

**Bat Echolocation:  
Triangulation Using Ultrasonic Microphones**

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**Abstract:**

In this paper I will present results from a system of three microphones used to triangulate an ultrasonic signal. The signal from these three microphones is run into a computer where the difference in time between the signals can be used to locate the transmitting source in space. I will show that this system can be used to triangulate the position of a bat flying in the wild and that this system can be adapted for field work in the study of bat echolocation. Current methods of bat detection will also be presented as well as the different kinds of ultrasonic microphones used in bat detection. The advantages and disadvantages of different microphones with ultrasonic sensitivity will be discussed. In addition, methods of filtration will be presented. The microphones used for triangulation and the manner in which data is collected and analyzed will also be presented. This system of analysis opens up new possibilities for improved spectroscopic analysis of bat echolocation as it will enable researchers to closely correlate intricate bat flight patterns directly with each ultrasonic pulse.

## **Introduction:**

Many species of bats use echolocation to navigate their nocturnal lives.

Although the popular belief that bats have poor eyesight is not rooted in truth, it is difficult to see in the night, and most species of bats rely on echolocation to maneuver their flight and to feed. Bats echolocate by sending out a series of high frequency pulses and listening for their echoes. When the echo returns to the bat, information about the target can be determined by the amount of energy and timing of the reflected pulse. Frequencies of bat calls can range from 9kHz to 200kHz—extending far above the frequencies of human hearing, although the common big brown bats and small brown bats have a range of approximately 25-85kHz[1]. These calls range in intensity from approximately 110dB to 60dB, depending on the species [2]. Bats can emit a constant frequency (CF), a modulated frequency (FM), or both (CF-FM). Bats will also hear the harmonics of their pulses--often the 2nd, 3rd, and 4<sup>th</sup> harmonics of a pulse. From the Doppler shift and changes in the loudness of the echoes, the speed at which an insect is flapping its wings can be determined from the pulses that are reflected from the insect's wings. As the speed at which an insect flaps its wings correlates with the size of the insect, insect size can be inferred from the reflected pulse [3]. Bats also emit sound within the range of human hearing (commonly referred to as "chittering"). These lower frequencies are not related to echolocation, rather are believed to serve as some form of communication between roosting female bats and their pups[2].

In 1793, Italian zoologist Lazzaro Spallanzani theorized after a series of experiments that bats used their ears to "see" in the night. Urging that his colleagues

repeat his experiments, surgeon Charles Jurine discovered that if the ears of a bat were plugged or filled with wax, that it became clumsy and helplessly ran into obstacles.

Over a century passed after Spallanzani's death with little more knowledge of how bats appeared to "see" with their ears.

In 1938, Dr. Donald Griffin, then an undergraduate at Harvard University, was studying bat migration when it was suggested to him that he experiment with the ability of his bats to avoid obstacles. Griffin then approached physics Professor G. W. Pierce about using the apparatus he had recently developed to detect and generate a wide range of sounds above the audio range using a piezoelectric crystal. Pierce agreed to use the apparatus to experiment with Griffin's bats. By 1944 there was sufficient evidence that bats employed ultrasonic frequencies for navigation, a process which Griffin coined "echolocation"[2]. Although the basic idea of echolocation has been understood and accepted for half a century, there are still many questions surrounding how different species of bats delicately use echolocation to maneuver so precisely through the evening. In an attempt to more fully understand how bats use echolocation to fly in complicated patterns in dense areas, it is necessary to be able to determine which maneuvers coincide with specific pulses and pulse rates. Using ultrasonic microphones, a bat's position can be triangulated and stored. A series of these triangulated positions would then provide a three dimensional picture of the bat's flight path along with its coinciding frequency pulses.

## **Detectors:**

There are three main kinds of detectors currently used in bat research to locate and listen to different species of bats. One type of detector relies on heterodyning. With a heterodyne detector the input signal from an ultrasonic microphone is mixed with the output from an oscillator whose frequency is controlled by a tuning dial. Two frequencies are produced from adding and subtracting the oscillator's frequency and the input frequency. These signals are sent to an intermediate amplifier, which has a limited bandwidth (typically only  $\pm 5\text{Hz}$ ) so that only the low signal is passed, that is, we hear the beat frequency which is the difference, not the sum. This signal is then mixed with the second, fixed frequency, oscillator to bring the output from the first amplifier down to the human audible range. These detectors are good for determining upper and lower limits of frequencies, however there is not data of the spectrum, so the bat calls are not easily analyzed.[4].

Frequency division detectors produce a square-wave output with the same frequency of the input signal. This square wave is then divided by a predetermined amount so that, for example, the output signal will only trigger once ten input pulses have passed so that it can be divided by ten. This method is superior to heterodyning (although much more expensive) since no tuning is required and since the data can be used for some spectroscopic analysis[5].

The newest and most successful method of detection uses time expansion. With time expansion detectors, the signal from the microphone is sampled by a fast analog to digital converter at rates of about 500kHz into a FIFO(first- in, first-out) memory buffer. The signal is then output at a rate of usually 1/10th the sampling rate through a D/A

converter. These lowered, audible frequencies can be recorded and used for analysis. This is the most advanced form of detector, but high costs keep its use low[5].

### **Ultrasonic Microphones:**

The detectors use piezoelectric, electret, or solid dielectric microphones. Piezoelectric crystals vibrate when hit with a high frequency, generating small voltages that are then amplified. Piezoelectric microphones are inexpensive, sensitive and durable, but since the crystals are usually tuned to a narrow frequency range, these microphones usually have a narrow bandwidth, making them very sensitive at some frequencies and not at others[6].

Electret microphones use a thin permanently polarized membrane stretched over a metal backplate. A fluctuating voltage across the membrane and plate is created by ultrasound vibrating the membrane. This voltage is then amplified. This type of microphone was originally developed for hearing aids and the microphones have a flatter frequency response than piezoelectric microphones, although they are less sensitive[6].

Solid dielectric microphones work like the electret microphones, but the membrane has to be charged. When ultrasound hits the membrane and causes it to vibrate, this changes the capacitance and the charge between the plates, which will be amplified. Solid dielectric microphones use a thin insulating material that is metallized on one side and stretched over a perforated backplate. These microphones have a high sensitivity, but are very susceptible to humidity between the plate and the membrane[5].

**The Goal:**

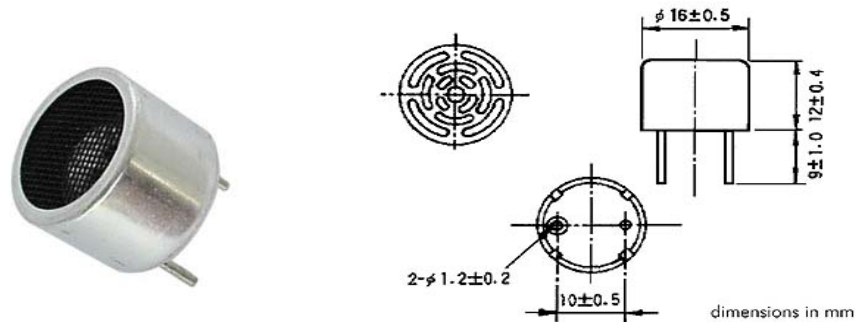
The goal of this project is to build a system of three amplified microphones read by a computer to triangulate a bat's position in real time. This is to be done using the knowledge of current bat detectors in use and microphones on the market with ultrasonic capabilities. This system could then be used to further analyze the intricacies of bat echolocation, as the researcher would be able to match individual flight movements and locations with exact ultrasonic pulses. A reconstruction of a bat's flight path in addition to spectroscopic analysis of the bat's echolocation would provide a more detailed knowledge of how bats use echolocation to navigate.

**Microphone Possibilities:**

Two different kinds of microphones have been considered for use in the experimental set up, each with its own advantages and disadvantages. The first is a piezoelectric Velleman MA40A5S Transducer Receiver, as shown in Figure 1. This transducer has a maximum input of 20V<sub>rms</sub> and a nominal frequency of 40kHz. This is a durable microphone with an operational temperature range of -20C to +85C. These microphones are slightly directional which inhibits the ability to collect data from a moving object (the bat). This microphone has a very narrow bandwidth and only receives frequencies of 40± 2kHz. The narrow bandwidth provides both advantages and disadvantages. Since the bandwidth is so small, other frequencies (both in and out of human hearing range) do not need to be filtered out. The bat's pulses sweep from a higher frequency to a lower one, passing through 40kHz, so the bat pulse can be detected by these microphones each time a pulse is emitted by a bat. This does mean, however, that



the data from the triangulation of the bat can not be directly used for spectroscopic analysis and that an additional detection device would need to be used if spectroscopic analysis of the pulses was desired.



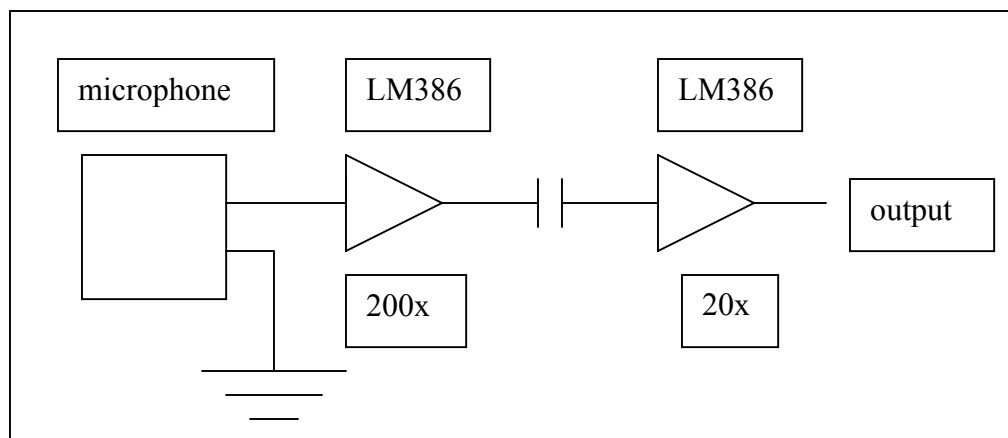
**Figure 1: Velleman MA40A5S Receiver**

The second type of microphone considered was an electret hearing aid microphone, the Knowles FG-3329. This microphone does not have a narrow bandwidth and thus data could be used for spectroscopic analysis. It is also more omnidirectional and thus would pick up a moving signal better. However, due to the wide range of frequencies that this microphone is sensitive to, a high pass filter must be added to the circuit to ensure that the bat pulses are picked up by the microphones instead of all the sounds we hear all around us. A bandpass filter would also help cut off higher frequencies than those that the bat is emitting, but at minimum a two pole high pass filter, such as the one described below for this particular microphone, must be used. These microphones also require a separate power supply and are less sensitive than the Velleman microphones, requiring a greater amplification. Since this microphone is designed for hearing aides, it is incredibly small: 2.57mm dia x 2.57mm [Figure 2]. This makes soldering difficult and the microphones require careful handling that the Velleman microphone does not.



**Figure 2: Knowles FG-3329 electret microphones**

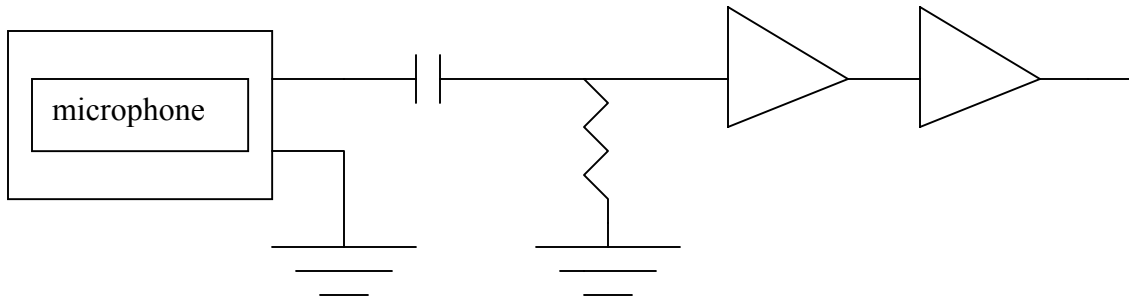
Weighing out the advantages and disadvantages of both these microphones, the Velleman MA40A5S microphone was chosen for the experimental set-up. The signal from these microphones is greater than that from the hearing aide microphones, however it does still require amplification. The LM386 low voltage audio power amplifier chip was chosen for the job of amplification. The LM386 can be powered by a 9V battery and two of these amplifiers are capacitively coupled in series to provided amplification for each microphone. With pins 1 and 8 open on the LM386, this amplifier provides a gain of 20. When a capacitor is inserted between 1 to 8 (as done with the first amplifier) the gain increases to 200. The first chip providing a gain of 200 capacitively coupled with a second chip with a 20 provides and overall gain of 4000.



**Figure 3: Circuit Diagram of Amplification**

## Filtering:

A one pole RC filter can be achieved by tying a capacitor between the output of the microphone and the input of the first LM386, and a resistor from the capacitor to ground.



**Figure 4: Circuit Diagram of RC filter**

This highpass filter cut off frequencies below where this frequency is determined by

$$\omega = \frac{1}{RC}$$

and the transfer function can be found using

$$H(j\omega) = \frac{j\omega RC}{1 + j\omega R}$$

where  $j$  is the imaginary  $i$  [7].

Multi-pole RC filters can be designed by cascading single pole filters together.

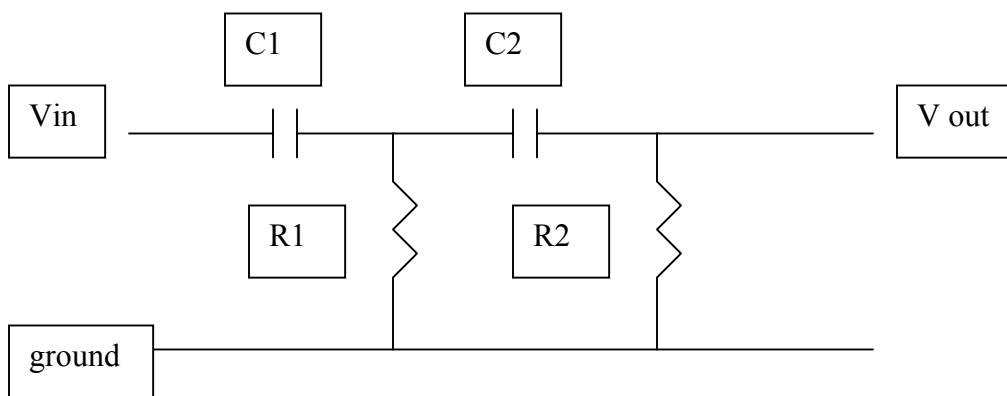
A two-pole filter should be adequate for the purposes of this filter. Two resistors and capacitors need to be chosen for this filter with  $R_1$  chosen to be ten times the output impedance of the microphone and the capacitance value chosen in the same manner as for the single pole filter.

$$\omega_c = \frac{1}{R_1 C_1}$$

R2 and C2 should be chosen as

$$C_2 = \frac{C_1}{100}, R_2 = 100R_1$$

The second capacitor and resistor values should be chosen this way to ensure that the impedance remains high. This two-pole filter has a faster roll off than the one pole RC filter and doesn't require any inductors[7].



**Figure 5: Two-Pole Highpass RC Filter**

### **Frequency Sweeps:**

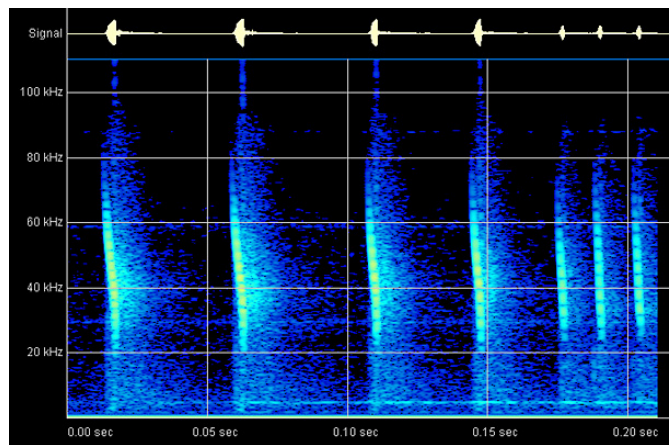
Using LabView, programs were written to produce frequencies similar to those of a typical small brown bat (*myotis lucifigus*). There are three main phases of echolocation for *m. lucifigus*. In the search phase the bat scans the location for targets.

These pulses are the longest in duration with the greatest pulse to pulse intervals. During the approach phase the pulse to pulse intervals decrease as the bat approaches a target.

Finally, during the terminal phase the bat rapidly emits pulses that sweep a smaller and lower frequency range. In the search phase, pulse to pulse intervals range between 50 and 100 milliseconds with longer intervals observed in larger spaces. The approach

phase intervals range between 50 and 10 milliseconds and in the buzz, or terminal phase, pulses are only separated by 4 to 7 milliseconds.

The frequency sweeps of these FM bats also vary from phase to phase. In the search phase, pulses generally drop from about 75-85kHz to 37-45kHz. Within the "buzz," frequencies only drop from about 30kHz to 25kHz [2]. Figure 6 is a sample spectrum of myotis daubentoni bat calls. The difference in sweeps can be observed between the first four sweeps and the last three.



**Figure 6: Spectrum of *m. daubentoni* Bat Calls**

In order to adequately simulate the bat in the lab, four programs were written, one for each of the phases and one that combined the three. Using these programs, the function generator simulates the bat pulses so that an experiment can be set up without the actual use of a bat.

### **Triangulation:**

Triangulation can be easily achieved using three microphones, determining the source coordinates from measured differences in the times the signals are received.

There are three microphones located at points  $m_i = (x_i, y_i, z_i)$  and a source at  $s = (x_s, y_s, z_s)$ .

The distance between the source and point  $m_i$  can be calculated with  $X_i$  denoting the distance.

$$\chi_i = \sqrt{(x_i - x_s)^2 + (y_i - y_s)^2 + (z_i - z_s)^2}$$

Measuring the time delays between microphones  $i$  and  $j$  each gives a linear relationship in the form

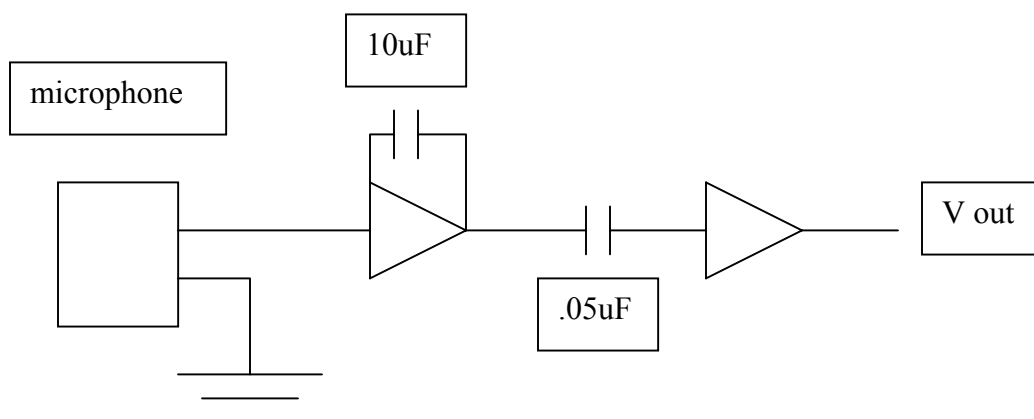
$$\chi_i - \chi_j = ct_{ij}$$

where  $c$  is the speed of sound and  $t_{ij}$  is the delay between signals. Time delays can be obtained from data analysis.

### **Test Setup:**

Three Velleman MA40H5S microphones are used to receive ultrasonic frequencies from a Mouser 255-400ST12 transmitter. A function generator is used to produce a 40kHz sinusoidal wave at 10Vpp, which is connected to the transmitter. A constant 40kHz frequency is initially adequate for the purposes of receiving a signal within the range of bat pulses. The transmitter has a minimum driving voltage of 1V and a maximum voltage of 20V at 40±2kHz. Therefore, to simulate bat pulses would require a different transmitter than the 255-400ST12 in order to transmit the complete sweeps over the full frequency range. A bat simulation could still be used, however, since each time the sweep passes through 40kHz the transmitter frequency would be within the bandwidth of the transmitter.

Each of the three Velleman MA40H5S microphones are amplified as shown in Figure 7 and powered with a 9V battery. The amplified microphones are then sent into channels 0-2 of the E Series Multifunction DAQ NI 6023E board that has been installed into the computer. The data acquisition card has 16 analog inputs sampling at up to 200kS/s, digital triggering and 4 analog input signal ranges. A special driver simplifies configuration and measurements. Using a LabView Virtual Instrument (VI), data is read into the computer and bundled, and displayed in a graph. A DAQ Assistant Express VI is used that creates, edits, and runs tasks. The DAQ Assistant is set to continuously read 20,000 samples per bunch at a rate of 4kHz. For continuous measurement and generation, a loop is placed around the DAQ Assistant Express VI. The E Series Multifuntion DAQ samples one channel at a time, gathering 20,000 samples at 4kHz from each channel before moving on to the next. The DAQ board can process this information at 200kS/s, but since we are using three microphones, this number must be divided by three, reducing the rate to 66.6kS/s. Since we have chosen to sample our signals at only 4kHz, this rate is within the range of possible sampling rates.



**Figure 7: Amplification of Microphones with Capacitors**

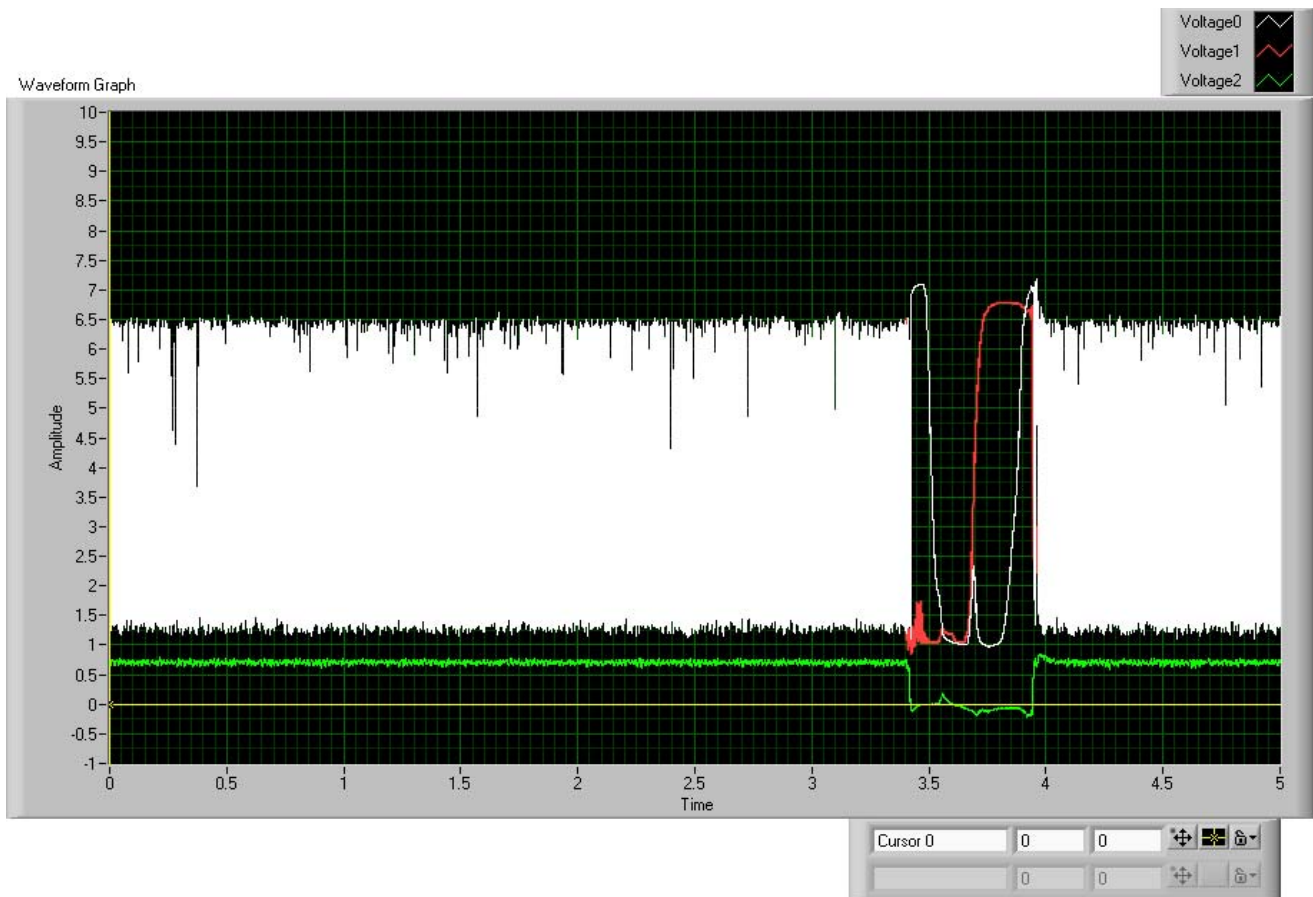
Each of the three receiving microphones are placed around the lab at various distances from the transmitter and the VI is set to run. The function generator continuously emits a 40kHz signal and by connecting and disconnecting the transmitter, the signal can be viewed as "on" or "off" by observing the graph of voltage versus time. This process is continued and the time difference between when each microphone picks up a signal from the transmitter is observed.

### **Results:**

The speed of sound in air is approximately 340m/s (varying slightly with temperature, and humidity). As each microphone is placed at a different distance from the transmitter, when the transmitter is turned "on" each microphone should receive the signal at a slightly different time. Multiplying that time by the speed of sound, the distance between the microphones and transmitter can be determined.

Figure 8 is a graph of the data being received when the transmitter is "off" and then turned "on". Currently the microphones are picking up a lot of noise when the transmitter is not sending a 40kHz signal. This could be attributed to many different factors. Although the cable connecting the microphone circuit to the DAQ board is insulated, one possibility is that the great length of the cable is acting like an antenna. Another possibility is that although the microphones have a very small bandwidth, they are still minimally responsive at other frequencies and since the signal is being amplified by such a huge gain, the usually tiny signal is amplified to a quite large signal, which can be seen in the graph. Although there is a fair amount of noise, the time at which the microphone receives the signal from the transmitter can be clearly observed.





**Figure 8: Graph of data input showing when transmitter is “on” and “off.”**

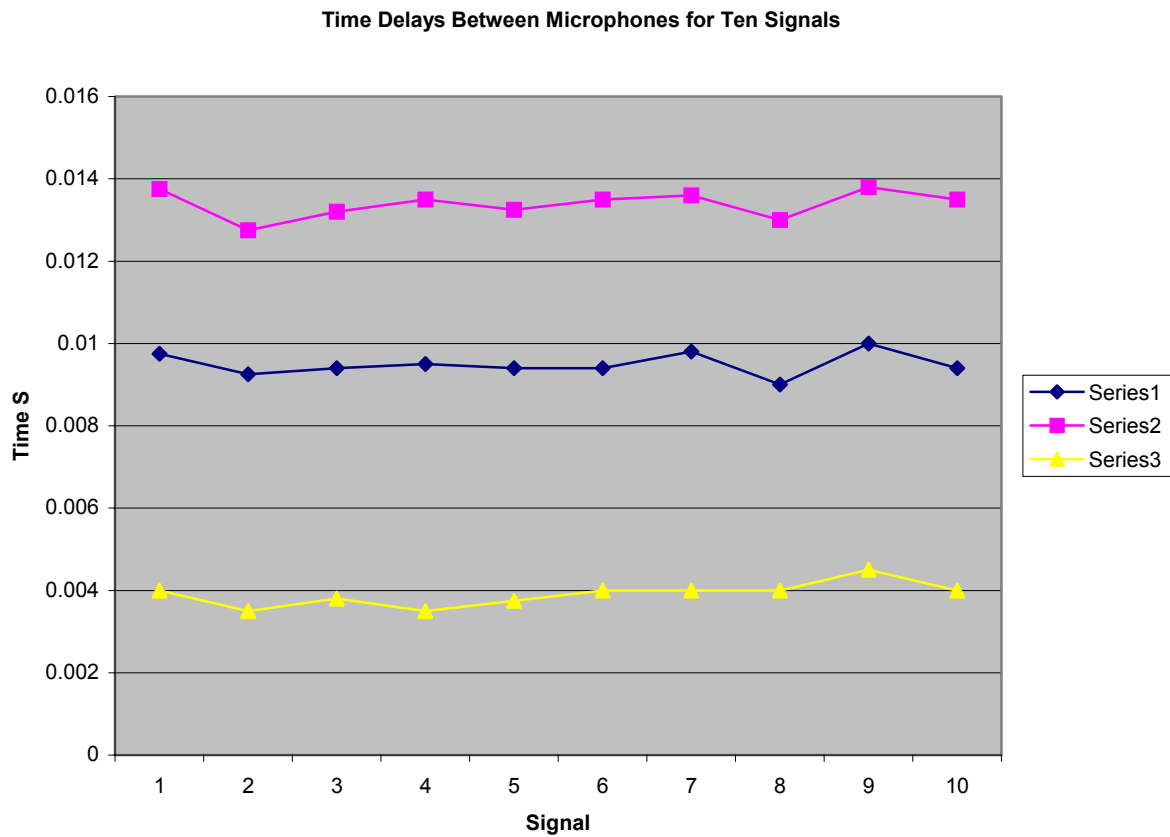
Channel 0 is the white signal, channel 1 is the red signal, and channel 3 is the green signal. The graph must be greatly expanded in order to be able to see exactly when the transmitter is turned on. Channel 1 can be observed to have received the 40kHz signal at 3.406s and channel 0 receives the signal at 3.424s. This is a difference of 18ms. Multiplying 18ms by 340m/s, a distance of 5.02 meters. The difference between the distances of these microphones from the transmitter was then measured and was approximately 5 meters!

The three microphones were then placed at specific locations in the lab and the transmitter was fixed from above. The distances between these microphones and the

transmitter were then measured and the differences in these distances divided by the speed of sound was noted (see Table 1). Repeating the process of turning the transmitter “off” and “on” and analyzing the differences in the times that the microphones received the signals revealed that the differences in distance between the microphones and transmitter could be determined and thus the location of the transmitting microphone can be triangulated. It is necessary to know the locations of the three microphones precisely in order to triangulate the position of the transmitter (or “bat”). Repeating this process revealed some error in the time delay between microphones. The standard deviation for the time delay between channel 0 and 1 was found to be .000289. The standard deviation between channel 0 and 2 was found to be .000333, and the standard deviation between channels 1 and 2 was found to be .000291. Figure 9 shows a graph of the time difference between channel, where series 1 is the difference between channels 0 and 1, series 2 is the difference between channels 0 and 2, and series 3 is the difference between channels 1 and 2.

	white/red	white/green	red/green
average measured difference, sec	0.00949	0.013385	0.003905
expected time difference, sec	0.0095	0.0134	0.004

**Table 1: Average Measured Difference Between Receiving Signal vs. Expected Difference**



**Figure 9: Graph of Time Delays Between Microphones**

**Future Goals:**

There are still more steps to this process that need to be done. First, the source of the noise when the transmitter is off needs to be determined and the signal needs to be cleaned up. If the noise is created by usually small signals being greatly amplified along with the 40kHz signal, then perhaps a bandpass filter between the ultrasonic microphone and amplifying LM386 chips could decrease some of this noise from being amplified.

The cable running from the microphones to the DAQ board may also need to be shielded

better. The signal needs to be cleaned up so that the time difference between signals can be more accurately determined.

Once the signal is cleaned up, many measurements need to be taken of the time difference between signals. The error between the time delays of the microphones needs to be measured again. This error needs to be factored into the triangulation so that it can be determined with what accuracy the position of the transmitter can be located.

Moving the transmitter and then triangulating many different positions can then provide a three dimensional picture of the movement of the transmitter through space.

The transmitter acting as a mock bat, the flight path of a bat could then be determined by taking the apparatus into the field and testing the set-up.

A final consideration would be to return to the hearing aide microphones that had a much greater bandwidth than the Velleman MA40H5S microphones. This would require additional filtration to filter out frequencies below 20kHz and above 80kHz so that only the bat pulses were amplified and set into the computer. The biggest benefit of returning to these microphones would be the ability of spectroscopic analysis of the bat pulses directly from the same data used for triangulation. An additional method of bat detection would need to be used in coordination with the Velleman microphones if spectroscopic analysis was desired in addition to the triangulation.

### **Williamsburg Bats:**

Without catching bats for identification, the specific species of bats inhabiting Williamsburg cannot be known with certainty, although it is likely that both big brown bats and small brown bats can be found in the area. Using a Peterson D100 heterodyning

bat detector shown in Figure 10, specific locations were observed for bat activity in early September. Locations with bat activity were observed for approximately one half hour to determine the amount of sustained activity. Locations that appear to have sustained bat activity from a single bat are preferred for fieldwork so that the echolocation detected can be easily assigned to one bat and there is no confusion as to which bat is emitting which pulse. Locations in Williamsburg with varying degrees of sustained bat activity were located as possible sights for fieldwork, such as by the Williamsburg Community Center, Lake Matoka, and the College of William and Mary Barksdale Field and Ludwell Apartments.



**Figure 10: Peterson D-100 Heterodyning Microphone**

Bat houses were installed in some of these locations in order to ensure bat activity in the future. If inhabited, the bats living in these homes could be easily caught for future identification if desired. The bat houses installed were smaller (1'x2'x6") than houses designed to be inhabited by entire roosts of bats (similar design to the bat house depicted in figure 9). The bat houses were painted with a dark green paint to increase the heat of the houses, but insulation was not installed due to the warm temperatures of Williamsburg summers. The design of these bat houses was modeled after larger bat houses with a grooved "landing pad" and three inner sections, also with groves to provide

the bats with an easier surface to hold to. The houses were installed at around 12' onto trees. Inhabitation of these bat houses has not been determined.



**Figure 11: Bat House**

**Conclusion:**

In conclusion, it was found that the location of a transmitter emitting ultrasonic frequencies could be found using three ultrasonic microphones to triangulate. Another source capable of transmitting ultrasonic frequencies, such as a bat, would also be able to be triangulated in the same manner. Although there would be new challenges involved in triangulating a moving object in the wild, it is still possible with the current set-up. Using electret microphones in place of the piezoelectric microphones in the current set-up would enable the researcher to have spectroscopic analysis from the same data as the triangulation, although this is not completely necessary and the level of necessity would depend greatly on an individual researcher's fieldwork. A gathering of more precise data will help to better our understanding of echolocation and how specific species of bats use these high frequency calls, and answer many questions surrounding the precise manner in which these high frequency pulses are used to maneuver so delicately that still remain.

## Works Cited

- [1] Griffin, D.R., Webster F.A., Micheal, C.R.(1960). The echolocation of flying insects by bats. "Animal Behavior." 8:151-154
- [2] Griffin, D.R. (1958) "Listening in the Dark", *Yale U.P.*
- [3] Model System in Neuroethology-Echolocation in the Bat.  
<http://soma.npa.uiuc.edu>
- [4] <http://batsound.com/psondet.html#D100series>
- [5] <http://www.biology.leeds.ac.uk/staff/daw/bats/Detector.htm>
- [6] <http://home.kabelfoon.nl/~betrik/bat/mics.htm>
- [7] Fortney, Loyd. (1987). "Principles of Electronics." 99-100, 108-111.
- [8] Hill, Windfield., Horwitz, Paul., (1989). "The Art of Electronics." Apendix H.  
1064-1067