Measuring the Seismic and Acoustic Time of Flight – Lessons in Earthquakes and Thunder

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Introduction and Equipment

When teaching the fundamentals of waves and wave propagation, students must appreciate and understand that different waves travel through different materials at different speeds. We describe simple experiments to explore acoustic wave propagation through the ground and the air and how to use those observations to locate the source of the waves. The experiment that can be performed with geophones, a microphone, and an oscilloscope.

While performing this activity students will learn important skills such as collecting real data, dealing with uncertainty, and critical thinking about the results of each experiment. This activity also connects to basic engineering skills and can be extended to encompass basic circuits and electromagnetism. Data analysis can be done with paper and pencil, spreadsheets, or with tools such as Python, R, MATLAB, or Mathematica.

Many physics classrooms will already have much of the required equipment, but all of the materials can be purchased for approximately $500, with $400 being for the oscilloscope that can be repurposed and reused in many basic science experiments.

Geophone

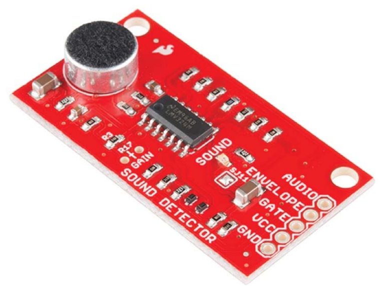
* Measures the velocity of the ground

* Outputs an electrical voltage proportional to the velocity

* Commonly used in oil and gas survey operations

* Can detect local earthquakes or quarry blasts

Microphone



* Measures the rapid air pressure changes that make up sound waves

* Outputs and electrical voltage proportional to the pressure

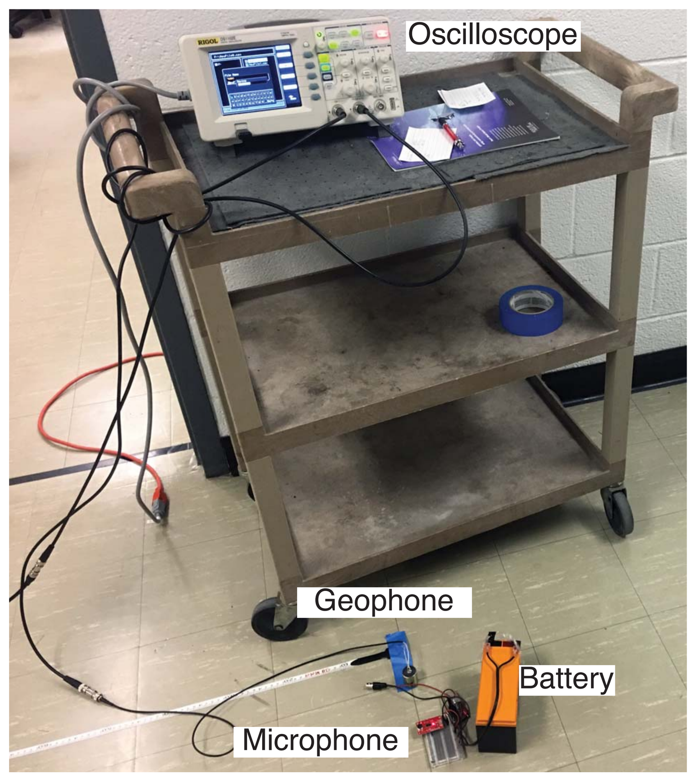
* Similar to microphones used to record audio or in cell phones

* Amplified to be able to detect quiet sounds

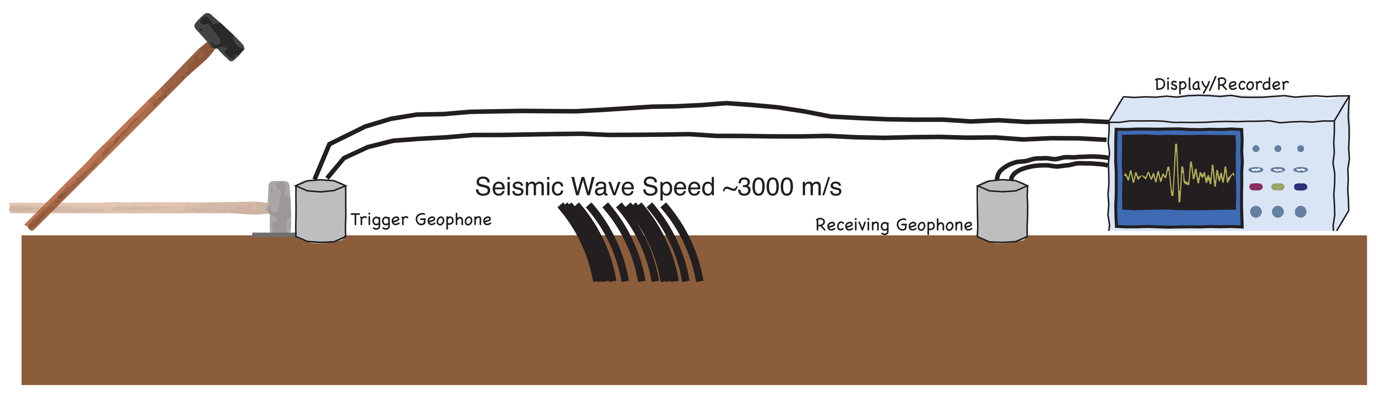
Equipment:

* Geophones (2)
* Microphone and amplifier
* Oscilloscope
* USB Thumb Drive
* Tape Measure
* BNC Cables
* Hammer

This equipment can be purchased from SparkFun electronics. Part numbers SEN-11744, SEN-12642, and BOB-07370.



Activity 1 - Determining Velocity



Setup

Place one geophone near the oscilloscope and stretch out the tape measure from that point. This geophone will be called the receiving geophone. Place another geophone at the 20 m mark of the tape measure. Connect the geophones to channels 1 and 2 of the oscilloscope and setup the scope to trigger on the rising edge of the trigger geophone. Make sure that both channels are AC coupled in the settings of the scope.

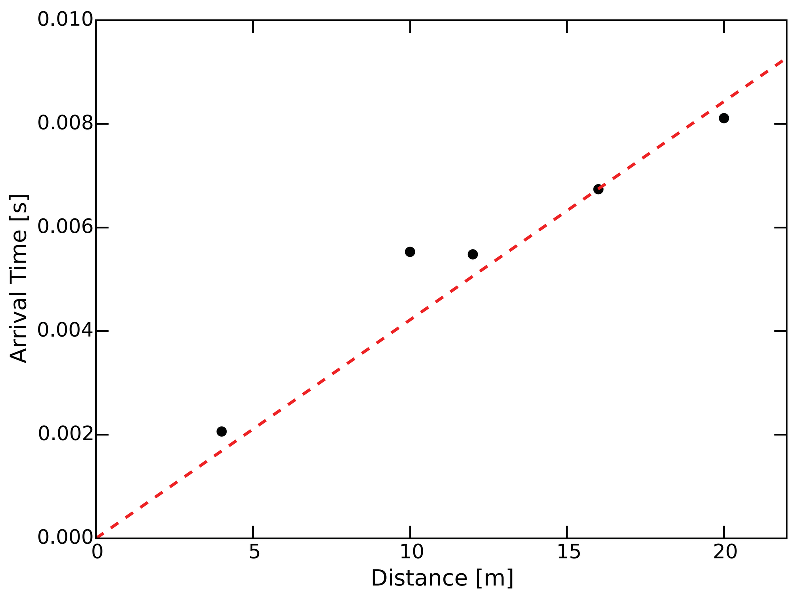
Procedure

Strike the hammer at the 20 m mark and save the data from the oscilloscope onto a USB thumbdrive. Repeat this every 2 or 4 meters to build up a dataset of 5-10 hammer strikes. Try to be consistent with the energy in each strike. Dropping a heavy piece of pipe from 0.5 m also works well as long as the pipe is quickly caught after it bounces off of the floor.

Analysis

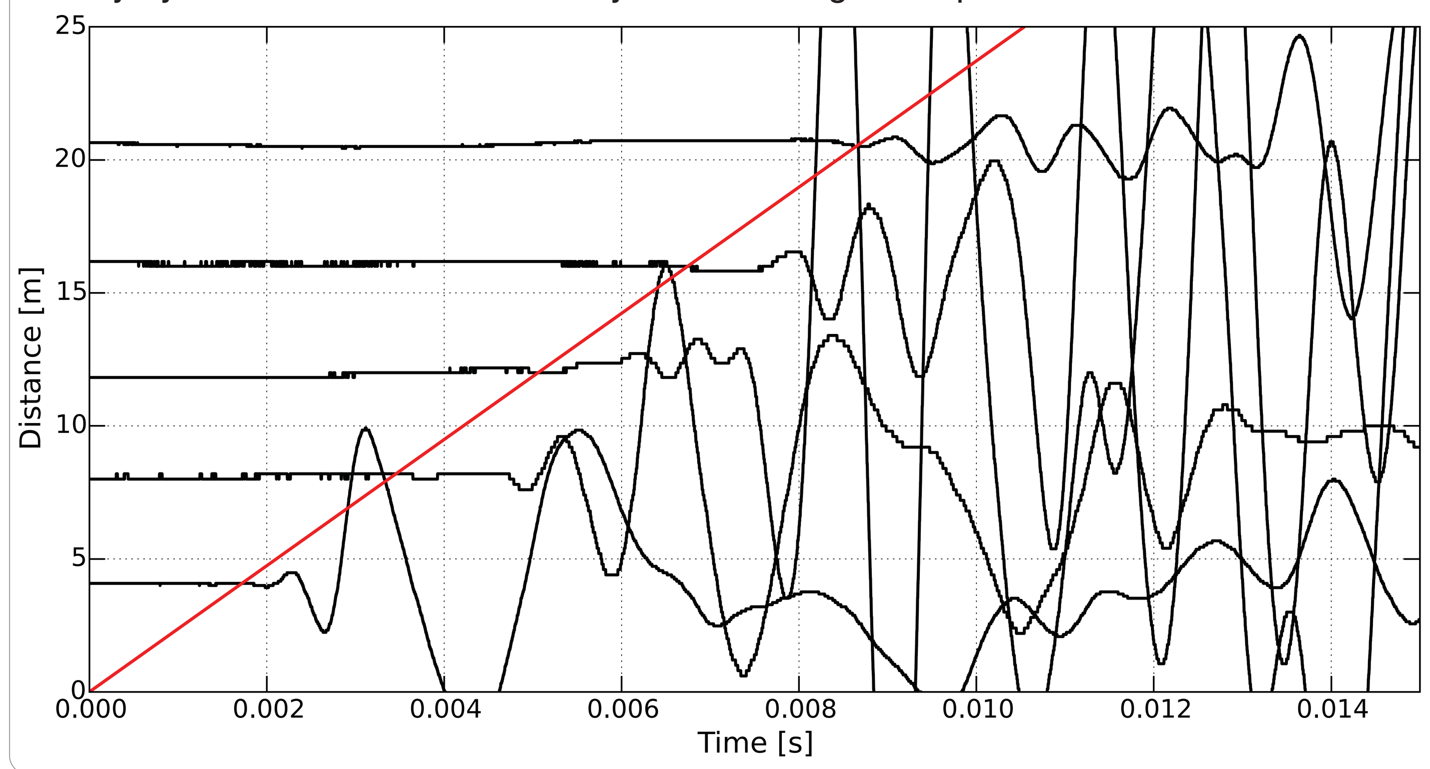
Make a plot of each geophone trace and pick the "first motion", or where the signal begins to swing away from the average. This is when that geophone received the first bits of energy from the hammer strike. Calculate the time the energy took to get from the trigger geophone to the receiving geophone:

$$t_{\text{travel}} = t_{\text{receiving}} - t_{\text{trigger}}$$

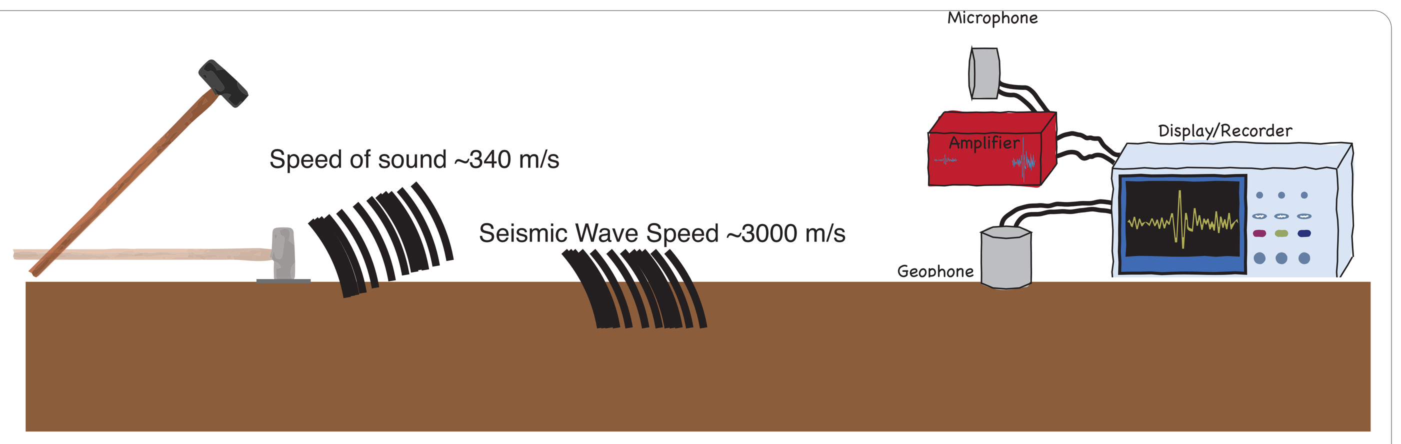


Make a plot of the travel time vs. the distance between the geophones. Fit a link, by eye or with a computer, to the data points. The slope of this line is the slowness of the ground. Calculate the reciprocal of the slowness to determine the velocity of the ground. The plot at the left indicates a velocity of approximately 2400 m/s.

Teachers can also make a plot showing each receiving geophone trace as a time-series with the y-offset representing the distance between geophones. Students can then fit a line by eye and determine the velocity without using a computer.



Activity 2 - Travel Time Differences



Setup

Place one geophone near the oscilloscope and stretch out the tape measure from that point. Connect the geophone to channel 1 on the oscilloscope. Connect the microphone break out board to a 5 VDC power supply and connect the audio input to channel 2 of the oscilloscope. Make sure that both channels are AC coupled in the settings of the scope. Trigger the data acquisition from the geophone's rising edge.

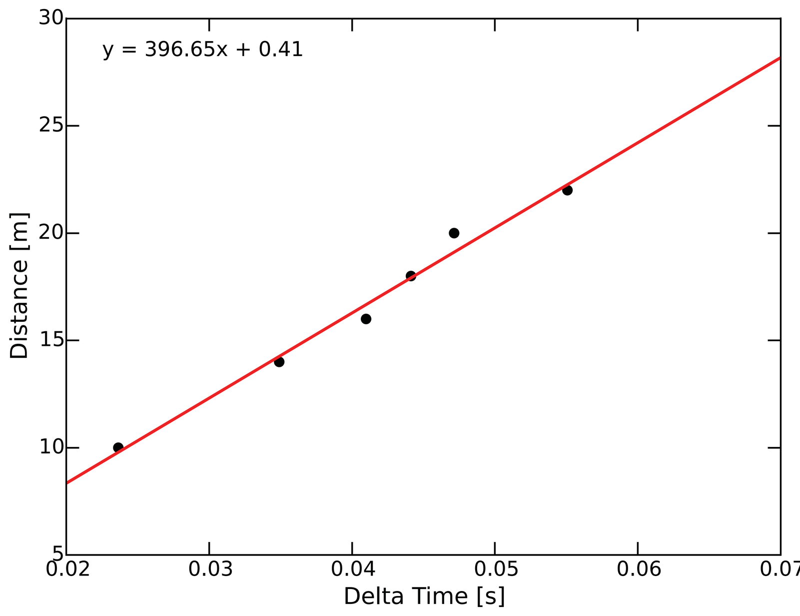
Procedure

Strike the hammer at the 20 m mark and save the data from the oscilloscope onto a USB thumbdrive. Repeat this every 2 or 4 meters to build up a dataset of 5-10 hammer strikes. Try to be consistent with the energy in each strike. Dropping a heavy piece of pipe from 0.5 m also works well as long as the pipe is quickly caught after it bounces off of the floor. Finally, have a student strike the hammer at a random distance which only they know.

Analysis

Make a plot of each geophone and microphone trace and pick the "first motion", or where the signal begins to swing away from the average. The sound wave travels slower than the p-wave, so we can calculate the difference in their arrival times:

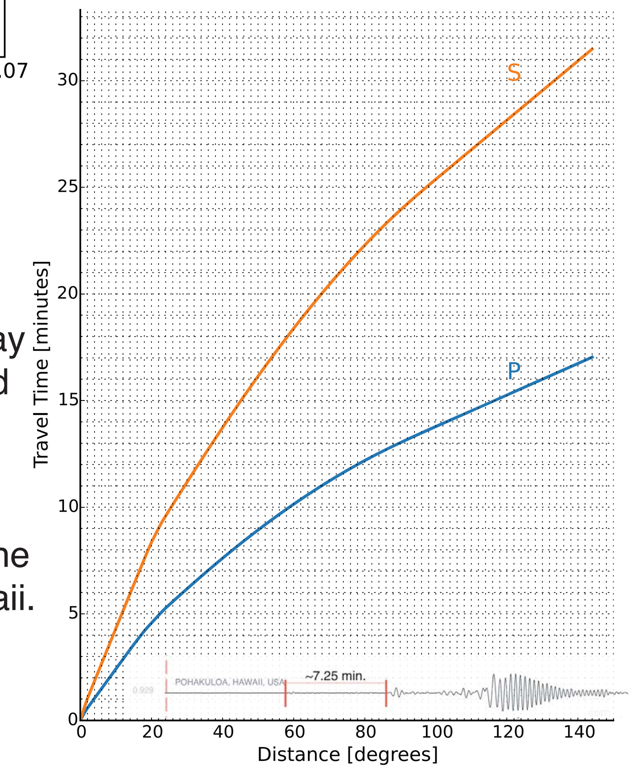
$$\Delta t = t_{\text{microphone}} - t_{\text{geophone}}$$



Plot the travel time difference vs. the distance for all of the strikes with a known distance. Using this plot, estimate the distance to the unknown strike. Verify this estimate with the student. Discuss how this could be useful and why the line is straight. Can you think of situations where this would not be true? Are their outliers in the data?

This is the same way we can quickly estimate the distance from a seismic station to an earthquake. The P and S waves travel at different speeds, so by measuring their arrival time difference we can determine how far away the event way. Look at the plot to the right and determine how far away the earthquake was from the station. Why are the lines curved?

This even occurred near the Fiji islands and the seismometer was located in Pohakuloa, Hawaii. Is your estimate reasonable? Using a globe determine the actual distance between the earthquake and the seismometer.

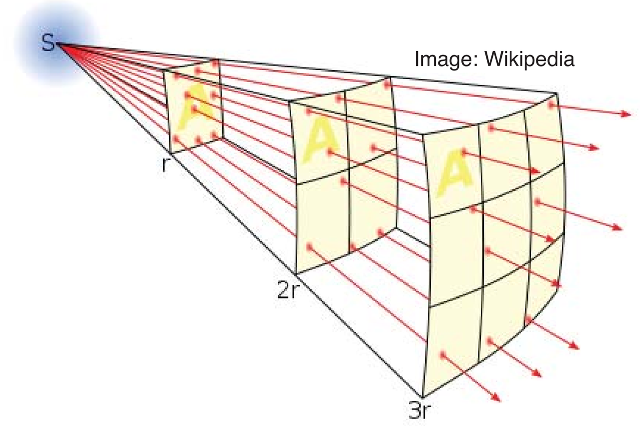


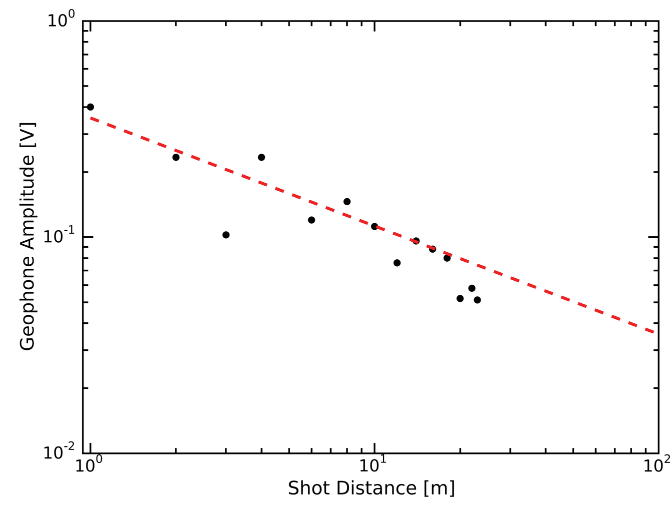
This travel time difference is much like that observed when we see lightning. The light travels to our eyes much faster than the sound can travel to our ears. By determining the arrival time difference, we can estimate how far away the lightning was.

Expansion Opportunities

Amplitude Analysis

The amplitude of body waves, such as P-waves decreases with the square of the source-receiver distance because the same amount of energy is spread over an increasing surface area. A similar decrease with the square of the distance can be observed in light intensity, sound intensity, and even gravitational acceleration.

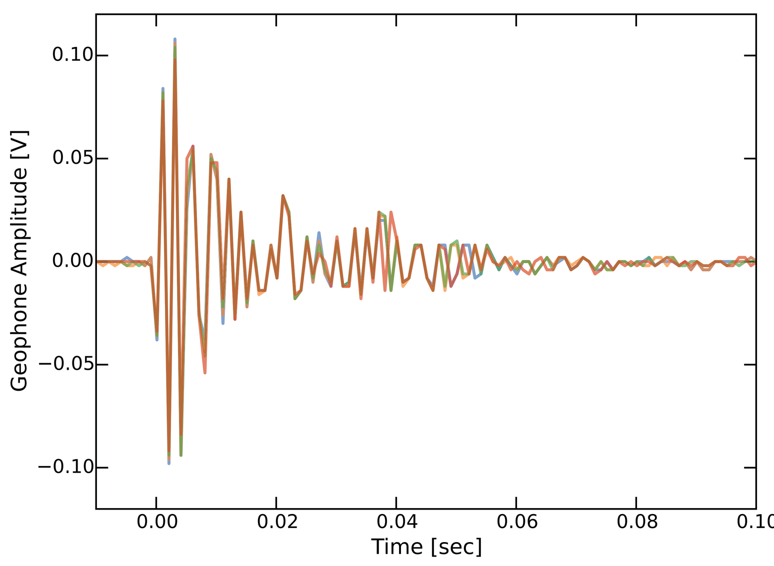




Plotting the maximum amplitude of the entire waveform as a function of the logarithm of distance shows this decrease clearly. On a log-linear plot like this, the squared fall-off appears as a line with a slope of -0.5.

Reproducibility

To see how reproducible each strike was, we dropped our weight from 0.5 m at a distance of 10 m from the receiving geophone four times. The waveforms are remarkably similar.



Sonification

The recorded audio waveform can be played back, just like normal recordings and we hear the sound of the strike. We can also play the geophone data back as a sound. Scientists do similar processing and can play earthquakes back as sound. Scan the QR codes to hear the sounds of the experiment and from a real earthquake.

Microphone Sonification

Geophone Sonification

2011 Tohoku Earthquake

MEMS Accelerometers

We also recorded our hammer strikes with a MEMS accelerometer, similar to those found in cell phones and other consumer electronics. The accelerometer was hooked to an Arduino Uno and data stored on an SD card. Using the example code from Adafruit Electronics, the accelerometer was only able to record at about 65 Hz, resulting in significant aliasing of the signal. The amplitude of the signals show that with further work, the MEMS accelerometers would likely be a viable alternative to using geophones and an oscilloscope.