Zero-Power Seismic Sensors for Discrimination of Foot and Vehicle Traffic

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ABSTRACT

A low-power (<10 mW) analog sensor capable of detecting ground vibration (i.e. seismic) signals and identifying their source possesses significant relevance in the field of national security. Very low power consumption by the sensor will allow long-term remote operation without battery replacement. A published frequency-domain algorithm was adapted for discrimination of foot and vehicle traffic. For simplicity, the scope of the project is limited to analog circuitry, eliminating the need for digital signal processing. Various sensor designs, including geophone and piezoelectric sensors were tested for comparison. The accuracies and sensitivities inherent in the sensors were determined through observation in field testing, and these observations assisted in determining the appropriateness of the various sensors for the project at hand. The results of these tests were compared with published results. A completed low-power seismic sensors would be suitable for integration into Distributed Sensor Networks, where they can be used to monitor foot and vehicle traffic in remote areas.

1 INTRODUCTION

1.1 Background

Discrimination of foot and vehicle traffic through sensor instrumentation has the potential to be a powerful means for reinforcing national security. Such sensors can be utilized for monitoring U.S. borders specifically for nuclear smuggling as well as for maintaining secure boundaries around chemical or nuclear facilities. This tracking process would be implemented through a large-scale Distributed Sensor Network, but it would require thorough surveillance of extensive areas to be effective. For practical application, these autonomous sensors would have to operate under long-term conditions and at full duty cycle. Thus, low power consumption is a crucial design characteristic for the sensors.

Current research on the use of seismic sensors, sometimes referred to as Unattended Ground Sensors (UGS), in footstep detection indicates that geophones are particularly effective as a result of their simplicity and their high sensitivity. Geophones consist of a spring-mounted coil surrounding a magnet, generating a voltage signal in response to motion without requiring an external power source (Figure 1).

After using standard geophones to collect seismic data, Houston and McGaffigan [1] apply band pass filtering, spectrum analysis,
and two-pass split-window normalization to obtain a spectrogram of signal-to-noise values for footstep discrimination against other noise sources. This procedure resulted in a 50% detection rate at a mean range of 64 meters for normal walking.

Richman et al. [2] use a filter-based algorithm to match data to a waveform similar to that of a footstep and measure the time differences of arrival for a signal at different geophone sensors to estimate the location of the source. The step detection probability was 80% at a range of 30 meters, and the average error for location estimation was 8.4 meters.

Rutledge et al. [3] describe both particle-motion trajectories and probability testing for the seismic vehicle tracking. This work focused on the design of an algorithm to be used with in-situ processing sensors. Azimuth data, obtained from eigenvector analysis across varying frequencies, was used to determine the intersection of the direction vectors produced by separate geophones.

For Special Nuclear Material (SNM) detection, Nemzek et al. [4] simulated a heterogeneous sensor network, including a random distribution of seismic, radiation, and metal sensors as well as a mobile spectrometer, for the purpose of distinguishing benign agents from malicious agents and further for determining the presence of SNM.

1.2 Motivation

Complete seismic data analysis is presently limited to digital post-processing. If integrated into a DSN, this technique would increase power consumption of the sensors and decrease the long-term, autonomous operating capabilities of the network. However, results from previous studies indicate that the seismic approach to footstep discrimination has significant potential. The design team would like to achieve detection rates similar to the results published by Houston and McGaffigan [1] and Richman et al. [2] by developing a low-power seismic sensor that would analyze data locally through analog processing, monitoring the source path. Improvements in the processing ability of these sensors will increase their energy efficiency and ultimately assist in the development of distributed sensor networks for national security applications.

1.3 Purpose

The primary objective of this project is to design and test a sensor for detecting ground vibration capable of performing a local discrimination algorithm while using simple analog electronics to reduce overall power consumption. Considering the low-power constraint (<10 mW; <1 mW if possible), the sensor cannot process signals digitally.

Different sensors, including geophones and piezoelectric sensors, will be compared in the laboratory for detection at frequencies within an appropriate range for pedestrian and vehicle traffic. Seismic data will be obtained through field testing using a data acquisition system, various signal sources, and changing conditions, including speed of gait, amount of loading, and number of walkers. The signal will be extracted using a developed algorithm, mitigating the effects of noise by means of filtering, and results will be compared to those of Houston and McGaffigan [1] and Richman et al. [2]. Finally, a breadboard sensor will be constructed to generate a signal proportional to the Signal-to-Noise Ratio (SNR) for the ground vibration frequency of foot traffic.

2 FOOTSTEP DETECTION PROCESS

2.1 Houston and McGaffigan Algorithm

Houston and McGaffigan describe a footstep detection process based on spectrum analysis rather than one that is transient-based. This process was adapted and tailored to suit the purposes of this project. Seismic data, sampled at a frequency of 1000 Hz, are band pass filtered, rectified, down sampled by a decimation factor of 30, and analyzed using conventional spectrum analysis techniques, including the Fast Fourier Transform (FFT) and a split-window normalizer. The processing approach, shown in Figure 2, was implemented using MATLAB 7.0.1.
The band pass filter removes data with undesirable frequency content, allowing the event of walking to be detected. Although normal walking footsteps are generated at or near a 2 Hz frequency, the footsteps themselves are broadband and consist of a variety of frequency components. Houston and McGaffigan demonstrate that the majority of the frequency content in the footsteps lies within the approximate range of 10-40 Hz [1]. By removing frequencies above and below this band, the remaining data can be analyzed in an attempt to uncover the occurrence of those footsteps, which occur about 0.5 seconds apart from each other (2 Hz frequency).

The rectification (absolute value) of the band passed data identifies footstep periodicity through an envelope detection operation. Houston and McGaffigan also assert that the absolute value compensates for the effect of random phases in the footsteps and allow for the coherent summation of the impulses [1].

Application of the two-pass split-window normalizer, a technique used in spectrum analysis, yields a background signal as a function of time that can be used to determine signal-to-noise ratios for the seismic data. The normalizer operates across the spectral data (data obtained after taking the FFT) and consists of two windows of adjusted width and spacing. The mean value of the spectral data within each window is taken, and these two values are averaged [5]. The windows move across the frequency range of the FFT data, and the average amplitude is plotted against frequency, resulting in what is called the first-pass mean. If the first-pass mean is less than the shearing threshold for the normalizer, the original FFT data is kept [6]. Any data further from the first-pass mean is replaced with the corresponding data from the first-pass mean. The substituted data should smooth the FFT plot, significantly diminishing sharp spectral peaks. The windows are applied once more to this substituted data to obtain the second-pass mean, which is utilized as an estimate for the background signal amplitude across the frequency spectrum.

The detection of walking was based on several criteria modeled after those of Houston and McGaffigan. First, the primary signal must be within 1 and 3 Hz. Additionally, for a single trial in which the SNR is calculated as a function of time, at least 50% of the SNR values for the primary signal must exceed 5 dB and 25% of the SNR values for the 2x harmonic signal must exceed 5 dB. It should be noted that these are informal detection rules and these values remain to be optimized.

### 2.2 Simulated Data

Simulated data was generated to test the ability of the algorithm to distinguish a walking signal from a sinusoidal background signal. Using a 2 Hz sine wave and a 2 Hz Gaussian Pulse (sinusoidal pulse occurring every 0.5 seconds to simulate walking) as two separate input functions. The sine wave was removed by the band pass filter, whereas the pulse was detected as a 2 Hz signal with harmonics, indicating that the band pass filter does not remove the signal event. The spectrogram in Figure 3 shows that a strong 2 Hz signal is indeed detected with harmonics for the Gaussian pulse. The cyan lines are the maximum amplitudes as a function of time within the boundaries of 1.5-2.5 Hz and 3-5 Hz for the lower and upper lines, respectively. This corresponds to the successful detection of a primary signal at 2 Hz and a 2x harmonic signal at 4 Hz.

![Figure 2: Footstep Detection Process](image)

**Figure 2: Footstep Detection Process**

![Figure 3: Spectrogram of simulated data (Gaussian Pulse) after band pass filtering, rectification, and decimation.](image)
From the signal amplitudes obtained from the spectrogram and the background estimates obtained using the split-window normalizer, a plot of SNR is plotted across time (Figure 4) and the criteria described for detection is applied.

The effectiveness of the reproduced Houston and McGaffigan algorithm as pertaining to the simulated Gaussian pulse indicates that the algorithm is an appropriate means of discriminating a walking signal.

![SNR (Simulated Data)](image)

*Figure 4: SNR as a function of time for simulated data (Gaussian Pulse) after bandpass filtering, rectification, and decimation.*

3 EXPERIMENTAL PROCEDURES

3.1 Background

Testing was performed to collect the response voltage data produced by geophones as and produced by configured piezoelectric sensors (further described in 3.2) in response to seismic signals induced by pedestrian and vehicle traffic. The primary goal of this testing was to determine the effects different degrees of variability in the seismic signal source, such as distance from the sensors, weight, signal frequency, noise, and vehicle type, have on the quality of the data collected.

3.2 Equipment

Three geophones, which have been purchased from Oyo Geospace, LP, were used for data acquisition (Figure 1). Two of these geophones, model GS-20DX, are uni-axial, measuring velocity exclusively in the vertical direction. The third geophone, model GS-11D, is tri-axial, capable of measuring velocity in three distinct, orthogonal directions. Both models of geophone couple to the ground by a metal spike.

A piezoelectric sensor has also been configured for testing as shown in Figure 5. This configuration is constructed in a plastic casing and consists of a piezoelectric sensor bonded to a mechanically tuned aluminum cantilever beam. The cantilever beam is tuned to 2 Hz which is within the frequency range generated by human walking. To the authors' knowledge, piezoelectric sensors have never been used in low frequency seismic wave detection. The absence of piezoelectric sensors in similar low frequency wave detection applications is due to the fact that piezoelectric sensors respond most effectively when operating under frequencies that are relatively high in comparison to the frequency ranges of concern for this project. The purpose of testing piezoelectric sensors is to determine the feasibility of their use in further ground vibration applications.

A data acquisition system has been designed and implemented using the LabVIEW 7.1 software package produced by National Instruments Inc. along with an eight channel 24 bit data acquisition board shown in Figure 6. Five channels were designated for geophone data, one for each axis of measurement, and one channel remained available for the piezoelectric sensor configuration. Raw data was collected at a sampling rate of 1 kHz.
from all test runs and saved for further processing, which included both noise reduction and spectrum analysis (further described in 4.1).

3.3 Setup

Pedestrian seismic data were collected from several trials with the walking distance from the sensors, pedestrian weight (or heaviness of footstep), footstep frequency, and number of pedestrians varying. Seismic sensors were arranged at predefined locations for each test run. Testing took place in an open field where one or more individuals walked along arcs of specific distances of up to 50 meters from the sensors and with specific footstep frequencies ranging from one to three footsteps per second.

Initially testing trials began with 30 seconds of background seismic data and ended with 30 seconds of background seismic data for the purpose of establishing a representative noise floor per trial. In later testing efforts this practice was modified such that for every 10 minutes of field testing one two minute background trial was obtained. Larger data sets which were dedicated entirely to either background content or pedestrian walking signals made later analysis much simpler from a programming standpoint and provided a data set describing all the seismic activity in the field which the testing personnel could not control otherwise known as the noise floor. These background trials produced similar content as detected by all five geophone channels, so it was determined that the noise floor present in each trial is the result of actual seismic content and not of random electronic noise (Figure 19).

Controlled pedestrian traffic was initially collected in between the background data windows for at least 30 seconds and later was collected in independent two minute intervals with background trials taking place about every 10 minutes. Again, the motivation behind this modification to testing procedure was to make data analysis much simpler. Generally two trials were run under similar conditions to ensure consistency in the acquired data. However, if the testing conditions were particularly noisy resulting in what appeared to be inconsistent data additional trials were run.

Vehicle data was collected simultaneously with pedestrian and background data acquisition. Urban Park (further described below), a public park in Los Alamos which was the second of two testing locations, is located between three roads, and the seismic sensors responded to the moderate levels of traffic on the road which was closest to them. Vehicles driving within about 70 meters of the sensing equipment produced a strong seismic which showed up in spite of any pedestrian seismic signals (Figure 20). As uncontrolled private vehicles passed close enough to the testing apparatus to produce responses in the sensors, the testing team took note of the time at which the vehicle passed as well as the vehicle type.

Testing conditions were varied in an attempt to determine the ideal conditions for sensor operation. As testing conditions improved, tests produced clearer data sets ultimately making analysis simpler. Testing was performed for two days on Los Alamos laboratory property at a site known as the Weedlot. After testing in the Weedlot,
where the ground is hard, dry, friable, and is covered with a random array of weeds, the project team took the equipment off of laboratory property to Urban Park where the ground is made up of moist soil and grass. The Urban Park setting proved better for pedestrian detection as the walking signals were much clearer (Figure 8). The effect of terrain on geophone response was further explored at Urban Park by using a concrete path, as opposed to a grassy field, for collecting pedestrian seismic data. The subject walked out along the concrete path to a specified distance from the sensors, returned to the sensors, walked out in the opposite direction to the same distance, and then returned again to the sensors. This process was repeated for a complete testing trial. A shunt resistance of about 970 ohms was added to the channel one GS-20DX geophone in order to reduce the sensor’s resonant response at about 8.5 Hz (Figure 7). Note that the GS-20DX model geophone used in this project had a resonant frequency of 8 Hz, not 10 Hz as Figure 3 might imply. Otherwise the output response is identical. About 970 ohms of shunt resistance were applied in this project. This addition reduced the geophone response at its 8.5 Hz resonance and improved the overall signal to noise ratio of the channel one geophone (Figure 10).

Figure 7: The Geophone Manufacturer’s Output versus Frequency Graph for the GS-20DX Model Geophone with Varying Degrees of Shunt Resistance (http://www.geospacelp.com/)
4 DATA ANALYSIS

4.1 Data Survey

In Figure 8 the blue curve represents data collected in the Weedlot and the red curve represents data collected at Urban Park. The difference in location appears to have a significant effect on the background signal content as well a 150% percent increase in walking signal harmonic peaks.

![Figure 8: Comparison of July 9th, 2007 Weedlot (Blue) Data with July 23rd, 2007 Urban Park (Red) Frequency Response Data both at a Constant 10 meter Distance](image)

Concrete appears to increase pedestrian walking signal peaks by about 200%, as shown in Figure 9.

![Figure 9: Comparison of Frequency Response Data from Walking along a Concrete Path (Blue) to Walking along a Grass Path (Red)](image)

Geophone performance with and without additional shunt resistance were compared and the shunt resistor appears to reduce background content, reduce geophone response at the 8.5 Hz resonant frequency, and improve the overall signal to noise ratio by about 50% as shown in Figure 10.
Figure 10: Comparison of Scaled Frequency Response Data from Walking at a Constant Distance of 2 meters with (Blue) and without (Red) Additional Shunt Resistance on Channel 1 (GS-20DX)

Figure 11 exhibits how the horizontal axes of measurement are sensitive to their 2 Hz and 4 Hz resonances, resulting in responses at frequencies which are not due to pedestrian walking. The trial shown in Figure 11 is from a pedestrian walking at a “fast”, 2.8 Hz, footstep frequency, indicated by the vertical (blue) curve. The 2 Hz and 4 Hz peaks are not part of the subject’s walking signal. This can be detrimental to pedestrian detection since an average walking frequency and its first harmonic are generally near 2 Hz and 4 Hz respectively.

Figure 11: Comparison of Vertically Oriented Sensor (Blue) to Horizontally Oriented Sensors (Red - WE and Green - NS) (all within tri-axial GS-11D Package) Frequency Response Data for Fast Walking (about 3 Hz) at a Constant Distance of 20 meters

The sensitivity of the piezoelectric sensor to the amount of sunlight it receives is exhibited in the rapid voltage change shown by Figure 12.

Figure 12: Time History Data of Piezoelectric Sensor Response to Cloud Coverage

Figure 13 shows how the piezoelectric sensor had a tendency to respond at its resonant frequency, even when the pedestrian walking signal was at an entirely different frequency.
Additional weight of about 40 kilograms caused the subject to walk at less distinct frequencies than those which were observed during unloaded walking as Figure 14 shows. This may have been due to either less pronounced footsteps or inconsistent walking frequencies, but in either case detection was made more difficult as a result of loading.

Heavy footwear significantly improved the clarity of a pedestrian’s walking signal by about 200% as shown in Figure 15.
Varied pedestrian speeds, or footstep frequencies, were clearly observable through the seismic sensors as shown in Figure 16. Resonant peaks occur at about 1 Hz, 1.9 Hz, and 2.9 Hz during slow, nominal, and fast walking trials respectively.

Figure 16: Comparison Frequency Response Data of Nominal (Blue), Slow (Red), and Fast (Green) Pedestrian Speeds at a Constant Distance of 10 meters

Figure 17 shows that multiple walkers whose footsteps were out of sync with one another were detectable from a distance of 10 meters. The resonant frequency and 2x harmonic peaks along with low background content shown in Figure 17 make pedestrians detectable.

Figure 17: Frequency Response Data from Multiple Pedestrians Walking Simultaneously in Sync (Blue) and out of Sync (Red) at a Constant Distance of 10 meters

Figure 18 shows that multiple walkers whose footsteps were at distinctly different frequencies were detectable and distinguishable from a distance of 10 meters. The resonant frequency and 2x harmonic peaks along with low background content shown in Figure 18 make pedestrians detectable.

Figure 18: Frequency Response Data from Multiple Pedestrians Walking in Sync (Blue) and at Varying Footstep Frequencies (Green) at a Constant Distance of 10 meters
Figure 19 shows the consistency in what has been described as background (or noise) signals between separate geophones. Figure 19 also exhibits the consistency from one geophone model to another. Aside from a slight increase in sensitivity (less than 1.5 mV increase in peak values) for the GS-11D model, which was indicated by the manufacturer as well as observed in data analysis (see Figure 19), no distinct differences in geophone performance were noticed.

Figure 19: Frequency Response Data Comparing Geophone Models GS-20DX (Blue) and GS-11D (Red) for a Background Signal Trial

Figure 20 shows the frequency content of vehicles driving by the test site at Urban Park. The vehicle types from left to right are as follows: Truck, SUV, Car, Truck, Truck, Truck, Car, and Car. The black rectangles indicate approximate time and frequency bounds for each vehicle; this approximation is simply a visual estimation. No consistent, quantifiable, discriminating features between vehicle types have been identified yet for vehicle discrimination.

Figure 20: Spectrogram of Vehicle Content from Various Trials

4.2 Background

The recorded foot traffic data consists of both signal and background. The walking signal is extracted from the background using the algorithm developed by Houston and McGaffigan [1]. This procedure requires, in order, applying a 10-40 Hz band pass filter, obtaining the absolute value, decimating by a factor of 30, and generating the FFT. If the periodic walking signal is observed in the post signal filtering FFT, then discrimination of foot and vehicle traffic is possible. While a positive traffic event is easy to extract given a clean data stream, it is also possible that the ambient environment generates sufficient noise to inadvertently trigger a false positive, that is, the algorithm affirms a traffic event when none has occurred. To counter the likelihood of a false positive, the 2 Hz SNR and its 4 Hz harmonic SNR must both exceed 5 dB in order to affirm pedestrian traffic in the area. These threshold values differ from those of Houston and McGaffigan [1], and were established through observations that the background signals, in general, did not generate a 4Hz harmonic that exceeded 5 dB. Also, an event must register either on channel 1 of the DAQ or a minimum three geophone channels to be considered a true traffic
event. Channel 1 collects data from a GS 20 DX coupled to a 790 Ohm shunt resistor. The shunt dampens the 8Hz resonance response of the seismic sensor and has been observed to reduce much of the background signal while simultaneously enhancing the walking signal. Should the signal meet both of these criteria, then a traffic event has occurred. An alternate algorithm is developed to prototype an actual analogue circuit. This system discriminates traffic by applying a 1.5-2.5 Hz and a 7.5-8.5 Hz band pass filter along with a leaky integrator function. If the output exceeds a specified threshold, then a traffic event occurred.

4.3 Results

Applying the digital signal filters and the detection criteria to the raw data enabled foot traffic discrimination. To begin, several background data channels were analyzed to assess the occurrences of false positives. Of the 40 background data trials listed in Table 1, only one test, trial number 16, showed a false positive. However, in examining the laboratory journal, a jogger was witnessed to have been running while background data was being recorded for trial 16. The false positive event is most likely an actual running event, and therefore, the probability of having a false positive event based on the given data, is 0%. In Table 1 and successive tables, the “Type” entry gives the type of data collect (BG=Background; 10N = 10m distance, Normal cadence, and so on), and “Bandwidth” is the bandwidth used in the initial step of the algorithm of Figure 2. All other columns are self-explanatory.

Table 1: Background Data

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<td>10,47</td>
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<td>---</td>
<td>10,48</td>
<td>---</td>
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</table>
Detecting foot traffic at the 10 m, 20 m, 30 m, and 40 m range proved to be less consistent than the false positive discrimination. For example, at a range of 10 m from the sensors, the probability of detection (Pd) of a normal 2 Hz walking signal was excellent (Pd=1) in Weedlot. However, at Urban Park, detection rates were only 0.40. Table 2 shows this trend.

Table 2: 10 m, Normal Speed of 2 Hz Data

<table>
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<tr>
<th>DATE</th>
<th>TYPE</th>
<th>LOCATION</th>
<th>WALKER</th>
<th>SHOES</th>
<th>BANDWIDTH (Hz,Hz)</th>
<th>CH. DETECT</th>
<th>DETECT</th>
<th>STEP FREQ (Hz)</th>
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<td>5,70</td>
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<td>9</td>
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</table>

At a distance of 20 m and a normal walking frequency of 2 Hz, the probability of detection further decreased. The detection rates were once again, higher for the Weedlot data in comparison to the Park, although the difference was not as large, Pd=0.33 for the Weedlot vs. Pd=0.20 for the Park. Table 3 highlights this trend.

Table 3: 20 m, Normal Speed of 2 Hz Data

<table>
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<th>LOCATION</th>
<th>WALKER</th>
<th>SHOES</th>
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<th>DETECT</th>
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<td>5,40</td>
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<td>Slip-on</td>
<td>10,40</td>
<td>---</td>
<td>No</td>
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<td>B</td>
<td>Slip-on</td>
<td>5,35</td>
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<td>B</td>
<td>Boot</td>
<td>10,40</td>
<td>1,3,5</td>
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<td>B</td>
<td>Boot</td>
<td>5,45</td>
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</tbody>
</table>
Figure 21 plots the various detection rates as a function of distance. None of the calculated probabilities matched the high detection rate of the Houston and McGaffigan experiment.

![Probability of Detection vs. Distance](image)

Figure 21: Comparing the Probability of Detection for Different Terrains

At a slow walk of less than 2 Hz, Pd=0 for all ranges and both terrains. The data is summarized in Table 6, where type 10S, 20S, and 30S represents slow walks at 10 m, 20 m, and 30 m, respectively.

**Table 6: All Distances, Slow Speed Data**

<table>
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<th>SHOES</th>
<th>BANDWIDTH (Hz,Hz)</th>
<th>CH. DETECT</th>
<th>DETECT</th>
<th>STEP FREQ (Hz)</th>
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<tbody>
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<td>10S</td>
<td>Weedlot</td>
<td>D</td>
<td>Tennis</td>
<td>5,50</td>
<td>---</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>7/24/2007</td>
<td>10S</td>
<td>Urban Park</td>
<td>E</td>
<td>Tennis</td>
<td>5,40</td>
<td>---</td>
<td>No</td>
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<tr>
<td>3</td>
<td>7/24/2007</td>
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<td>E</td>
<td>Tennis</td>
<td>5,45</td>
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<th>LOCATION</th>
<th>WALKER</th>
<th>SHOES</th>
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<th>STEP FREQ (Hz)</th>
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<td>Tennis</td>
<td>5,40</td>
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<tr>
<td>2</td>
<td>7/24/2007</td>
<td>20S</td>
<td>Urban Park</td>
<td>E</td>
<td>Tennis</td>
<td>5,40</td>
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<table>
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<th>TYPE</th>
<th>LOCATION</th>
<th>WALKER</th>
<th>SHOES</th>
<th>BANDWIDTH (Hz,Hz)</th>
<th>CH. DETECT</th>
<th>DETECT</th>
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<td>Tennis</td>
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<tr>
<td>3</td>
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<td>30S</td>
<td>Urban Park</td>
<td>E</td>
<td>Tennis</td>
<td>5,40</td>
<td>---</td>
<td>No</td>
</tr>
</tbody>
</table>
Probability of detection increased significantly if the subject was jogging or running. However, the increased detection rate is not necessarily attributed to a faster cadence, but instead, to the generally higher force and subsequently higher amplitude of the pulses being imparted into ground. High amplitude pulses result in the foot traffic signal being transmitted further, so a higher probability of traffic detection occurs at all distances.

Table 7: All Distances, Fast Speed Data

<table>
<thead>
<tr>
<th>DATE</th>
<th>TYPE</th>
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<th>WALKER</th>
<th>SHOES</th>
<th>BANDWIDTH (Hz,Hz)</th>
<th>CH. DETECT</th>
<th>DETECT</th>
<th>STEP FREQ (Hz)</th>
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<td>Tennis</td>
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<td>E</td>
<td>Tennis</td>
<td>5,40</td>
<td>---</td>
<td>No</td>
<td>---</td>
</tr>
<tr>
<td>3 7/24/2007</td>
<td>10F</td>
<td>Urban Park</td>
<td>E</td>
<td>Tennis</td>
<td>5,70</td>
<td>1,2,4,5,6</td>
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<td>2.8434</td>
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</table>

Several additional tests were performed to examine the capabilities of the seismic sensors. For example, the first four tests in Table 8 were conducted by walking a 2 m radius circle around a GS-20DX sensor to generate a sharp signal. This data was compared with the same sensor having a shunt resistor added to reduce the likelihood that the geophone resonant frequency would be excited. The shunt resistor improved the quality of the data collected by reducing noise and enhancing the walking signal, so it remained installed on the GS 20 DX sensor, channel 1.

Trials 5-9 attempted to find a traffic event due to a subject carrying a weighted pack of approximately 40kg. No traffic event was detected, and it is surmised that this failure to detect the slow, but forceful, walking steps may be due to the pack acting as a dampener. As the subject steps on the ground, the pack shift considerably and may interfere with the frequencies being imparted into the ground.

The trial type “L” represent a linear path to and away from the sensors, to a distance of 30 m or 50 m. Two trials, designated at “L30C” were performed by walking along an adjacent asphalt path to a distance of 30m to either side of the sensor array. Since all trials of this type had at least some data taken within the 10 m range, the probability of detection was very high.

Multiple walkers were tested at a distance of 10 m. For trials 15 and 16, the two walkers marched in sync, yet the Pd was only 0.5. This probability should be 1 since the subjects are in close range to the sensor and are generating a consistent and strong 2 Hz signal. The Pd remains 0.5 when the subjects walk out of sync in trials 17 and 18. Walking at different velocities in trials 19-21, however, was detected with a probability of 1.

Table 8: Additional Tests

<table>
<thead>
<tr>
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<th>TYPE</th>
<th>LOCATION</th>
<th>WALKER</th>
<th>SHOES</th>
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<th>CH. DETECT</th>
<th>DETECT</th>
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<tbody>
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<td>1,4,6</td>
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</table>
Finally, the feasibility of using a piezo on a cantilever beam was checked. For the large majority of trials, the extreme sensitivity of the setup could not distinguish between the background and a walking signal, so no traffic events could be extracted. However, for two of the four trials where the piezo did return a traffic event, the walking frequencies were very close to frequencies recorded by the geophone sensors.

Table 9: Piezoelectric Sensor Data

<table>
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<tr>
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</table>
Plotting the detection rates for normal speed, slow speed, and fast speed, in Figure 22, in contrast to the Houston and McGaffigan results highlights low probability of detection rates for this experiment.

**Figure 22: Plot of Probability of Detection versus Distance from Project Results and Published Results**

### 4.4 Interpretation of Results

In examining Figure 22, it is apparent that the probability of detection of foot traffic did not match the results of the Houston and McGaffigan experiment. At best, the walking traffic could be detected with a Pd=0.57 at a distance of 10m. Houston and McGaffigan, in comparison, report a Pd=1 at 10m, and a Pd=0.50 at 84m. The results of Richman et al. [2], using a different analysis method, also showed a lower Pd (~50% at 30m distance) than Houston and McGaffigan [1], though still higher than achieved here. Although the detection rates for this experiment were much lower than expected, they are not necessarily in error. Several critical factors and variables were noted to affect the detection rates. Soft and porous soil, for example, should attenuate the walking signal more than a hard and homogeneous foundation. However, neither location could be strictly classified in either of these two categories. Urban Park had a soft yet compacted soil, while the rocky Weedlot was very hard yet prone to fracture. Although the signal analysis showed greater signal propagation and less noise in the Park data, the probability of detection showed just the opposite, that is, the Park was much less likely to register a traffic event. It is highly possible that adjusting the false positive threshold would perhaps allow more genuine traffic events to pass through for the Weedlot. However, both terrains faced lower detection rates than the cold winter Aberdeen Proving Grounds where Houston and McGaffigan conducted their project. Also, the walking signal was observed to be less distinct in comparison to the Houston and McGaffigan data. While attenuation in the ground may be responsible for reducing the detected signal, it is believed that the ambient conditions at both the Weedlot and Urban Park contributed significantly to the background signal. Vehicle and pedestrian traffic and electrical interference (60 Hz harmonics) from equipment in the area are clearly visible in the analyzed data.

We found that, for this application, the GS-11D and GS-20DX geophones delivered essentially identical results, in terms of detection probability and noise floor. The smaller size and lower cost of the GS-20DX, then, makes it a more suitable choice for deployment in a large-scale personnel tracking network. We found no advantage to using a multi-axis geophone over a single, vertical-axis installation.
Concerning the piezo sensor on the cantilever beam, the lack of damping hindered its ability to distinguish traffic events. Once the beam was perturbed by either ambient conditions or a real traffic event, the system would continue to oscillate for an extended period of time. Thus distinct traffic events occurring at approximately 0.5s apart would not be clearly visible. Also, the long, slender aluminum beam was greatly influenced by direct exposure sunlight. A passing cloud easily doubled the amplitude of the output signal.

5 ANALOG CIRCUIT

5.1 Background

Although the FFT may provide reasonable traffic detection, an alternate analog signal processing design is still necessary. The reason for this procedure is that digital FFT circuits are more complex and require more power than a simple analog circuit. For a “zero-power” seismic sensor network, the power draw is such a significant design constraint that an analog system is required.

6.2 Analog Circuit Design

The analog circuit algorithm is presented in Figure 23 below.

![Flow Chart for Analog Circuit](image)

The raw signal is initially processed in the same manner as outlined in the Houston and McGaffigan paper. A 10 Hz – 40 Hz band pass filter is applied to the signal, which captures the majority of the frequency content due to foot traffic. The filtered signal is then rectified, since foot traffic generates both positive and negative pulses in the ground. Rectification ensures that the negative pulses, which may be out of phase with the positive pulses, does not inadvertently interfere with the positive pulse.

The rectified signal is then split and passed through two band pass filters, a 1.5-2.5 Hz filter and a 7.5-8.5 Hz filter. The sharp 2 Hz band pass filters is tuned specifically to isolate the 2 Hz walking frequency, while the 8 Hz filter is designed to extract the background data very close to the signal.

Each filtered signal is integrated independently by means of a leaky integrator. To be clear, the leaky integrator sums the varying voltages over a time domain, its “leaky” nature effectively serves as a reset function, keeping the integration process from continually increasing the output signal. The domain of the integrator is adjusted by varying resistance and capacitance in the actual analog circuit. Finally, the 2 Hz signal is divided by the background data to obtain the SNR. The analog circuit schematic is presented in Figure 24.
Unfortunately, due to time constraints, the analog circuit was not completed in time for actual field testing. Specifically, the leaky integrators have not been properly tuned to the correct frequency bands. The SNR dividing circuit is still in development; single-chip, instrumentation-quality dividers are too power-intensive for our purposes.

### 6.3 Signal Analysis using Computer Model

Although the circuit was not completed in time, a computer model of the analog circuit provided a glimpse into the anticipated results. The domain of the integrator is set to 2400 data points. For a 1 kHz sampling rate, this domain represents 2400 ms. By inspection of Figure 25, it has been noted that when the SNR exceed a threshold of at least 200% over the lowest value, a foot traffic event has occurred.

Using a GS-20DX geophone set to measure along the vertical axis, a clear 2 Hz frequency is observed for a 80 kg subject walking at a constant pace. The test subject approached the geophone, walked right over the sensor, and walked away. This walking path was traversed for two minutes.
The periodic peaks in Figure 26 represent instances where the subject walked right over the sensors, thereby generating large amplitudes. The periodic 2 Hz signal to be analyzed includes these large motions as well as the much smaller pulses in between them. After applying the 10-40 Hz filter, rectifying, decimating by a factor of 30, and calculating the FFT, the ~2.1 Hz walking signal and its harmonics of ~4.2 Hz and 6.3 Hz are visible in Figure 26. The ~8.5 Hz geophone resonant frequency is also visible, with 2 Hz and 4 Hz harmonics appearing at 10.5 Hz and about 12.5 Hz, respectively. Here, the FFT would indicate the occurrence of a traffic event (i.e., the SNR at the fundamental and 2x harmonic frequencies is >5dB).

The same channel, when passed through the computer model of the analog circuit, also indicates a traffic event has taken place. The peaks correspond to large amplitude traffic occurring in addition to the background data.
In contrast, applying the analogue algorithm to the background signal indicates that the ambient conditions do not generate enough activity to register a traffic event.

6 FUTURE WORK

While adhering to the process as outlined in the Houston and McGaffigan paper did result in the discrimination of pedestrian traffic, the relatively low probabilities of detection require further investigation. In future studies, it would be beneficial to study different types of terrain, to understand how soil conditions affect signal transmittance. Also, it was observed that some of the actual traffic events registered just under the SNR threshold for a positive event. Thus, it would be very interesting to adjust the criteria for triggering a false positive,
thereby allowing more traffic events to register, and see if such results could be achieved without affecting too much, the excellent (very low) false positive probability. Concerning the actual development of the low power seismic sensors, continued efforts must be done to finish the current prototype, and test its abilities to discriminate foot and vehicle traffic. The sensors must also be able to discriminate between a subject and a subject walking with a weighted pack, to better assist in protecting borders and facilities where movement of nuclear material is monitored.

REFERENCES


