF input signals would be very high, yet hard to predict, anywhere from hundreds of KHz to single digit MHz. In order for this to work theoretically, the oscillator would need to operate over a huge range of high frequencies. This would be expensive to implement due to needing to acquire ring modulation components with a very high frequency response, and construct or purchase an oscillator capable of operating at these high frequencies. In addition to this, it is unclear if ring modulation would even be a viable demodulation technique for these kinds of signals, since the changes in the frequency over time may exceed the range of audible frequencies even if it is centered around an audible frequency when multiplied by the carrier. This circuit is also passive and consumes no power.

2. **Basic AM Demodulator/Envelope Detector**

Consisting of a half-wave rectifier using a germanium diode, fed into an RC filter, the design we considered for a basic AM Demodulator ended up being the design we chose. This design is an application off of a simple envelope detector circuit from a lab manual of University of North Carolina, Charlotte [5]. Further technical details are in section 3f. One major advantage of this is that it is a passive circuit.

3. **AD8313**

A more sophisticated alternative considered was the Analog Devices **AD8313**, an integrated circuit broadband RF detector capable of detecting and converting RF energy to a DC voltage over a wide frequency range up to 2.4 GHz [6]. While it offered high sensitivity and consistent performance, its cost, power requirements, and complexity made it less suitable for a low-cost, educational/artistic prototype.

**Table 2: Pugh Matrix for Demodulator**

| Criteria | Weight | Ring Modulator | Envelope Detector | AD8313 |
|---|---|---|---|---|
| Signal fidelity | 1 | -1 | 0 | +1 |
| Sensitivity to weak signals | 2 | 0 | 0 | +1 |
| Complexity of implementation | 2 | 0 | +1 | -1 |
| Power requirement | 1 | +1 | +1 | -1 |
| Cost | 3 | 0 | 0 | -1 |
| Suitability for RF frequencies | 3 | -1 | +1 | +1 |
| Total | | -3 | +6 | 0 |

Ultimately, we selected the envelope detector as the demodulator. Requiring only basic discrete components and no power source, this option was simultaneously the cheapest and most practical.

Since we had already acquired some of the components for the ring modulator, we re-evaluated its role within the circuit. The primary goal of having two antennas and demodulation sources was to give the user a way to shape the output sound in some way other than gain, to add a layer of creative control when making an EM recording. With this criteria in mind, we wanted to have some way to modify the tone. Since the main negative points for the ring modulator were due to its practical incompatibility with RF, the utilization of the ring modulator after demodulation as an **audio effect** was a promising option. Additionally, a lower frequency carrier oscillator could be used, which would be more realistic due to the narrower frequency range and lower cost.

The other major component of this project which involved alternative designs was the amplifier design. Regardless of demodulation technique, a variable gain control was an essential element of our overarching goals. The following options were considered.

1. **Pre-Demodulation Positive Feedback Op-Amp with LM741**

Using the LM741 Op-amp IC, this amplifier applied gain to the signal before demodulating, with the intention of amplifying varying strengths of EM emissions [7,8]. This would have a variable gain of 100x-400x, which was an arbitrarily set gain. Gain would be determined through empirical testing at later stages.

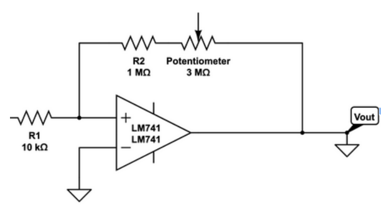



**Figure 2: Original Positive Feedback Amplifier Schematic**

2. **Post-Demodulation Negative Feedback Op-Amp with LM741**

Using the LM7441 Op-amp IC, this amplifier applied gain to the signal after demodulating [7,8]. This would have a variable gain of 1x-20x, which was an arbitrarily set gain. Gain would be determined through empirical testing at later stages.

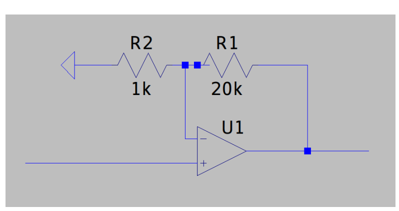



**Figure 3: Post-Demodulation Negative Feedback Op-Amp with LM741**

### 3. Post-Demodulation Negative Feedback Op-Amp with NE5532

Using the NE5532 Op-amp IC, this amplifier applied gain to the signal after demodulating. This would have a variable gain of 1x-20x, which was an arbitrarily set gain. Gain would be determined through empirical testing at later stages. The primary advantage of this IC is that it is designed for audio applications specifically as a low-noise amplifier. This design also incorporated filtering capacitors [8].

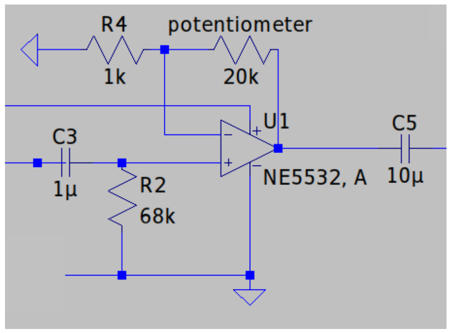



**Figure 4: Post-Demodulation Negative Feedback Op-Amp with NE5532**

**Table 3: Pugh Matrix for Amplifier**

| Criteria | Weight | Pre-Demodulation LM741 | Post-Demodulation LM741 | Post-Demodulation NE5532 |
|---|---|---|---|---|
| Noise Introduced | 2 | -2 | -1 | 0 |
| Amplification | 2 | 0 | 0 | +1 |
| Power requirement | 1 | 0 | 0 | 0 |
| Cost | 2 | 0 | 0 | 0 |
| Suitability for amplified frequencies | 3 | -1 | 0 | +1 |
| Total | | -5 | -2 | +5 |

All of the devices had the same flexible power supply requirements which would allow for using one or two 9 volt batteries depending on the power demands of the oscillator. The non-ideality of LM741s made them non-suitable for this design, since we wanted to minimize system-introduced noise in favor of capturing an accurate picture of the input signal. The filtering capacitors in the NE5532 designs also helped minimize this noise in addition to the design of the IC.

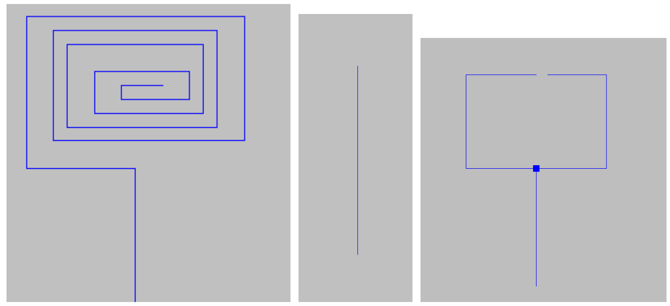


**Figure 5: Antenna Shape Considerations**

For the antenna, we theorized three different shapes of antenna. The first, on the left, was a spiral antenna, which is a design of antenna which is approximately **frequency independent** due to their non-resonant geometry [9]. We also considered loop and monopole antennas. However, those designs are much more frequency dependent and thus less ideal for our mixed-frequency inputs.

## 3f: Technical Analysis for System and Subsystems

**The full schematic showing how each subsystem connects can be found in the appendix.**

The following section provides the technical details and relevant mathematical models for the subsystems of the Spatial Wave Accumulator.

1. **Antenna and Resonant Circuit**

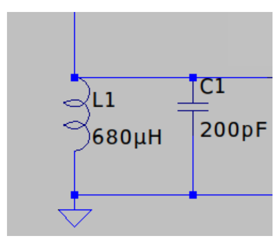



**Figure 6: Antenna and Resonant Tank**

The resonant tank in the circuit uses $f = \frac{1}{2\pi\sqrt{LC}}$

with a fixed coil of $L = 680\ \mu$H and a 40 – 200 pF variable capacitor. At $C_{min} = 40\ pF$ the upper limit becomes $f_{max} = \frac{1}{2\pi\sqrt{680 \times 10^{-6} H \times 40 \times 10^{-12} F}} = 0.97\ MHz$

and at $C_{max} = 200\ pF$ the lower end is $f_{min} = 0.43\ MHz$

So the capacitor alone sweeps 0.43 - 0.97 MHz without altering the coil. This frequency range is based off of the frequency range of AM radio, since we are using a demodulation technique designed for AM radio applications [10].

A monopole that would resonate purely by its physical length must satisfy the quarter-wave relation $h = \frac{\lambda}{4}$ with $\lambda = \frac{c}{f}$

So at the top of the desired resonant frequency range, f = 1 MHz, the wavelength is 300 m and the required rod length is $h_{1MHz}$ = 75 m. While at the bottom, f = 0.4 MHz, the wavelength grows to 750 W, and the rod must be $h_{0.4MHz}$ = 188 m. These figures come from the standard quarter-wave monopole model [13].

For a loop that is self-resonant without any external capacitor, the first resonance occurs when the loop's perimeter is approximately one free-space wavelength, for a circular loop, the diameter is therefore $d = \frac{\lambda}{\pi}$

Applying the same wavelengths as above gives $d_{1MHz} \approx 95\ m$ and $d_{0.4MHz} \approx 240\ m$. This is not feasible as the structure would span well over a football field even at the highest frequency of interest. Either antenna must be tens to hundreds of meters in size to resonate on 0.4 - 1 MHz without reactive loading, which is why the design substitutes the compact, high-inductance spiral and variable capacitor instead of trying to build full-size antennas.

2. **Envelope Detector Demodulation**

The output of the antenna and resonant circuit goes through a germanium 1N34A germanium diode. When a positive forward voltage across the diode is not met, the diode does not conduct. As a result, the zero-symmetrical signal passed into the diode will only conduct the positive half of the wave. This acts as a half-wave rectifier.

After this, a filter bank consisting of a resistor and capacitor in parallel filters the high frequency components of the signal, leaving only the envelope of the wave changing over time in audible frequencies.

The cutoff frequency of the filter is:

**f = 1/(2pi*RC), C = .001uf (10kpF: 2 5kpF in parallel), R = 47k ohm**

**f = 3386 Hz**

This frequency was chosen as a cutoff frequency since it is at the upper end of the human auditory range (with a high C at ~1,000 Hz and our overall audible frequencies extending to about 20,000 Hz).

3. **Amplifier**

The amplifier circuits used in this project are non-inverting op amp configurations based on the NE5532 chip, which is optimized for low noise audio applications [8]. In a non-inverting amplifier, the voltage gain is determined by the ratio of the feedback resistor ($R_f$) and the input resistor ($R_{in}$), using this equation:

$$\mathbf{A_v = 1 + R_f/R_{in}}$$

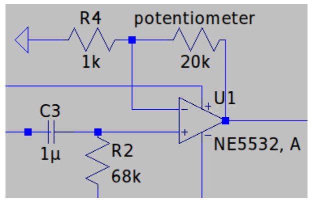



**Figure 7: Post-Demodulation Negative Feedback Op-Amp with NE5532**

For the demodulated signal amplifier with variable gain, the minimum gain is:

$$\mathbf{R_{f,min} = 0\ ohm,\ R_{in} = 1k\ ohm}$$

$$\mathbf{A_v = 1 + 0/1k = 1}$$

The maximum gain is:

$$\mathbf{R_{f,max} = 20k\ ohm,\ R_{in} = 1k\ ohm}$$

$$\mathbf{A_v = 1 + 20k/1k = 21}$$

This range was chosen to provide enough flexibility to boost weak demodulated signals without introducing clipping or excessive noise. The range was determined empirically by measuring the peak-to-peak voltage of a demodulated signal from a single source and varying amplifications until a peak-to-peak voltage of .1-.5V was obtained. This amplification was then set as the middle value (~10x amplification) of the range.  The potentiometer allows the user to adjust the gain by ear depending on the EM environment and desired output level.

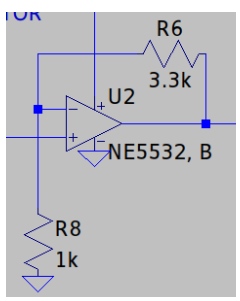



**Figure 8: Oscillator Signal Amplifier**

For the oscillator signal amplifier with fixed gain, we needed to ensure the oscillator signal was strong enough to modulate the amplified demodulated signal. The gain for this amplifier is:

**$R_f$ = 3.3k ohm, $R_{in}$ = 1k ohm**

**$A_v$ = 1 + 3.3k/1k = 4.3**

This fixed gain of 4.3 was empirically chosen to bring the oscillator signal into the same amplitude range as the variable gain demodulated signal, around 0.6V. Matching these levels was important for producing clear and effective ring modulation.

4. **Ring Modulator**

The ring modulator employed after the envelope detector multiplies the audio-rate oscillator signal c(t) with the demodulated interference x(t). Mathematically, this is modeled as

$$y(t) \;=\; x(t)\, c(t)$$

Which is the defining action of a balanced (four-quadrant) multiplier. If both inputs are pure sinusoids, $x(t) \;=\; A\, cos(2\pi f_x t)$ and $c(t) \;=\; B\, cos(2\pi f_c t)$, the standard trigonometric product identity

$$sin\, u\, sin\, v \;=\; \frac{1}{2}[cos(u \;-\; v) \;-\; cos(u \;+\; v)]$$

(equivalently with cosines) expands the product into

$$y(t) \;=\; \frac{AB}{2} cos(2\pi(f_c + f_x)t) \;+\; \frac{AB}{2} cos(2\pi(f_c - f_x)t)$$

So the output contains only the sum and difference side-bands $f_c \;\pm\; f_x$ while the two original tones are ideally suppressed.

The physical circuit realises the multiplication with a diode ring. Four identical diodes are wired so that during the positive half-cycle of the carrier two conduct and two are open, passing the modulating signal through unchanged; during the negative half-cycle the conducting pair swaps, inverting the polarity of the path. Because the carrier is much larger than the programme signal, the diodes act as high-speed switches under the control of the oscillator, creating an effective sign function $sgn[c(t)]$. Written explicitly,

$$y(t) \;=\; sgn[c(t)]x(t)$$

which is equivalent to multiplying x(t) by a square-wave version of the carrier and therefore reproduces the same spectral side-bands while removing the carrier itself; the transformer centre-taps guarantee that any residual carrier common-mode component is cancelled at the output.

For the project's oscillator range of roughly 60 Hz to 400 Hz and typical ambient-noise envelopes below a few kilohertz, those side-bands are always audible because $f_c \pm f_x$ stays inside the 0 – 6 kHz pass-band set by the preceding amplifier and the 3.3 kHz demodulator filter. Balancing the two op-amp gains so that the carrier amplitude is about six times the envelope amplitude ensures clean diode commutation, minimises distortion products that would otherwise leak the individual inputs, and yields the double-sideband suppressed-carrier behaviour on which the intended musical textures depend [14].

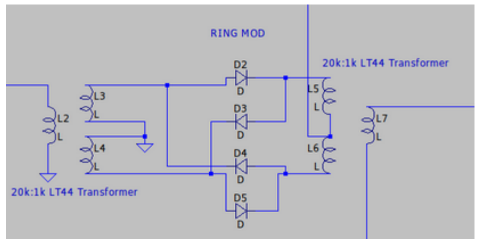



**Figure 9: Ring Modulator. The wire going up is the carrier input, going right is the output.**

## 5. Oscillator

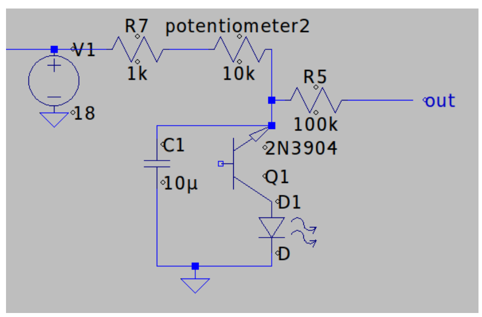



**Figure 10: Oscillator**

This circuit is based on an LED blinker circuit designed by electrical engineer and hobbyist Kerry Wong, which makes use of the "avalanche" region of the BJT, in which the BJT exhibits negative collector-emitter resistance [11]. The circuit operates by charging up C1 until it reaches the reverse breakdown voltage of Q1, which is often much lower than the forward breakdown voltage, hence the reversed BJT. At this voltage Q1 will allow current to flow through it, quickly discharging C1 again. Then Q1 resumes normal operation and the next cycle of the oscillator begins, acting as a sawtooth oscillator with its output taken from the voltage across Q1.

$$V_C(t)=18(1-e^{-t/RC}),\ \text{until}\ V_c(t) > V_{\text{reverse breakdown}}$$

Therefore the approximate output frequency $f_{out} \approx 1/(RC*\ln(18/(18-V_{BR}))$

However, reverse breakdown voltage is not measured by manufacturers in the datasheet, so additional research was done to find potential resistor and capacitor values for this circuit. A circuit diagram created by electronic musician and hobbyist Sam Battle using this oscillator design was used in this implementation since it had determined a viable RC constant for the chosen BJT model, a 2n3904 [12]. One of the main issues with this is that since the reverse breakdown voltage is not a measured property, we cannot effectively predict the frequency range of the oscillator. However, as a creative tool, it is not essential that this frequency range be all-inclusive of the human auditory range, and the simplicity of the oscillator makes up for its lack of consistency in analysis.

The 100k resistor limits current to the output, which is subsequently connected to an op amp.

## 3g: Design Validation for System and Subsystems

### 6. Antenna and Resonant Circuit

This was a difficult system to validate the functioning of, since it was impossible to simulate the unpredictable input. Therefore, our validation was interlinked with the test plan. Once the rest of the circuit had been constructed and verified with test signals, we connected the antennas of various types and tested the ability of the device to pick up the interference from the flyback transformer of a CRT TV. Although all tested objects were able to pick up the interference, the spiral antenna was able to pick up the interference from the widest variety of angles and positions around the exterior of the CRT TV. Relative to other forms of interference, the lower (sub-100kHz) frequencies of CRT TV transformers was selected to verify the lower end of the frequencies which this device could pick up, which is where the most uncertainty lied due to the high resonant frequencies (0.5-1MHz) of the resonant tank.

### 7. Envelope Detector Demodulation


**Figure 11, 12: Test Signal before and after half-wave rectification**

Using a generated wave centered around 0V, we verified the functioning of the germanium diode as a half-wave rectifier.

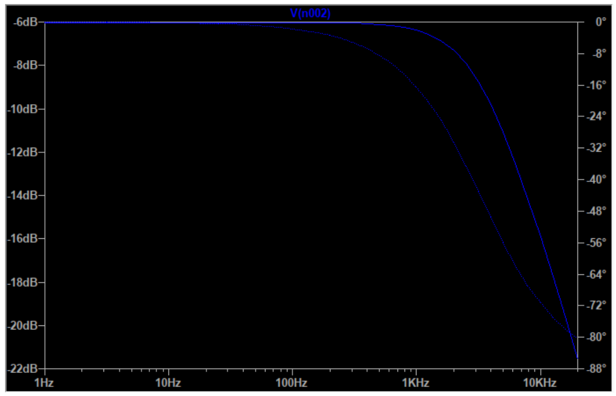
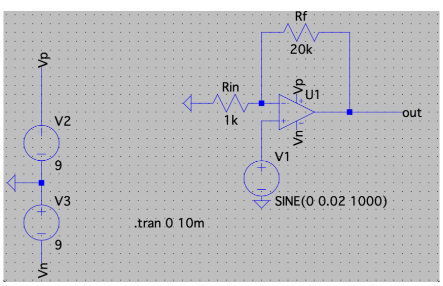



**Figure 13: Frequency Response of Demodulator RC Circuit**

We simulated the RC circuit in LTspice the demodulator to determine if it had suitable frequency response to allow only audible frequencies within the range of musically useful pitches. The above figure verified this intended frequency response.

### 8. Amplifier

The following LTSpice simulations verify the functionality of our amplifiers.



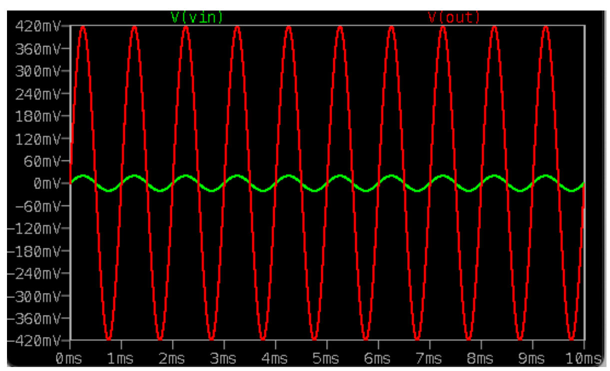
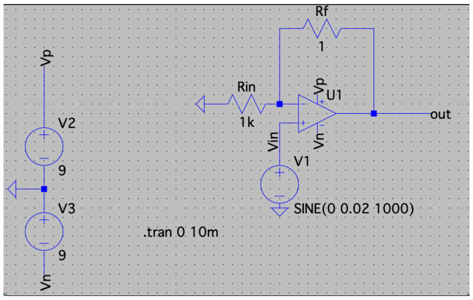




**Figure 14: Variable Gain Amplifier (MAX), Figure 15: Gain of Variable Gain Amplifier (MAX) (21x)**



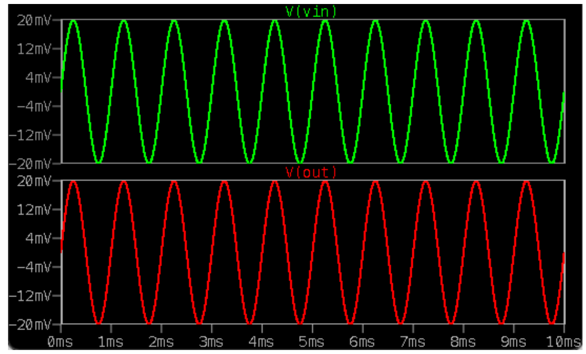
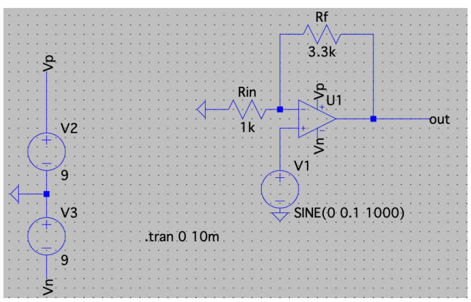



**Figure 16: Variable Gain Amplifier (MIN), Figure 17: Gain of Variable Gain Amplifier (MIN) (1x)**



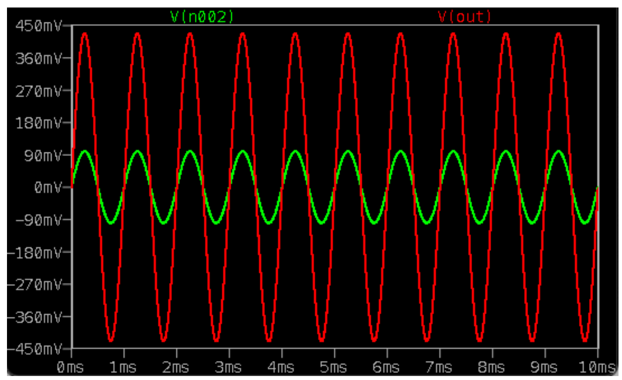


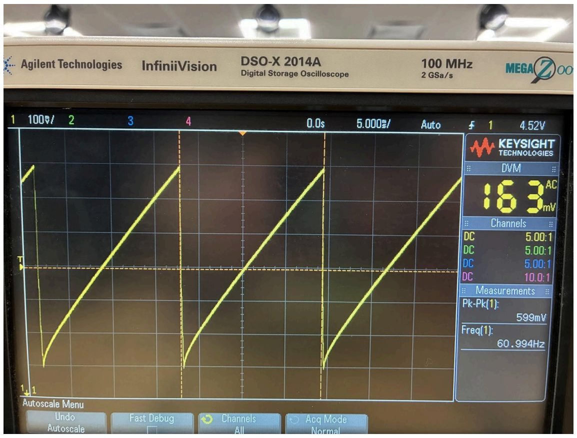

**Figure 18: Fixed Gain Amplifier, Figure 19: Gain of Fixed Gain Amplifier (4.3x)**

### 9. Ring Modulator

This device had its functionality verified by inputting a 1KHz and 2KHz generated wave into the ring modulator, and observing on an oscilloscope that the two waves were multiplied. However, we failed to record these results during the design process, we simply noted that the device functioned and proceeded to the next step in the build process.

### 10. Oscillator

We were unable to simulate this device due to the fact that it hinges on a non-measured property of BJTs. However, to verify the operation of this device, we connected it to an oscilloscope and measured the outputs at the minimum and maximum variable resistances.



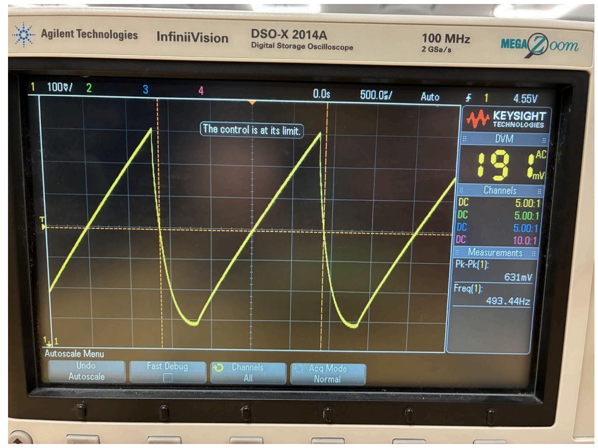




**Figure 20 and 21: The highest and lowest frequency of the oscillator, amplified to ~0.6V.**

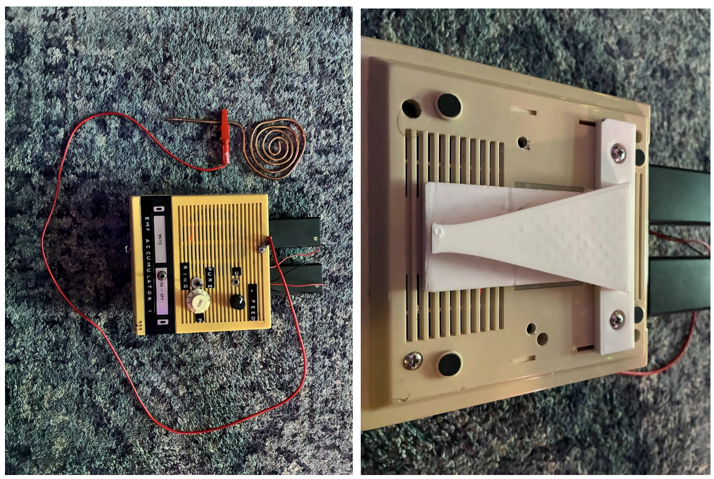
The highest and lowest found frequencies were 60 Hz and 493 Hz. The instability of the oscillator, while thematically consistent with the creative intention of the project, did not give us the full frequency range we hoped for.

**Table 4: Satisfied Criteria**

| **Property** | **Specification** | **Satisfied?** |
|---|---|---|
| Demodulated signal gain | **1-21x** | **Yes** |
| Oscillator gain | **4.3x** | **Yes** |
| Oscillator frequency | **20-1000 Hz** (High C) | **Partially (60-400Hz)** |
| AM Demodulator cutoff frequency | **4.3 KHz** | **Yes** |
| Antenna resonant frequency | **0.5 - 3MHz** | **Yes** |
| Power supply voltage | **18V** | **Yes** |

### 11. Enclosure

The printed belt clip spans 104 mm across the mounting bar and projects 93 mm forward, dimensions chosen so the enclosure sits snugly against a standard 40 mm-wide belt without wobble. All load-bearing walls are 3.5 mm thick and were sliced with four perimeter walls (double the usual two) plus 25 % rectilinear infill at 0.15 mm layer height; that combination gives the thin arms enough shear strength to last repeated flex while keeping print time reasonable. The twin clearance holes visible in the bar line up with the enclosure's existing M4 hardware, so the clip installs flush and the tapered tongue simply slides under the belt to lock the unit firmly in place. Images of the final design are available in the Appendix. The final design in the Appendix has slight visual changes but is functionally the same as the one which was printed, seen below in figure 23.



**Figures 22 and 23, the front and back of the final device**

## 3h: Test Plan and Results

The following criteria and testing methods will be evaluated to determine the functionality of the completed project. These tests will be completed in the order listed by connecting the Spatial Wave Accumulator to a Zoom H1N field recorder's 3.5mm audio input.

1. **EM Radiation Detection and Demodulation**
    a. When the antenna is held near three different sources of EM radiation, including an AC-DC wall converter, CRT TV, and the power supply of a computer, does it produce sound from the audio output which correlates to the position of the antenna relative to the emission source?
2. **Ring Modulation**
    a. While held in a position with an active signal being detected, switch the device into ring modulation mode. Does the sound change, and if so, can a fixed-pitch oscillation now be heard within the signal?
3. **Oscillator**

   a. With ring modulation enabled and an active signal detected, change the position of the pitch potentiometer. Does it change the pitch of the oscillator?
   b. Do the oscillation and noise have equal subjective volume within the combined waveform output by the ring modulator?

4. **Amplification**
   a. Is the audio output high enough to be recorded on a field recorder?
   b. Can this output level be adjusted on the Spatial Wave Accumulator?
5. **Portability**
   a. Can the device be used without being connected to a computer or wall outlet?
   b. Can the device be clipped onto the belt of the user?

**Table 5: Test Results**

| Criteria | Outcome |
|---|---|
| EM Radiation Detection and Demodulation | **Success** |
| Ring Modulation | **Success** |
| Oscillator: Pitch Adjustability | **Success** |
| Oscillator: Amplified Volume | **Success** |
| Amplification: Final Output Volume | **Success** |
| Amplification: Gain Adjustability | **Success** |
| Portability: Power Requirement | **Success** |
| Portability: Belt Clip | **Success** |

## 3i: Project Planning & Management

The project was developed collaboratively by a three-person team, with responsibilities assigned according to individuals strengths. Project management followed a flexible structure that allowed for rapid prototypic, frequent iteration, and creative exploration, all of which were necessary due to the experiments and unpredictable nature of the input signals. Each team member's roles and responsibilities are listed below:

**Oliver Foley:**

- Designed the demodulation circuit, oscillator, and ring modulator.
- Led signal level testing and contributed significantly to soldering and final assembly.
- Participated in antenna testing and tuning procedures.

**Cassandra Zent:**

- Designed the amplification stages and led the testing and refinement of the ring modulator.
- Built the oscillator's initial prototype and handled documentation duties.
- Led construction and tuning of antenna prototypes.

**Mohammad Abd-Elmoniem:**

- Worked on mixer design (not included in final version - would have mixed the two demodulators).
- Assembled and tested the ring modulator and oscillator.
- Designed and modified the enclosure using CAD and handled 3D printed components.

While the roles were initially divided, many parts of the design overlapped, requiring cooperative troubleshooting and shared prototyping sessions.

**Compliance with Schedule**

The Gantt Chart can be found in the Appendix and should be consulted while reading this section. While the project generally adhered to the original tasks breakdown, flexibility was crucial due to the exploratory nature of the work. Some deviations from the schedule occured, including:

- Extended experimentation with antenna design and signal demodulation due to the variability and unpredictability of ambient EM signals.
- The original plan to use two antennas and demodulators was revised mid-project to a single antenna with post-demodulation audio processing, which required reallocation of time from design to testing.
- The ring modulator's role shifted from demodulator to audio effect, which demanded additional tuning and hardware adjustments during weeks 8-10.

Despite the changes, the team maintained steady progress by frequently reassessing priorities and working in parallel when possible. Collaborative testing and flexible time management ensures that the final prototype was completed on time and met its artistic and technical goals.

## 4: Conclusions

The Spatial Wave Accumulator was developed through a process that combined traditional analog electronics with an experimental, exploratory design philosophy. Our goal was to create a functional yet expressive tool that bridges engineering and sound art, capturing ambient electromagnetic radiation and rendering it audible.

Due to the unpredictable nature of EM signals, our design process relied heavily on iterative testing rather than simulation. Each circuit module was first breadboarded and tested using signal generators before being combined into the full system. We chose a passive envelope detector for demodulation and complemented it with modular analog signal processing, including amplification and ring modulation.

A major creative decision was the repurposing of the ring modulator. Initially intended to serve as a demodulator, we instead integrated it post modulation as an artistic sound shaping tool. This change not only solved technical limitations but also enhanced the device's expressiveness, allowing users to sculpt tonal qualities in real time.

Our focus on analog circuits kept the design straightforward and easy to understand. The device is simple to use and gives the user hands-on control. Even though the system is ot complex, it can still produce a wide range of interesting sounds. This makes it useful for creating experimental music and for showing how electromagnetic signals work in an educational setting.

**Challenges Faced**

Several key challenges emerged during the development of this device. The first was dealing with unpredictable input signals. Since EM noise is different everywhere and hard to simulate, we tested with real sources like chargers and power supplies. This helped us understand how the antenna and demodulator needed to perform.

Another challenge was balancing the signal levels between the demodulated EM signal and the oscillator. For the ring modulator to work correctly, both signals needed to be at similar volumes. To achieve this, we used a variable gain amplifier for the EM signal and a fixed gain amplifier for the oscillator.

The antenna design also proved to be challenging, since we couldn't design it for a specific frequency due to EM sources all being different frequencies. To address this, we made the antenna flexible, just a copper wire with an alligator clip so it had the ability to be swapped out or changed depending on the test.

We also faced challenges with our initial system architecture. Our original plan included two antennas and two demodulators, but this setup proved overly complex and difficult to tune. We ultimately ended up having just one antenna and added tone shaping after demodulation. This made the project easier to build and more reliable.

Lastly, we encountered problems with unwanted circuit noise. To reduce internal interference, we selected low noise op-amps and added filter capacitors to reduce unwanted sound from inside the circuit and to ensure the sound captured by the device was coming from the environment.

**Lessons Learned**

Throughout this project, we gained valuable insight into both technical problem solving and creative engineering. One of the biggest takeaways was the importance of flexibility in the design process. Our original plan changes significantly over time, and being open to revising ideas allowed us to adapt the system to real-world conditions and improve the final outcome.

We also learned that hands-on testing is essential when working with unpredictable inputs like EM noise. Since simulation tools couldn't accurately model the kinds of interference we were capturing, we had to rely on physical testing with real EM sources. This taught us to work iteratively and trust our observations during development.

Another key lesson was that analog circuits require careful tuning. Small changes in gain or filtering can have a big impact on performance, especially when working with weak and noisy signals. We learned to balance simplicity with performance and to prioritize clean signal paths.

We also saw the value of repurposing and reimagining components. The ring modulator was originally intended as a demodulator but ended up becoming a tone shaping tool after demodulation. This shift added a creative layer to the project and showed how flexible thinking can lead to new possibilities.

Finally, we learned that a successful design isn't just about technical function. It also matters how the user is going to interact with the device. By focusing on hands on control, portability, and intuitive signal flow, we created something that is not only functional but also expressive and enjoyable to use.

The Spatial Wave Accumulator fulfills its original vision: a portable, analog device capable of making the electromagnetic world audible. By transforming invisible noise into expressive sound, it opens up new possibilities for musicians, educators, and engineers alike. Its success lies not just in technical execution, but in its invitation to listen more closely to the world around us.

## 5: References

[1] European Union, “Directive (EU) 2015/863 on the restriction of the use of certain hazardous substances in electrical and electronic equipment,” *EUR-Lex*, Jun. 4, 2015. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32015L0863

[2] Bel Fuse Inc., “IEC 62368-1: An Introduction to the New Safety Standard for ICT and AV Equipment,” [Online]. Available: https://www.belfuse.com/resource-library/tech-paper/iec-62368-1-an-introduction-to-the-new-safety-standard-for-ict-and-av-equipment

[3] U.S. Government Publishing Office, “Title 47 – Telecommunication, Part 15 – Radio Frequency Devices,” *Electronic Code of Federal Regulations (eCFR)*, [Online]. Available: https://www.ecfr.gov/current/title-47/chapter-I/subchapter-A/part-15

**[4] R. Orton, "Ring Modulator," in *The New Grove Dictionary of Music and Musicians*, 2nd ed., vol. 21, S. Sadie and J. Tyrrell, Eds. London, U.K.: Macmillan Publishers, 2001, p. 429.**

[5] University of North Carolina at Charlotte, “Experiment 8: Amplitude Modulation and Demodulation,” University of North Carolina at Charlotte ECE Department, [Online]. Available: https://ece.charlotte.edu/wp-content/uploads/sites/301/2023/05/ecgr3156-experiment-8-amplitude-modulation-and-demodulation.pdf

**[6] F. Leferink, "Fast, Broadband, and High-Dynamic Range 3-D Field Strength Probe," *IEEE Transactions on Electromagnetic Compatibility*, vol. 55, no. 6, pp. 1015–1021, Dec. 2013, doi: 10.1109/TEMC.2013.2256360.**

[7] Electronics Tutorials, “Operational Amplifier Applications,” [Online]. Available: https://www.electronics-tutorials.ws/opamp/opamp_3.html

[8] A. Garaipoom, “Universal Mono Preamplifier using IC LM741,” ElecCircuit [Online]. Available: https://www.eleccircuit.com/universal-mono-preamplifier-using-ic-lm741/

**[9] P. E. Mayes, "Frequency-independent antennas and broad-band derivatives thereof," *Proceedings of the IEEE*, vol. 80, no. 1, pp. 103–112, Jan. 1992, doi: 10.1109/5.119570.**

[10] Federal Communications Commission, "Why AM Stations Must Reduce Power, Change Operations, or Cease Operations at Night," FCC.gov. [Online]. Available: https://www.fcc.gov/media/radio/am-stations-at-night. [Accessed: May 15, 2025].

[11] K. Wong, "BJT in Reverse Avalanche Mode," Mar. 19, 2014. [Online]. Available: http://www.kerrywong.com/2014/03/19/bjt-in-reverse-avalanche-mode/

[12] Battle, S, “Simplest Oscillator,” [Online]. Available: https://www.lookmumnocomputer.com/simplest-oscillator/

[13] Wikimedia Foundation. (2025, May 13). *Monopole antenna*. Wikipedia. https://en.wikipedia.org/wiki/Monopole_antenna

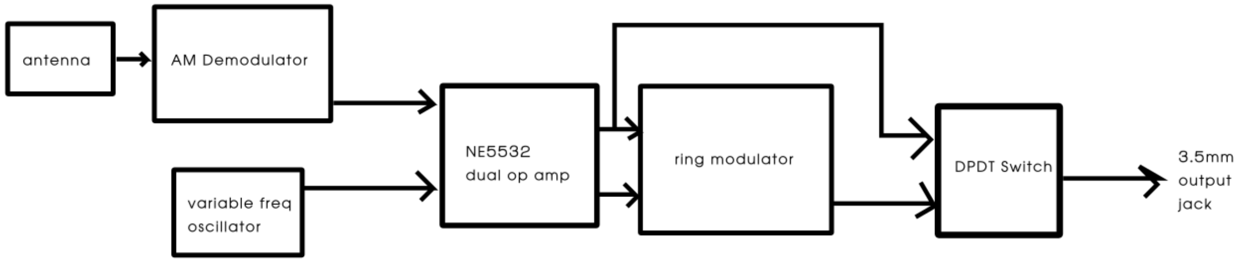
[14] *Activity: Diode ring Modulator - ADALM2000 [Analog Devices Wiki]*. (n.d.). https://wiki.analog.com/university/courses/electronics/electronics_lab_diode_ring_modulator

# 6: Appendix

a. Bill of Materials

| Spacial Wave Accumulator Bill of Materials | | | |
|---|---|---|---|
| **Component** | **Unit Cost** | **Quanitity** | **Cost** |
| **Ring Modulator** | | | |
| P631M Transformer | $6.25 | 2 | $12.50 |
| 1N34A Schottky Diode | $0.13 | 4 | $0.52 |
| Perf Board | $4.49 | 1 | $4.49 |
| **Oscillator** | | | |
| 1kΩ Resistor | $0.12 | 1 | $0.12 |
| 100kΩ Resistor | $0.60 | 1 | $0.60 |
| 10kΩ Potentiometer | $2.24 | 1 | $2.24 |
| 2N3904 Transistor | $0.03 | 1 | $0.03 |
| LED (red) | $0.15 | 1 | $0.15 |
| 10µF Electrolytic Capacitor | $0.15 | 1 | $0.15 |
| **Amplifier** | | | |
| NE5532 Dual Low Noise Audio Op Amp | $0.57 | 1 | $0.57 |
| 10µF Electrolytic Capacitor | $0.15 | 1 | $0.15 |
| 1µF Electrolytic Capacitor | $0.33 | 1 | $0.33 |
| 1kΩ Resistor | $0.12 | 2 | $0.24 |
| 68kΩ Resistor | $0.10 | 1 | $0.10 |
| 3.3kΩ Resistor | $0.10 | 1 | $0.10 |
| 20kΩ Potentiometer | $2.20 | 1 | $2.20 |
| 0.1µF Ceramic Capacitor | $0.44 | 1 | $0.44 |
| **Demodulator & Antenna** | | | |
| 47kΩ Resistor | $0.06 | 1 | $0.06 |
| 0.005µF Capacitor | $0.24 | 2 | $0.48 |
| 680mH Ferrite Loopstick Inductor | $3.60 | 1 | $3.60 |
| 60/141p \F Variable Capacitor | $0.99 | 1 | $0.99 |
| 1N34A Schottky Diode | $0.13 | 1 | $0.13 |
| Copper Wire (22 gauge) | $13.99 | 1 | $13.99 |
| Strip Board | $3.95 | 1 | $3.95 |
| **Miscellaneous** | | | |
| 22 Gauge Sheilded wire | $2.00 | 1 | $2.00 |
| 6 Gauge Copper Wire, 2 feet | $8.00 | 1 | $8.00 |
| 9V Battery | $3.81 | 2 | $7.62 |
| 9V Battery Connector | $2.50 | 2 | $5.00 |
| 3.5mm Mono Jack | $3.82 | 1 | $3.82 |
| 3.5mm Audio Cable | $4.98 | 1 | $4.98 |
| Double Pole Double Throw Mini Switch | $3.25 | 1 | $3.25 |
| Plastic Intercom Enclosure | $0.00 | 1 | $0.00 |
| #8 Machine Nuts and Bolts | $0.03 | 4 | $0.12 |
| | | **Total Cost:** | **$82.92** |

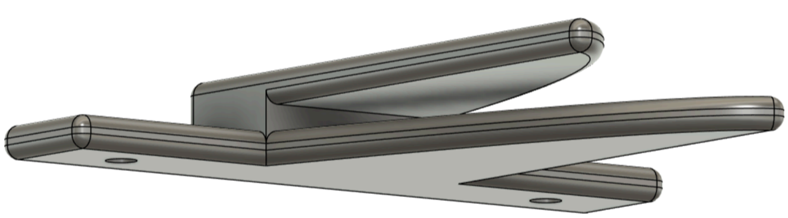
b. Block diagram



c. Gantt Chart

| SPATIAL WAVE ACCUMULATOR GANTT CHART | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tasks | Week of | | | | | | | | | | | Capstone Expo |
| | 24-Feb | 3-Mar | 10-Mar | 17-Mar | 24-Mar | 31-Mar | 7-Apr | 14-Apr | 21-Apr | 28-Apr | 5-May | 7-May |
| **Design & Order Phase** | | | | | | | | | | | | |
| Design/select antenna types | | | | | | | | | | | | |
| Design amplifier schematics using 741 op-amp | | | | | | | | | | | | |
| Choose processing techniques | | | | | | | | | | | | |
| Create block diagram and define enclosure | | | | | | | | | | | | |
| Order components | | | | | | | | | | | | |
| **Build Phase** | | | | | | | | | | | | |
| Build antennas | | | | | | | | | | | | |
| Assemble amplifier on breadboard | | | | | | | | | | | | |
| Build demodulation & mixer circuit | | | | | | | | | | | | |
| **Test & Debug Phase** | | | | | | | | | | | | |
| Test signal reception & amplification & demodulation | | | | | | | | | | | | |
| Debug & optimize circuit | | | | | | | | | | | | |
| **Finalize & Present Phase** | | | | | | | | | | | | |
| Build enclosure & final assembly | | | | | | | | | | | | |
| Final presentation & documentation | | | | | | | | | | | | |

d. Technical Drawings

e. Modeling Details