Smartphone Seismology: Data Acquisition Through Consumer Available Devices

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Smartphone Seismology: Data Acquisition Through Consumer Available Devices

Research Study by: Matt Olsen

Conducted from: June 27 – August 12, 2016

Physics 4900 (2 Credits) and Geology 4900 (2 Credits)
“Science!”, is an exuberant exclamation of achievement or satisfaction in the actual results of science that can be heard in a loud comic tone from time to time throughout the Geology department. Science is also defined as, “knowledge about or study of the natural world based on facts learned through experiments and observation” by Merriam-Webster dictionary. Whether the science is Physics or Geology, Biology or Chemistry, scientists seem to get excited when science happens. But science is always happening, so scientists should always be excited and exuberant, which if math serves me correctly would definitely equal happy.

Physics is a discipline that can be difficult at times to perceive the difference between the initial idea of what is physically happening, and the subtle nuance of what is actually physically happening. Through studying physics, I have learned to make those initial observations and then dig deeper to determine if those observations are truly what is happening. Mathematics play a large role in this process, yet math often becomes a stage on which the actual science is played out, once the concepts of the math are understood and followed.

I became interested in exploration seismology while taking Geophysics 5660 from Dr. Tony Lowry here at Utah State University. In this process of learning we discussed the mathematics of how seismology is the study of sound or waves that travel through and around our Earth. The understanding of Huygens’ Principle (Figure 1), which describes how sound waves radiate out from an originating point, became a basis of the general principles of seismology. Huygens’ Principle starts with a very simple equation: \( V = \frac{d}{t} \). Here \( V \) is velocity, \( d \) is distance and \( t \) is time. For sound, the velocities are are quite high in comparison to a person
running or even a very fast car. In air the velocity of sound is ~340 m/s, while in the Earth the velocity of sound can be many thousands of m/s (m/s = meters per second).

As simple as determining the velocity of sound through the Earth may seem, there are many circumstances that can complicate this. All of these many circumstances are described by Fermat’s Principle, often called the Principle of Least Time. Fermat’s Principle states, “…the wave path between any two fixed points is the one along which the travel time is the least of all possible paths.” This describes the many paths (Fig. 2) that sound can takes through mathematics, mostly trigonometry and algebra, and includes Snell’s Law to assist in describing Reflection and Refraction.

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Huygens’ Principle and Fermat’s Principle support one another, and therefore the correlation supports that the results of either are reliable. Reliability and correlation are important principles in science. Two methods to get the same results (Fig’s 3 and 4) becomes a pattern that scientists rely on to build confidence in the results of their research and eventually their jobs.

Articles from NASA, The Department of Homeland Security as well as other agencies and organizations have led me to believe we are beginning to see a shift in computing platforms that we use for scientific data acquisition. The desktop computer and then the laptop computer have each held their place in the realm of data acquisition. The desktop still has the most power and therefore continues to be the stalwart equipment for data analysis at an office or laboratory. For a long time, the lightweight and small size of laptops combined with their near desktop computing power have made them obvious choices for field work and on the road analysis. But these small devices, smartphones and tablets, that nearly all of us have in our pockets are also finding their place in our lives and jobs.

NASA scientists have not only built a platform for smartphones to acquire data, NODE+, but have developed and launched satellites that solely use smartphones as their onboard computing and communications systems. The small size, light weight and long battery life of smartphones have made them indispensable tools all of us use as well as being ideal for the high cost per ounce of sending anything into space. Measured in billions of dollars, the market smartphones have carved out increases the rate at which their technology advances in comparison to the technology of desktop and laptop computers. Smartphones have been around for roughly 20 years, yet today they have the computing power of super computers 20
years ago. This is because of the money driven technology advancements smartphones demand through their market power.

Technology is what makes smartphones intuitive for consumers to use. Gyroscopes allow the aspect ratio to automatically adjust depending on the orientation the user is holding it in. Accelerometers allow smartphones to determine if the device is in motion, how fast and even count footsteps to determine distance traveled and compute statistics about our health and progress made. Apps allow these bits of tech inside our smart devices to do what we want them to do, and how they do it. Platforms like the NODE+ allow the tech to be outside our phones, but use our phones through other tech like Bluetooth that was also developed to make these portable small devices even more useful, to display the data acquired through the NODE+ on our smart devices.

This got me wondering, “Could the technology in smart devices, like accelerometers be used for exploration seismology?” And, “Could apps themselves be used to use the technology in smart devices for exploration seismology.” These questions, along with the all-important student budget became the focus of my research. Here is how I researched these questions to find answers, and ultimately, “Science!”

Exploration seismology is done much like the diagram in Figure 2. Of course this is a simplified version of how calculations are made for exploration seismology, but the simplicity of the equation $V = \frac{d}{t}$ combined with determining the path taken is how exploration is done using seismology. Simply, a hammer can be used to strike a metal plate, transferring the energy of the hammer into the ground upon which the metal plate sits in the form of sound as a wave. This wave travels through the ground following the Principles discussed earlier until it is
detected by a device known as a geophone that has been placed a known distance from where the hammer started this event. The timing of this whole event needs to be done very precisely, from the exact moment that the hammer strikes the plate to the moment that the wave arrives at the geophone will only be a few milliseconds.

A millisecond represents a 1000 seconds. Likewise, a microsecond represents 1000 milliseconds. Also, if an event happens a certain number of times per second, or, say a sample is taken once every second, we call this relation a hertz or Hz, for the frequency at which this relation happens. This can be written like this: \(1Hz = \frac{\text{# samples}}{\text{time in seconds}} = \frac{1\text{ sample}}{1\text{ second}}\). But different powers of time and samples can also be compared, for example: \(\frac{1000\text{ samples}}{1\text{ second}} = 1000Hz = 1\text{KHz}\) and likewise, \(\frac{1,000,000\text{ sample}}{1\text{ second}} = \frac{1000\text{ samples}}{1\text{ millisecond}} = \frac{1\text{ sample}}{1\text{ microsecond}} = 1,000,000\text{ Hz} = 1000\text{KHz} = 1\text{MHz}\).

Sound waves travel so fast through the Earth, a minimum of \(~340\text{ m/s}\), that recording of when these events begin and are detected needs to be to the millisecond to see all the data. Imagine trying to take a picture of a bullet in midflight with just a regular camera. Although you might be lucky enough to press the shutter button at just the right moment, the photo will likely be blurred and the bullet just a streak due to how long the shutter is left open and how many times you can press that button. But if you can press the button fast enough, and get enough pictures in a small amount of time, you just might get a clear picture of that bullet in midflight. Exploration seismology is like taking a picture of a bullet, you need to get enough pictures in a short amount of time to know if you got a picture of that sound wave. More pictures make a clearer picture.
“Pictures” for electronic equipment are called samples, or sample rates, and these samples are electric signals sent back to a receiver which is often a computer or microcontroller. A microcontroller is similar to a computer but does not have a graphical user interface operating system similar to the desktop that one would find on most computers. Because of this, it poses less problems to work with because the protocols of an operating system don’t get in the way. Simply write code, upload the code to the microcontroller and it executes that code. That is all it does, the code that it runs is its only purpose, but that purpose can be changed with code. There are many kinds of microcontrollers, which are often lumped together under the slang term Arduino.\(^5\) Arduino is both a company’s name and the computer code language used to write code for the microcontrollers.

All electronic sensors send data back to a central recorder in the form of electric signals in the form of values for voltage or current. These values are produced in a number of ways. For the geophone, the current is produced by movement of a coil spring about a cylindrical magnet at its center. The spring coils around the magnet, and current is pushed either to the positive (red) or negative (black) lead based on if the coil moves up or down in relation to the magnet (Fig. 5 and 6).

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Often many geophones are placed a predetermined distance from the source of the wave, which can be a hammer or many other sources. The geophones are evenly spaced from each other in a straight line so that the time between each distance can be accurately know in relation to the traveling wave. The data is recorded and often displayed as a trace of the data for each geophone in order and in relation to time (Figure 7). This process that produces a current in a geophone is known as Electromagnetic Induction.

Accelerometers sense motion through electric charge produced by a different process. Some crystals and other materials produce an electric charge when a pressure or mechanical force is applied to them. This is known as the Piezoelectric effect which is derived from the Greek piezein, which means to squeeze or press, and piezo, which is Greek for “push”. There are also piezo films that when bent or deflected produce a charge. In a smartphone these crystals are encased in silicone and placed on a chip. The crystals are “grown” in an environmentally controlled lab to produce a uniform, and consistently reproducible crystal. Much like a fast car or roller coaster presses you into your seat, accelerometers produce an electric charge from the pressure of motion, or changes in the constant forces of gravity. Because they detect these changes in the force of gravity, gravity is also the unit of measure for accelerometers in gravity or G-forces. A G-force is 9.80665 meters per second squared or equivalently 9.80665 newtons of force per kilogram of mass.
Smartphones and tablets are everywhere these days. Seismic apps also are not it short supply, and range in price from free upwards of $50.00, most cost about $1.99. I had planned to compare a paid and free app to determine the usefulness of these apps. But there is a common difference between most free and most paid apps. Data. Most free apps provide a snapshot of the trace lines collected while recording data in the form of a photo saved on the device. Most paid apps also provide this snapshot but it is accompanied by the actual raw data that can be sent as a .txt or CVS file from within the app. This access to the raw data makes the paid apps much more useful for exploration seismic as travel times and velocities can be determined from this information. The free apps on the other hand would not be useful, as a lot of processing and analysis would need to be done and at best this would still be speculation if derived from a snapshot photo. Because of this I did not use a free app.

Accelerometers are also available on small electronic boards known as breakout boards. These boards allow the user to connect the devices to microcontrollers and computers to record the data these sensors detect. There is a wide range of sensors and prices, but I chose to stay within a student’s budget and didn’t spend over $50 on any single sensor. I chose the MMA8451, ADXL377 and the BNO055 accelerometers. The ADXL377 never actually worked for collecting data, so although I did get this sensor I will not discuss it any further. For collecting data from an actual geophone I used the INA219 current sensor (Fig. 8).

Figure 8: Pictured from Left to Right, MMA8451, INA219 and BNO055
Each one of these devices is smaller than a quarter (Fig. 9) but each is also capable of collecting data useful for exploration seismology. The specifications of each sensor are listed in Table 1.

![Figure 9: Sensors size comparison with quarter](image)

<table>
<thead>
<tr>
<th>MMA8451</th>
<th>BNO055</th>
<th>INA219</th>
</tr>
</thead>
<tbody>
<tr>
<td>• ±2 / ±4 / ±8 g Accelerometer</td>
<td>• ±2 / ±4 / ±16 g Accelerometer</td>
<td>• 26V / ±3.2A</td>
</tr>
<tr>
<td>• Max Data Sample Rate: 2.25MHz</td>
<td>• Max Data Sample Rate: 1.95 MHz</td>
<td>• Current Sensor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Adjustable 1kHz-8Hz Filter</td>
</tr>
</tbody>
</table>

*Table 1: Features and Comparison of Sensor Breakout Boards*

Table 2 lists the features of the microcontroller used and the addition parts, as well as pricing for parts and a total.

<table>
<thead>
<tr>
<th>MMA8451</th>
<th>BNO055</th>
<th>INA219</th>
<th>Precision RTC</th>
<th>Prototype Board</th>
<th>Vibration Switch</th>
<th>Total:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adafruit Feather M0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$104.65</td>
</tr>
<tr>
<td>Datalogger</td>
<td>$21.95</td>
<td>$7.95</td>
<td>$34.95</td>
<td>$9.95</td>
<td>$13.95</td>
<td>$14.95</td>
</tr>
<tr>
<td><em>• 48 MHz Arm Cortex Processor</em></td>
<td></td>
<td></td>
<td></td>
<td>Real Time Clock</td>
<td>OR</td>
<td></td>
</tr>
<tr>
<td><em>• 256 KB Flash / 32 KB RAM</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$8.95</td>
<td>$99.65</td>
</tr>
<tr>
<td><em>• 3.3V Operation</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>• Built in SD Card Read/Write</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 2: Bill of Materials List and Total Cost*
The total cost varies based on the use of two versions of a RTC (Real Time Clock) add-on board often called a “shield” in the Arduino community or a “wing” in the realm of Feather products. The Precision RTC ($13.95) has an onboard thermistor to modulate the time based on temperature which alters the oscillation frequency of the time crystal, and the alternate RTC ($8.95) includes a SD Card Read/Write which is also on the main microcontroller Feather Datalogger.

Microcontrollers simply run the code that is uploaded to them, but that code has to come from somewhere. In the case of many electronics today, and nearly all breakout boards, code is often provided by the manufacturer or can be found at online repositories like the popular GitHub. In the case of the sensors used in this study, the operation code for the sensors was provided by the manufacturer and retailer, Adafruit Inc. But in order to record the time between a source wave production and sensor detection, code needs to be written to initiate the recording of the event. This is what the little Vibration Switch (Fig. 10), or Trigger is for. Code was written that determined if the trigger had completed or closed a circuit. If the circuit is open, nothing happens, but when the circuit is closed the microcontroller begins counting the time in relation to the data the sensors are reporting at that time. The circuit is closed when the spring around the central pin is deflected or bent and touches the pin in the center. This happens by taping the trigger to the sledge hammer near the head of the hammer. When the hammer hits the metal plate, the force of the impact

Figure 10: Vibration Switch or Trigger and cutout Internal View

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will cause the spring to bend and touch the central pin, thereby closing the circuit.

The RTC gives the ability to time stamp, or mark the date and time that the event begins and append this to the data set. Sound travels very quickly through the earth and in as little as 3 seconds at 400 m/s could as much as 1200 m from where it began. More than enough time to record a lot of data. As part of an Event Timer function, I set the time that the microcontroller would record the data set to 3 seconds. Every microcontroller has a built in function to count time from the moment that it is turned on in milliseconds. The RTC does not perform this function, but can, but this function of any microcontroller will continue even if the code written does not use this function. Figure 11 shows a sample of the code written to operate as a timer function.

As I wrote the code and tested it I did this on a breadboard with an LED that served as the sensor input to let me know it was working. As I did this I noticed the fastest that the microcontroller could read and execute the code was once every 3 milliseconds. I edited and cutout unneeded lines of code to reduce this to once every 2 milliseconds, but this was before I adding the sensors

Figure 11: Code to function as a Timer with time/date stamp and Serial Monitor output

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operations code. When the sensor operation code was added, I again had to edit and reduce the operations of the code to maximize the sensor data sample rate to get as many samples as possible per second, or millisecond. After cutting back the time as much as possible, I was able to achieve one sample every 3 milliseconds. Not optimal, as I wanted a sample rate of 1KHz. To achieve this rate I was not able to utilize the functionality of the on board SD card to record the data. Most microcontrollers have a built in function to output data to what is called a Serial Monitor. What this really is, is another computer, in this case my laptop that I am uploading the operations code to the microcontroller with. The output of the microcontroller to the serial monitor can be seen in the right hand half of Figure 11.

With the code written and working it came time to make the sensors into geophones. I did this with 3D Printing by making models of the geophone housings for each sensor in software designed for digital engineering (Fig. 12).

These models were then digitally sliced into layers so a 3D printer could assemble, or print, these layers to create a physical model. These physical models make the geophones, (Fig. 13) current sensor as well as the Feather more durable and able to withstand the rigors of being in the field and collecting data. For the Feather, it provides a platform to organize and secure
connections that will need to be changed for each sensor. Each of the geophones included embedded hardware, which is placed during the printing process and then printed over and into the final printed model.

Because these sensors need to be changed to allow each to be tested and data collected I decided to make this process less of a problem by using quick and easy to connect/disconnect Ethernet cables. I also used this same idea with the trigger switch by placing it on a telephone cable with its similar to Ethernet connection style. Ethernet CAT5 has 8 lines of power or communication that can be utilized. Each of the sensors needed the same 4 connections for Power (orange), Ground (brown), SDA (data, blue) and SCL (data, blue stripe). The INA219 current sensor also required an analog battery reference power and ground for a total of 6 out of 8 lines used on the Ethernet cable. While setting up the wiring connections the ADXL377 would have used two more lines had it been used, or 8 out of 8 lines used.

Geophone and sensors housings made it came time to collect data. I collected data in my front yard after attempting two previous times in the field, only to return without data to problem solve issues I encountered in the field. I measured out a straight line, and placed small green flags at each meter from the origination point. At this origination point I placed an 8 inch round metal plate (Fig. 14). I placed my geophones and current sensor at 5m to 12m and collected 5 sets of 3 second (3000 millisecond) data at each of these 8 locations. At each set of
data collection I also placed an iPad running a paid for app called “myVibrometer” ($1.99). This collected 3 times more data for the app than any single sensor. The app has a limitation of not having a trigger to start an event, so I would begin recording data with the app and then correlate it back to each triggered event initiated for the sensor in use at that time. These events occurred each time I struck the metal plate with the sledge hammer with the trigger switch attached.

The raw data when collected was plotted against time, with time on the horizontal X axis, and data on the vertical Y axis. This produced the graphs seen in Figure 15. These graphs gave little obvious detail that any seismic waves had been detected by the sensors. Consultation with Dr. Lowry and Xiaofei Ma informed me that signal processing techniques could mathematically filter out the noise of the earth and reveal the underlying signal.

The Earth is full of noise from anything in the earth and above that makes noise. Whether this noise is sound we can actually hear or just vibrations, the noise is conducted and travels very quickly through the earth. Washing machines, highways, even buildings and the
electricity they use create sound and vibrations that are noise inside the earth. Each bit of noise is like a piece of fruit in a fruit salad. When we look at a fruit salad we can see the different kinds of fruit it has in it (Fig. 16).

We can make a recipe for the fruit salad by making a list of what kinds of fruit are in the salad and how many pieces of each kind of fruit there are in the salad. If we take this fruit salad and put it into a blender and chop all the pieces up into tiny indistinguishable pieces, it makes writing a recipe much more difficult. But we already know the recipe because we wrote it down before we put it into a blender.

Mathematical signal processing filter techniques perform a similar function for noise. If we have a signal that is noisy it is hard to see how many noises there are and what kinds of noise they are, much like the fruit smoothie. But the Fourier Transform is an equation that helps us to know the recipe of the data signal by filtering each noise and letting us know how much of it there is compared to everything else. In this case, our raw data is like a fruit smoothie, and we want to know what it would look like as a fruit salad. The Fourier Transform can do this.

The Fourier Transform: \(X(j\omega) = \int_{-\infty}^{\infty} x(t)e^{-j\omega t} dt\) takes data as a function of time \((x(t))\) and turns it into the real part of that same data now turned into a function of frequency \((X(j\omega))\). Here \(\omega\) is the frequency, \(j\) is the real part, and \(X\) is \(x\) but as a function of frequency, while \(x\) is \(x\) as a function of time. The term \(e^{\pm j\omega t}\) is a mathematical identity for a circle, because Fourier Transforms look at data that occur in some repeating cycle or frequency. This identity is how this process is performed. Figure 17 shows raw data plotted against time, and how this
same data appears when filtered by the Fourier Transform and plotted as a frequency against magnitude.

Figure 17: Above: Time vs Data  Below: Frequency vs Magnitude
This same process can also be done in reverse using the Inverse Fourier Transform:

\[ x(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} X(j\omega) e^{j\omega t} d\omega \]

which returns the data as a function of time from the data as a magnitude as a function of frequency. There is also a method by which each of the Fourier Transforms can be viewed as a Cardinal Sine function or:

\[ x = \frac{\sin(xt)}{xt} \]

which can assist in determining the portion of the overall signal that is the data and which part is the noise.

Performing this function once presents the data as a Gaussian distribution known as a Bessel function curve (Fig. 18). These curves are often found in nature, much like the natural noise of the earth. The central main peak is the signal that is data and knowing this frequency can assist in making a numerical filter to eliminate the noise that is all along the other much small peaks. Performing the function again such that \( x^2 = \frac{\sin^2(xt)}{xt} \) allows the data to be converted or Inverse transformed and filtered removing the noise. But these techniques are above the level of course work I have been exposed and are at this point only avenues for further study. The Fourier Transform and the Inverse Fourier are functions that can be performed in most spreadsheets like Excel and MatLab. Applying the Fourier Transform presents the data in such a way that the signal from the wave can be seen as a spiking peak that rises high above the rest of the low lying noise.

Knowing that mathematically I can filter my data from the noise of the Earth reassured me that my wave was being detected. But a part of me wanted to see that in the raw data without having to rely on filtering. ***It should be noted that both the MMA and the BNO
sensors have built in filtering functions that needed to be stripped from the code to produce better sample rates.*** I devised a method to determine without signal processing that a wave was being detected. I did this by not having the trigger start a recording event, but instead manually started the microcontroller recording and I hit the metal plate 5 times in a row. I called this the 5 Bang Test series. This produced the raw data in Figure 19.

![BNO6m5bang](image1)

![MMA6m5bang](image2)

Each chart clearly shows the 5 strikes to the metal plate (marked in red). The BNO data is less clear than the MMA, yet both have 5 clear spikes of wave detection. The iPad data stream also seems to show this data in the simple picture output of the data collection (Fig. 20). The picture output from the iPad app can be presented in 3 magnifications, 1x, 10x and 100x. The images shown are 10x, while 1x had little or no detail of discernable wave detection. Although it seems
that the five strikes on the metal plate are present in the pictures, this fact became less clear when I noticed that there are in fact 6 blips in the photos. I cannot ascertain if the app performs some amount of overlap for each photo which could explain one of the blips being in two of the individual frames of the photo series.

The results of the 5 Bang Test series confirm that my geophones are capable of detecting a hammer induced wave with the equipment that I arranged together. However the amplitude at which the wave is detected in relation to all of the background noise may be small because of the timing of when the wave is detected in relation to the sample rate of my arrangement. This limits the feasibility of using this arrangement for exploration seismology.

Figure 20: Paid App data from 5 Bang Test
Other limiting factors that I encountered included ethernet cable length. I had purchased a new 25 foot ethernet cable to enable my equipment setup to extend over a greater range. The BNO sensor continued to function properly, but the MMA sensor would not initiate communication with the microcontroller and caused the controller to reply that the sensor was not present. When the MMA sensor was placed on a 16 foot ethernet cable it began to function correctly again. This limitation of cable length is not clear, but is presumably a shortcoming of the low 3.3 voltage that the microcontroller operates at. The MMA is capable of 5 volt operation, and many microcontrollers also operate at this voltage. Further testing would need to be done to determine if this is the cause of the sensor failing while connected to a 25 foot ethernet cable.

Sample rate acquisition became the significant factor for both the apps and the hardware. The maximum sample rate for the app is 100Hz while the microcontroller came in around 300-400Hz. Preferably the sample rate would be 1000Hz or 1MHz or higher for consistent wave detection. This could be achieved with faster processing controllers or a computer. The Raspberry Pi would be a low cost replacement at $35 for the Pi 3 with a quad-core 1.4 GHz processor or Pi Zero at $5 for the single-core 1 GHz processor. Further testing would need to be done to determine if this would produce an arrangement suitable for exploration seismology.

This brings us back to the questions I originally asked that initiated this research.

Question: “Could apps themselves be used to use the technology in smart devices for exploration seismology.”
Answer: Not at a maximum 100Hz sample rate. The lack of a trigger also makes the apps difficult to use when calculating velocities because time correlation from a triggered and timed event is not part of the app.

Question: “Could the technology in smart devices, like accelerometers be used for exploration seismology?”

Answer: Yes, the sensors that the smartphone industry has produced are capable of being used for this purpose. If sample rates can be achieved at 1Mhz or higher while performing filtering functions these devices would make great geophones. Even operating without the filters at 300-400Hz, the sensors detected waves. These results can be further processed as outlined in this paper, but would be improved with high sample rates and active filtering.

The budget of a student is not much, but in this case it was enough to produce useable results from a low cost devices. Analysis of the results determined that the data was viable and could be used as is, but require further processing after being acquired. The act of asking questions and using the education and concepts of physics and geology produced scientific data. In the process of conceiving the idea, producing a plan and acquiring data, I became a part of science, and the science became a part of me. This research study may have come to a conclusion, but I know that I will continue to think upon these principles of science, and find answers to questions that the science also posed along the way.
References


https://www.arduino.cc/


