

Detection of Atmospheric Infrasound

Physics 303

a final project report by Chris Orban

Introduction:

The human ear has the ability to detect sound waves in a frequency range from about 20 kHz down to 20 Hz. Infrasound is defined to be any sounds, or pressure waves that lie below this range. Since the wavelengths of these waves may be on the order of kilometers the term “pressure waves” may give a better physical picture of the phenomenon. These disturbances still obey the wave equation:

$$\frac{\partial^2 p}{\partial t^2} = \frac{1}{c^2} \nabla^2 p$$

where p is the pressure as a function of time and space. Electromagnetic waves also obey this equation, but they are transverse waves because the electric and magnetic fields vary in directions perpendicular to the direction of motion. Sound waves are mainly longitudinal waves (both transverse and longitudinal oscillations obey the wave equation), which means that the oscillations that compose the wave travel in the direction it is traveling. A simple physical picture of longitudinal waves is watching oscillations propagate back and forth across a slinky.

Sound can only travel in air, but electromagnetic waves can travel in a vacuum. The speed of electromagnetic waves is determined by the dielectric, and magnetic permeability of the substance, but the speed of sound waves are determined from atmospheric quantities, assuming adiabatic conditions, the speed of sound is

$$c = \sqrt{\gamma RT} = 343 \text{ m/s at STP}$$

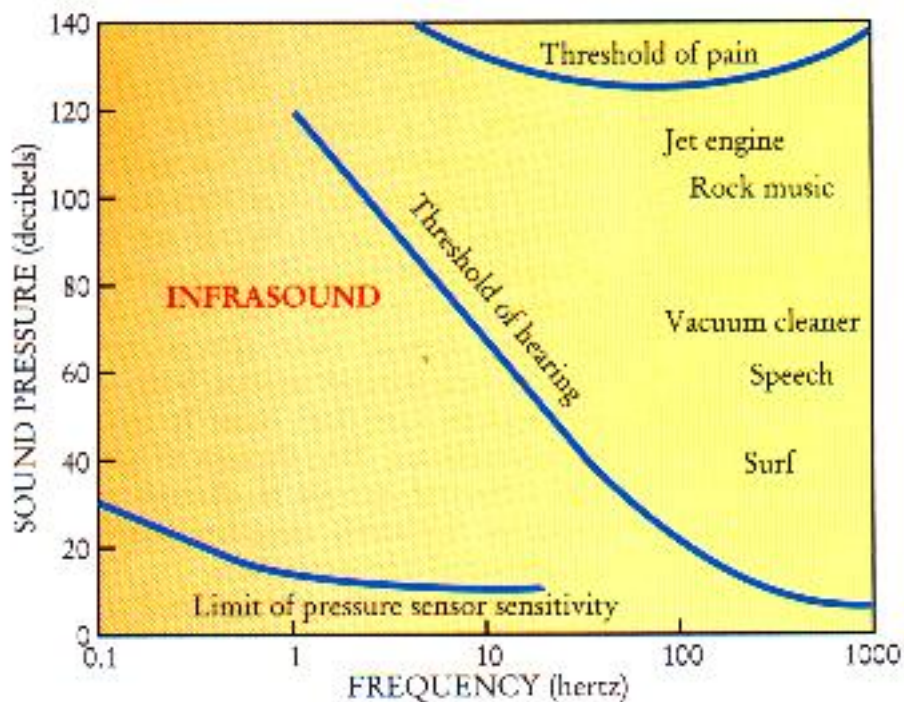
where T is temperature, γ is the adiabatic gas constant, 1.401 and R is 8.314 J /mol K.

Sound waves also obey:

$$f \lambda = c$$

So for infrasonic frequencies, say for example, 3 Hz, the frequency at which my detector is sensitive, the wavelength of this wave is about 100 meters. The best professional infrasound observatories have the ability to detect frequencies down to 10^{-3} Hz, so the wavelength of the waves can be as large as 300 kilometers or more. (At those frequencies the pressure variations can be more accurately called acoustic-gravity waves since they are so large.) Professional infrasound observatories can detect pressure variations in these ranges down to 10^{-5} Pascals. (Whitaker and Mutschechner 1997)

This figure from “Atmospheric Infrasound” in Physics Today 3/00 is very helpful in illustrating the dynamic ranges involved.



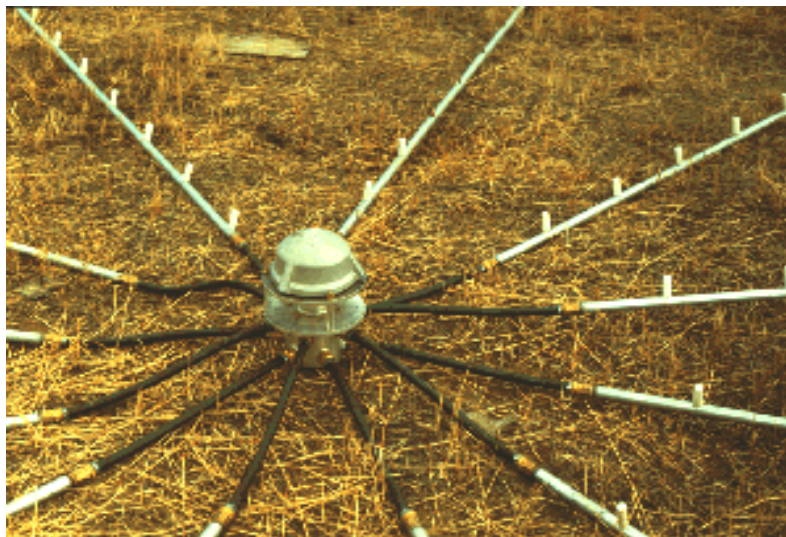
Notice that current infrasonic detectors have the pressure sensitivity comparable to the human ear, except at much lower frequencies. The threshold of hearing in this diagram extends to 1 Hz since these waves can be “felt” rather than heard if the amplitude is large enough.

Sources of Infrasound:

Much of the list of known infrasound sources are not surprising; explosions, avalanches, earthquakes and severe weather all produce measurable infrasound signals from their pressure waves. Other sources are more exotic; meteors and supersonic jets create infrasound from their shock waves (ReVelle, Douglas and Whitaker 1998), and infrasonic signals can be correlated with varying local magnetic field strengths during auroral displays. (Procunier 1971) Also worth mentioning are microbaroms, which are signals created from kilometer size standing waves on the ocean. They are a very strong, sporadic signals that are very important for frequencies near 0.1 Hz. (Bedard and Georges 2000)

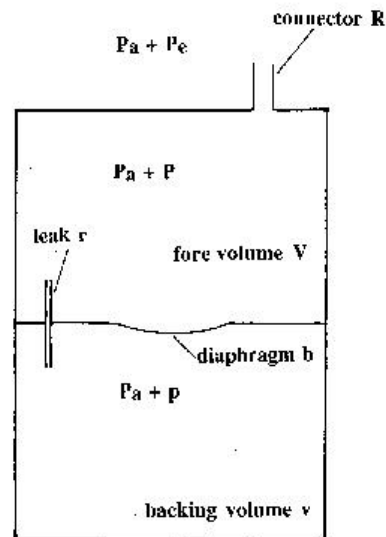
Scientific Instrumentation:

Infrasound observatories typically consist of an array of detectors that allow the direction of the incoming wave to be determined by time delay of the arriving sound between the detectors. One such detector is shown below:



The center capsule contains what can be accurately described as a large condenser microphone (and the accompanying electronics) and the twelve hoses extending from it serve to connect the microphone to the outside air and reduce the effect of wind, which could otherwise be mistaken for legitimate pressure waves.

A schematic of the microphone is displayed below (Whitaker and Mutschlechner 1997)



The hoses connect to the opening at the top, and the diaphragm in the middle vibrates with the pressure disturbances in the air just like a conventional audio microphone. The “leak” is a small capillary tube that connects the air behind the mic to the front chamber. If it is very thin, the time constant associated with the backing volume pressure equalizing with the pressure in the fore volume will be very long, so there is a physical limitation on the time resolution. A thin leak can be said to resist pressure changes, so it has “acoustic” resistance, a concept that will be expanded upon later. From general considerations from the viscosity of the air, the acoustic resistance of a capillary tube is given by the Hagen-Poiseuille relation:

$$r = 8L\eta/\pi a^4$$

where η is the molecular shear viscosity of air, L is the length of the capillary and, a , is the radius of the capillary. This capillary tube is important for the frequency response of the device. The center frequency of greatest sensitivity of the microphone is given by:

$$f = \frac{a}{2\pi\sqrt{RrV(v+ab)}}$$

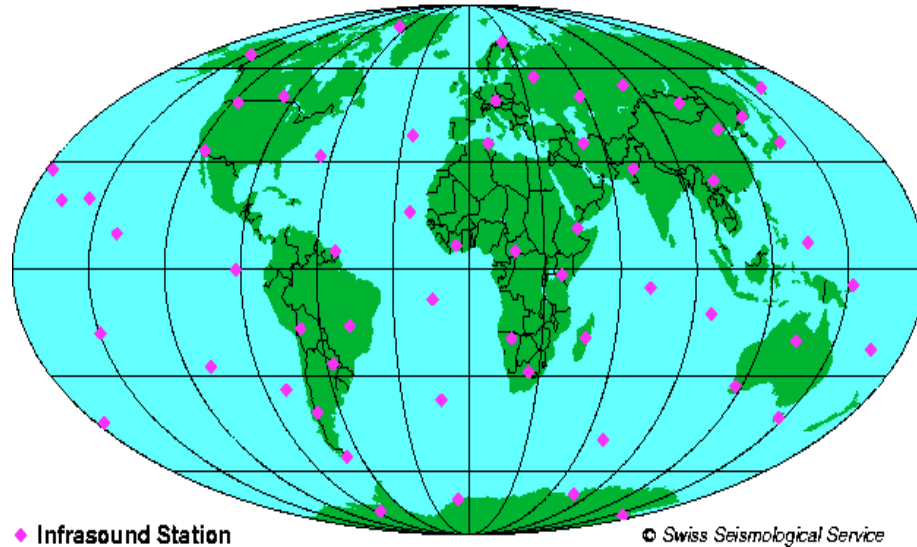
(Whitaker and Mutschlechner 1997) where a is an atmospheric constant, R is the acoustic resistance from the pipes (which is not nearly as much as the capillary tube, r) V is the volume of the fore volume including pipes, v is the volume of the backing volume and b is a constant of the microphone diaphragm. The response does not have a strong peak, but the center frequency is still important for the frequency range of the detector.

The motion of the diaphragm is detected with a backing plate (not shown in the diagram) which is a circular piece of metal raised to a voltage. The capacitance of this configuration varies with the sound pressure since the diaphragm and the backing plate form two plates of a capacitor and the displacement of the diaphragm changes the capacitance similar to the simple case of varying the distance between two capacitive plates to change the capacitance between them.

An important historical note is that much of the current interest in infrasound stems from the monitoring and enforcing the Comprehensive Test Ban Treaty, which has encouraged a worldwide network of infrasonic observatories to grow since they serve as incredibly useful tools in detecting nuclear explosions and tests, now prohibited by the treaty. Infrasound observatories associated with this project are indicated in pink in the map on the next page. These observatories also collect scientific data as well as monitor

for nuclear tests. (Bedard and Georges 2000)

CTBT - Infrasound Stations



An Alternate Approach to Detection:

Instead of using professional quality engineering and electronics to detect a wide range of frequencies, one can use an acoustic resonator to amplify a narrow range of frequencies for detection. The most familiar example of an acoustic resonator is blowing across a root beer bottle. The bottle resonates at a specific frequency determined by the size of the bottle, and how much liquid remains inside. The same idea can be applied at a frequency of 3 Hz using a large 725 gallon water tank as a resonator.



The exact frequency of the resonance of this tank is theoretically determined by

$$f = \frac{c}{2\pi} \sqrt{\frac{A}{lV}}$$

(Swenson 1953) Where A is the cross sectional area of the exit pipe, l , is the length of the exit pipe, and V is the volume of the tank. This result expands the idea of acoustic resistance mentioned in the previous section and treats the tank as an acoustic RLC circuit with a capacitance of $C = \rho_o c^2 A^2 / V$ and acoustic inductance of $L = \rho_o A l$. The resistance is very small, so the resonant frequency, f , is just the resonance of an LC circuit. The derivation of the capacitances and inductances, etc. comes from volume displacement considerations. If the air in the exit pipe is displaced one way or the other, the pressure of the tank will react accordingly. Assuming adiabatic conditions, those considerations yield a differential equation of the same form as an RLC circuit. The following table is useful for this analogy:

	Pressure-Voltage Analogy
Sound Pressure (newton meter ⁻²)	Voltage (volts)
Volume Velocity (meter ³ second ⁻¹)	Current (amperes)
Volume Displacement (meter ³)	Charge (coulombs)
Acoustic Mass (kilogram meter ⁻⁴)	Inductance (henrys)
Acoustic Stiffness (kilogram meter ⁻⁴ second ⁻²)	Capacitance ⁻¹ (farad ⁻¹)
Acoustic Resistance (kilogram meter ⁻⁴ second ⁻¹)	Resistance (ohms)
Acoustic Impedance (kilogram meter ⁻⁴ second ⁻¹)	Impedance (ohms)

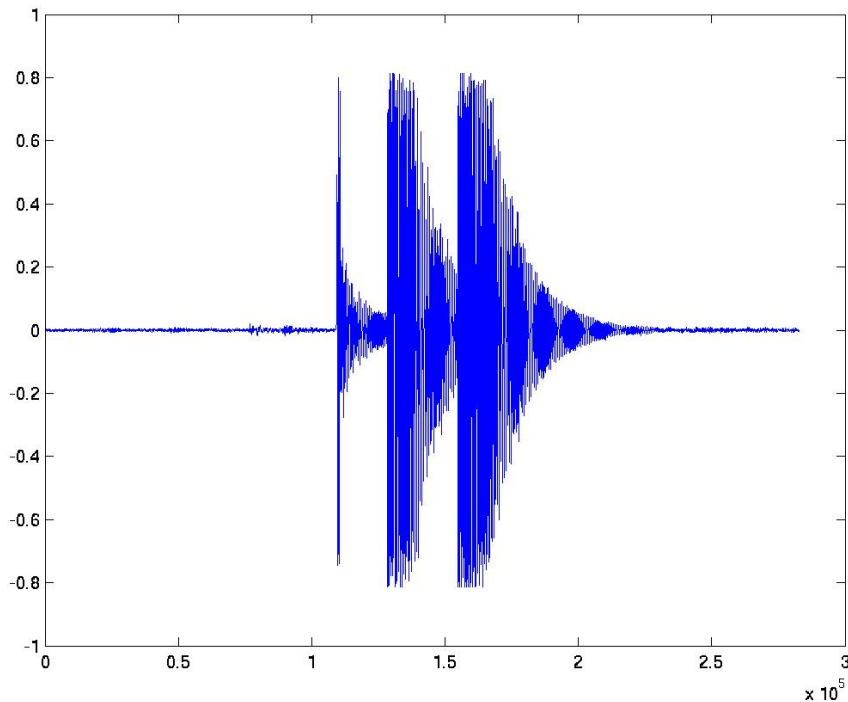
We will see how the microphone can also be analyzed with this language, and even the hoses connecting to microphone in the professional observatory design can be thought of as resistors in parallel, however, a mass-damping-spring analogy may be more appropriate in some circumstances, since the units of the acoustic inductance is actually just mass, similarly the capacitance is just a spring constant. (Swenson 1953)

The effective acoustic resistance of the tank is given by the Huygen-Poiselle relation, $R = 8L\eta/\pi a^4$. (Note that the air itself does not have significant acoustic resistance at infrasound frequencies) Dimensions of the exit pipe were “tuned” to a 3 Hz resonant frequency (Length = 1 foot, and radius = 1 in, tolerances are low since an experimental value for the resonance is much more valuable than the theoretical), by using these same dimensions to find the acoustic resistance is determined to be $3.35 \cdot 10^{-4}$ Ohms, which predicts a Q of the oscillator of 45. The higher the Q, the slower the tank dissipates energy, so by determining the time constant of decay, one can check this prediction.

This was done with a conventional audio microphone (likely an electret mic to be exact) connected to a preamplifier before being recorded through the microphone input

on a laptop. The preamplifier had a built in adjustable low-pass filter that was set to attenuate frequencies above 30Hz by 6 dB so that the low range of the audio spectrum was being used, and even if the microphone had no response below 20 Hz, the total signal will be proportional to the total energy in the tank, and thus can be used to determine Q.

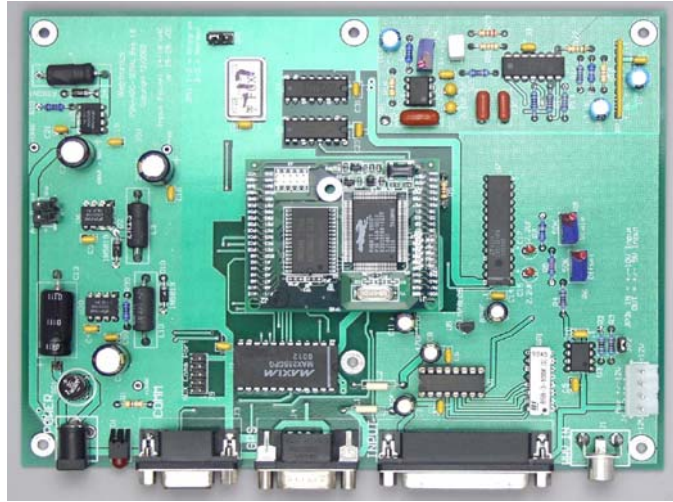
These data are displayed below.



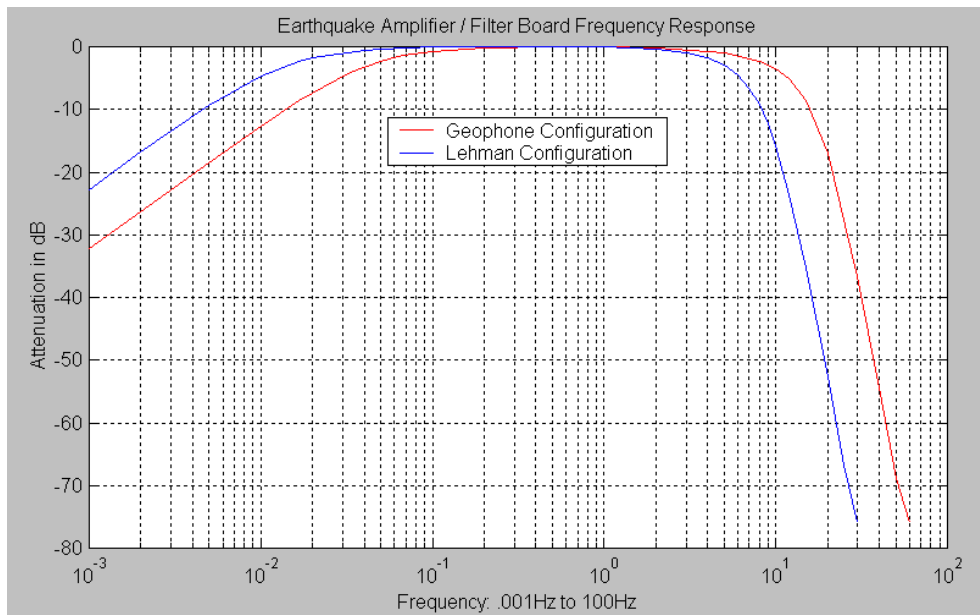
This voltage versus time plot was recorded with the GNUsound program in Linux, and analyzed in Matlab. The Y axis is arbitrary, but it is proportional to the voltage at the microphone input. The X axis spans 4.3 seconds. There are three separate slaps of the exit pipe, producing a DC pressure wave, which dies down with a decay constant of $3.85 \text{ seconds}^{-1}$, implying a Q of 5, inconsistent with the theoretical determination of 45.

Infrasonic Measurements:

Testing this system at infrasound frequencies was achieved with an adapted audio condenser microphone, and a seismometer A/D board borrowed from Larry Cochrane of Webtronics.



The microphone required some work, but the A/D board was originally designed for amateur seismometer data acquisition, so the frequency response was well suited for infrasonic measurements at 3 Hz. The frequency response of the amplifier that accompanies the A/D board is presented below (Cochrane 2003)



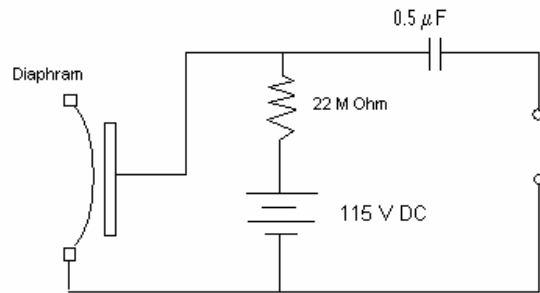
(The Lehman and Geophone configuration differ in that one can detect differentiate different types of seismic waves, and has a lower range. This data treats the seismic detector and A/D board as an entire system for the frequency response.)

The microphone, a Samson Audio C01 condenser mic, is similar in design to the microphone schematic on page four, except that the capillary leak probably vents to the outside air (it is difficult to be sure, the company could not give me engineering information) and it is smaller. The American Institute of Physics Handbook of Condenser Microphones (1995) suggested plugging up the capillary to dramatically increase the acoustic resistance and improve the low-frequency performance. Sticky tack was used on the back of the diaphragm to do just this.



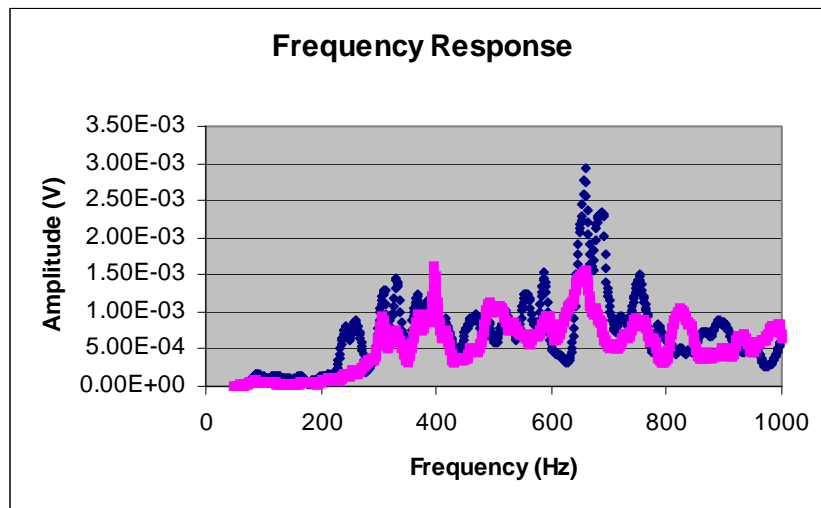
The diaphragm is the circular gold object near the center. The front is facing up, and the sticky tack is on the bottom. This is not the only modification to extend the frequency range of the microphone. The audio circuitry that came with the mic cuts off sounds lower

than 20 Hz, so a new circuit was made with capacitance and resistance values tuned to allow a 3 Hz signal to be unattenuated.



The large resistance prevents high amperages from passing through the diaphragm, and the signal rides on top of the DC 115 volts which is blocked by the capacitor so that only the AC signal is detected across the leads on the right. This configuration is similar to a high pass filter, but the 3dB point of the circuit is $f = 1 / (2 \pi 22 * 10^6 0.5 * 10^{-6}) = 0.01$ Hz, safely below 3 Hz.

The (high) frequency responses of this system as measured with the Hewlett Packard 3562A dynamic signal analyzer and a conventional audio speaker are presented below.



The pink corresponds to measurements taken without the tack on the diaphragm, and the blue corresponds to the same measurement using the tack. The response was measured by slowly sweeping a sinusoidal signal through the speaker, and measuring the rms voltage at the microphone. Note that the blue's lowest peak is ~50 Hz lower than the pink. This confirms that the tack does improve the low frequency response. The falloff after ~250 Hz likely does not imply that infrasound frequencies are severely attenuated through the mic since signals can still be detected even after going through a low pass filter at 10 Hz. The peaks are likely resonances in the room.

Detectability:

Of particular interest is whether or not the setup actually has the ability to detect infrasound. A few calculations can shed some light on this question. First, the microphone sensitivity to pressure (V / Pa) is given by

$$M = \frac{E}{h} \frac{(1 - b^2 / 2a^2)}{(1 + (C_i + C_s) / C_{to})} \frac{a^2}{8T}$$

(Wong and Embleton 1995) Where E is the voltage across the diaphragm, 115 V in my case, h is the distance between the diaphragm and the back plate which is still a mystery according to Samson Audio phone operators, I assume 25 microns from the typical values given in the AIP Handbook of Condenser Microphones. The radius of the diaphragm is a, and is 9.5mm according to the owners manual of the CO1. The radius of the back plate is b, and the optimum value for b/a is 0.8165 for best signal to noise (AIP) so assume b = 7.756 mm. C_i and C_s are stray capacitances around 1 pF each, and C_{to} is the average capacitance of the diaphragm which was measured to be 40 pF. The tension, T, can be determined from the resonance of the microphone. The published frequency spectrum for

the mic has a peak at 6 kHz, which is a mechanical resonance of the diaphragm. This resonance is given by

$$f = \frac{2.408}{2\pi a} \sqrt{\frac{T}{\sigma}}$$

(Wong and Embleton 1995) where σ is the mass per unit density of the diaphragm.

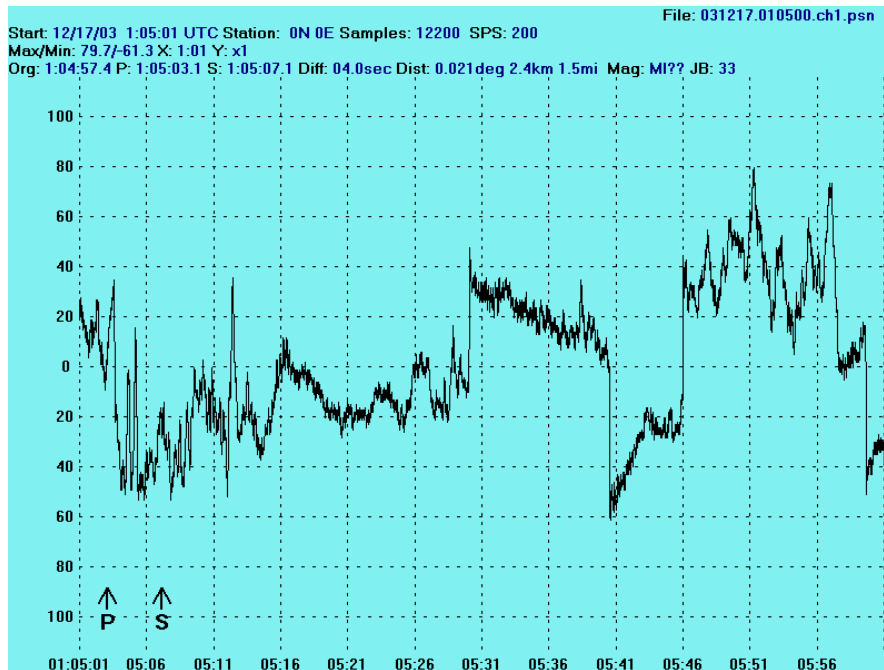
Assuming the diaphragm is made of nickel, $\sigma = 0.0267 \text{ kg/m}^2$. This gives a tension of 590 N/m. Finally, putting these together, the sensitivity is $M = 55 \text{ mV/Pa}$, which is

actually higher than the standard case of 30 mV/Pa (at 200V) from the AIP handbook.

This is likely due to the lower tension, since the standard case has a tension of 2000 N/m or from the audio mic having a thinner diaphragm than the scientific mic, and thus can react to pressure more easily.

This sensitivity is in addition to the gain from the Q of the tank. This places the level of the high amplitude infrasound waves, 0.1 Pa well within detectability as long as there is not an overwhelming background of wind or other effects.

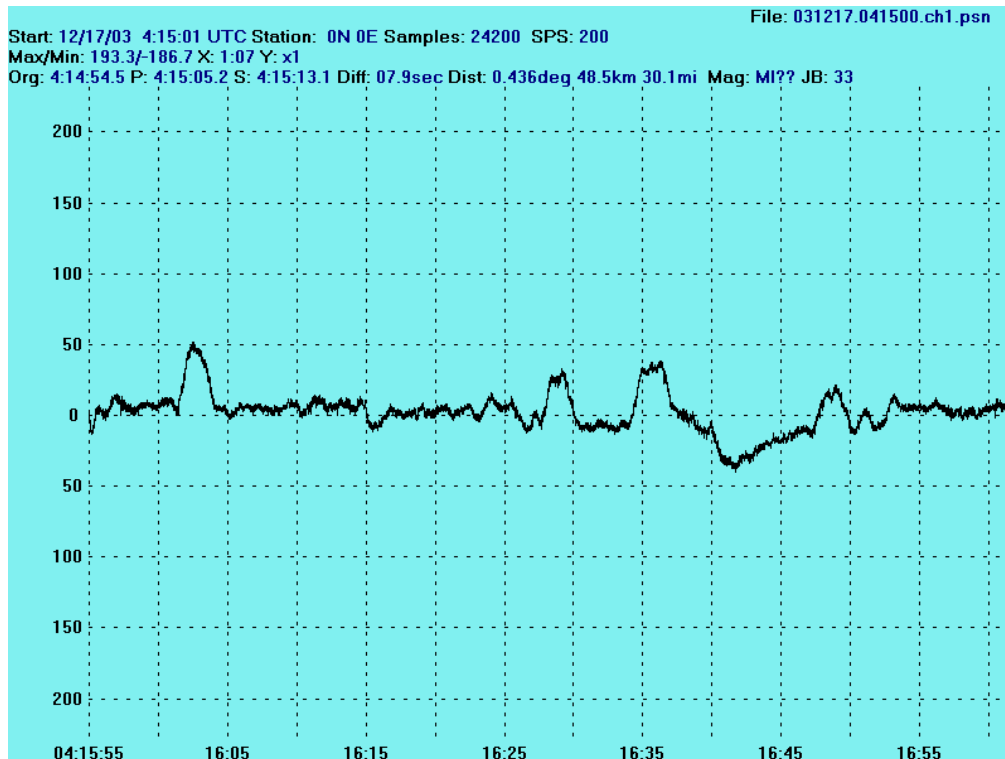
Before the tank, microphone and A/D board were used in unison, the mic was tested by slamming the door to the lab room to cause a pressure change similar to an infrasonic signal. The data and results of this test are presented on the next page.



The left half of this microphone voltage with time plot is just from walking around the experiment, but the right has two door slams which occurred at 5m31s and 5m46s. The sharp jump is the principal indicator that the signal is not just random noise or interference. Although MHz radio waves were easily filtered out, there was particular difficulty with interference from other radio sources since walking around the setup would change the radiation field and cause large fluctuation at the A/D board as seen in the left half of the plot. All conclusive measurements mentioned here were taken while standing completely still.

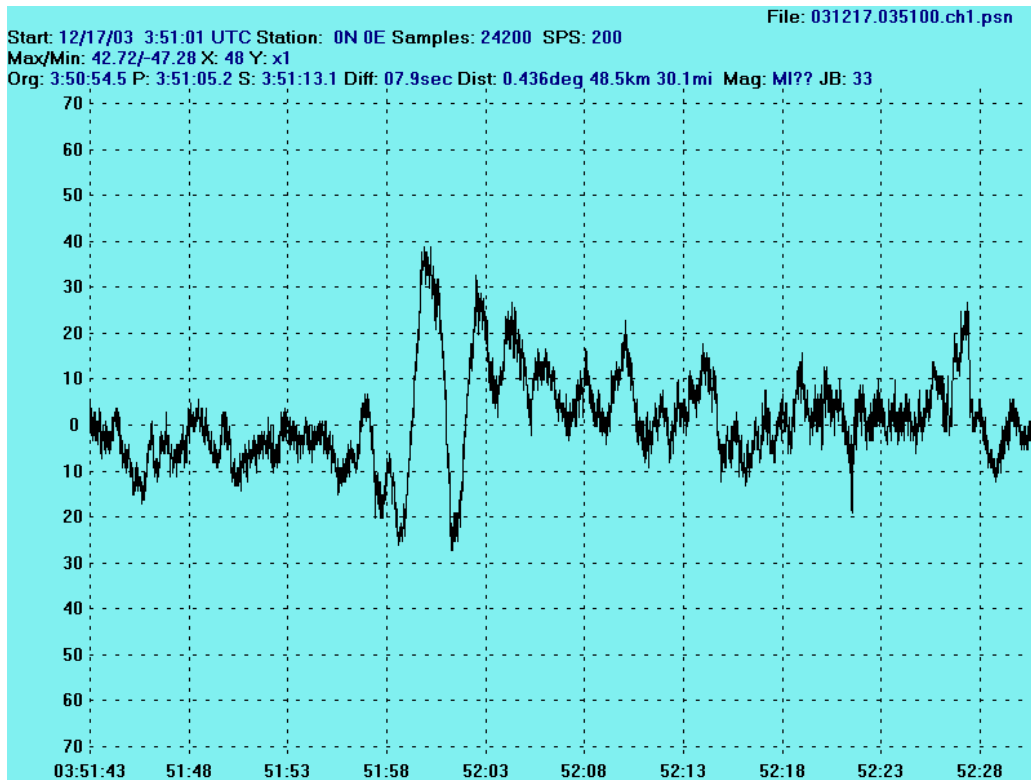
Data:

The entire system was operated for about an hour. A few periodic events were seen, and the resonance of the tank was tested similarly to the method with the conventional microphone discussed in the “Alternate Approach” section. Those measurements appear below:



The first three large peaks are the resulting signals from hitting the tank and watching the decay. The exponential fit to the decay of the second peak, gives a time decay constant of 0.71 s^{-1} (and an R^2 of 0.95), which implies a Q of 25 for the tank. This is encouraging since the empirical value determined with the conventional mic and laptop recording indicated a Q of 5. The new measurement suggests that the tank is a strong resonator of 3 Hz waves. The previous result may have been due to high frequencies dying out faster than lower frequencies.

Another interesting signal in these data lies after the 3rd hit. After I hit the tank, I noticed that the wind picked up for a few seconds and died down. It seems to have caused the signal, which looks sort of like the impulse of the hit and the fall off, but there also seems to be a sinusoidal decay after the hit. This particular signal was seen four times in eight minutes of data. The one with highest amplitude appears below:



There obviously seems to be some sort of sudden jump in the signal, then instead of decaying exponentially, the signal decays with sine like variation. The tank's resonance is 3 Hz, so the period of waves that it amplifies is 0.33 seconds. The peaks of the sine waves indicate a period of about 2.5 seconds, so it is unlikely that this is an effect of resonance. This signal is likely related to the wind as well, but it is definitely worth more investigation.

Conclusions:

Although using Helmholtz resonators to detect infrasound is not a new idea (Procunier 1971), technology has improved so that all of the data acquisition can be accomplished with an A/D board and a laptop rather than a large mainframe sized device used in previous studies. (Bedard and Cook 1971)

The goal of this project was to detect infrasound for as cheaply as possible. Success with the microphone system and the indications that the tank is a strong resonator are enough to keep optimism high that this type of measurement can be rediscovered. At present there are no infrasound observatories in the midwest.

Much work still needs to be done. In particular, interference from ambient radio sources are a huge problem, the microphone may be improved further by housing it in a compartment similar to the professional infrasound observatories, and more data can be taken to determine exactly how much of a problem that wind will be for these measurements.

An overwhelming majority of the work presented here, and all of the data, were conducted this semester. This project was started for Engineering Open House 2002 with the Audio Engineering Society. They still have an interest in it, and I hope to finish it with their help before I graduate in May 2005.

References:

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