Spectrum Analysis Techniques for Personnel Detection Using Seismic Sensors

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ABSTRACT

There is a general need for improved detection range and false alarm performance for seismic sensors used for personnel detection. In this paper we describe a novel footstep detection algorithm which was developed and run on seismic footstep data collected at the Aberdeen Proving Ground in December 2000. The initial focus was an assessment of achievable detection range. The conventional approach to footstep detection is to detect transients corresponding to individual footfalls. We feel this is an error-prone approach. Because many real-world signals unrelated to human locomotion look like transients, transient-based footstep detection will inevitably either suffer from high false alarm rates or will be insensitive. Instead, we examined the use of spectrum analysis on envelope-detected seismic signals and have found the general method to be quite promising, not only for detection, but also for discrimination against other types of seismic sources. In particular, gait patterns and their corresponding signatures may help discriminate between human intruders and animals. In the APG data set, mean detection ranges of 64 meters (at P_D=50%) were observed for normal walking, significantly improving on ranges previously reported. For running, mean detection ranges of 84 meters were observed. However, stealthy walking (creeping) remains a considerable problem. Even at short ranges (10 meters), in some cases the detection rate was less than 50%. In future efforts, additional data sets for a range of geologic and environmental conditions should be acquired and analyzed. Improvements to the detection algorithms are possible, including estimation of direction of travel and the number of intruders.

Keywords: Footstep detection, personnel detection, seismic sensors, spectrum analysis.

1. INTRODUCTION

Intruder or personnel detection is required for many military missions. Several sensor modalities may be used, including bistatic and monostatic microwave, passive and active infrared, seismic, magnetic, break-wire, etc. Many of the most effective modalities are best suited for semi-permanent installations because components require considerable size, weight, and/or power. There is also a continual need for improved, highly portable sensors which are suitable for short mission durations, i.e. a few days to a few weeks.

Acoustic and seismic sensors, often referred to as UGS (Unattended Ground Sensors), are well suited to tactical missions because they can be made very compact and low-power. However, while UGS are commonly applied to vehicle detection, tracking and ID, personnel detection using these sensors (in particular seismic sensors) has received relatively little attention. There is a general need for improved detection range and false alarm performance. The capabilities of seismic sensors to detect, classify and track intruders are unclear, and in particular the following:

- Achievable coverage/detection range - run, walk, creep (stealthy walk), crawl
- Ability to estimate direction of travel
- Ability to estimate the number of intruders

In this paper we describe a novel footstep detection algorithm which was developed and run on seismic footstep data collected at the Aberdeen Proving Ground (APG) in December 2000. The initial focus was an assessment of achievable detection range. The results were quite good relative to those reported elsewhere, as will be described below.

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2. DATA COLLECTION SUMMARY

The footstep collection was performed over two days in December 2000 on Spesutie Island on the Chesapeake Bay at APG in Aberdeen Maryland. Temperatures were near freezing, with winds typically 5-10 mph. Test subjects included the authors, one soldier and three civilians carrying varying amounts of gear, including rucksacks and rifles. Test subject weights ranged from 170 to 225 lb.

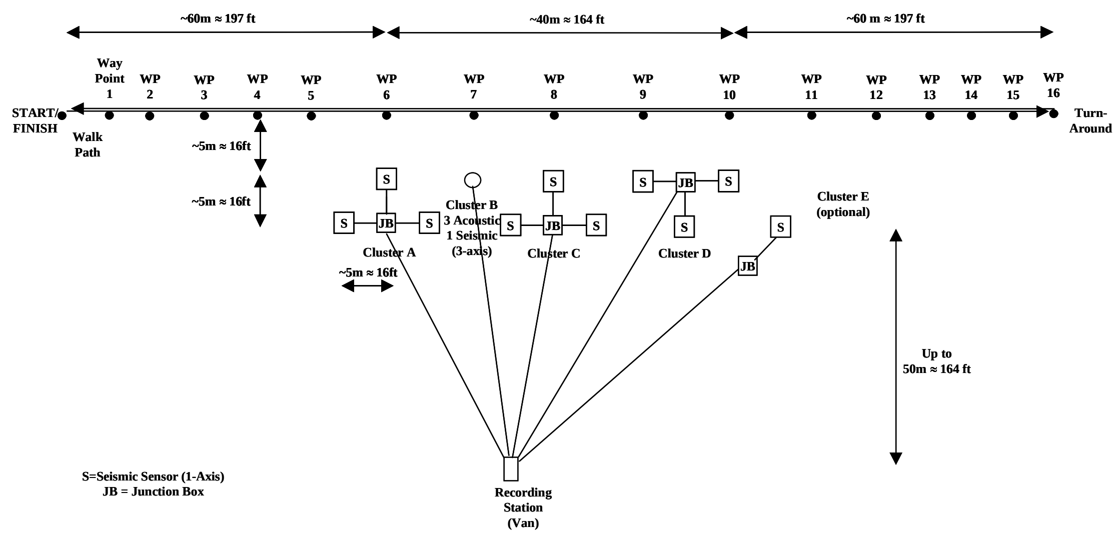


Figure 1
Walking Path and Sensor Configuration

A test range was developed on open grassy terrain in between the test track (dirt) and Spesutie Island road (paved). A total of 10 sensor positions with 5 meter separations were defined in a staggered line (Figure 1). At 9 of the 10 sensor positions were single-axis seismic sensors (Geospace GS-14L9). At one position was a cluster consisting of a 3-axis seismic sensor (Geospace GS-20DM in PC-3D land case) and three microphones. A straight line path covering 160 meters was defined for walkers to follow, with a closest point of approach of 5 and 10 meters to the various sensors. On each run, walkers would follow the 160 meters path, turn around, and return to the start point. At each 10 meters, the walker would announce passing a way point into a radio by saying “Way Point [N] - Mark”. The voice radio channel was recorded alongside the sensor data channels, and was a simple means for establishing ground truth.

A total of 47 round-trip runs were conducted involving normal walking, stealthy walking, and running. Several runs were conducted for multiple walkers, including side-by-side at 1 meter separation (2 walkers), single file at 10 meters separation (4 walkers) and a “wedge” formation (4 walkers). Given 10 sensor locations and two sensor passes per round trip, a total of 940 sensor passes were recorded covering about 4 hours of raw data. Recording was to a 16-channel DAT in parallel with a 16-channel data acquisition to a laptop PC. The 16 channels were sampled at 6 KHz.

3. PROCESSING APPROACH

The first processing step was to time-align all channels (removing A/D skew) through interpolation filtering, and to decimate to 1200 Hz. Figure 2 shows the time domain waveform for a representative run, indicating approximate segments which might be detectable based upon visual inspection of the data. Figure 3 shows a conventional spectrogram of the data. Bright areas occur near the closest points of approach (approximately 40 and 180 seconds), as well as when a pickup truck passes on Spesutie Island road about 40 meters away (note that the road was not controlled and many interference sources, including distant artillery impulses, were present in this data set). The spectra are seen to be relatively broad-band, covering approximately 10-40 Hz. A careful inspection of the spectrogram at fine resolution also shows bright lines followed by dark lines corresponding to intervals when footsteps occurred and didn't occur.

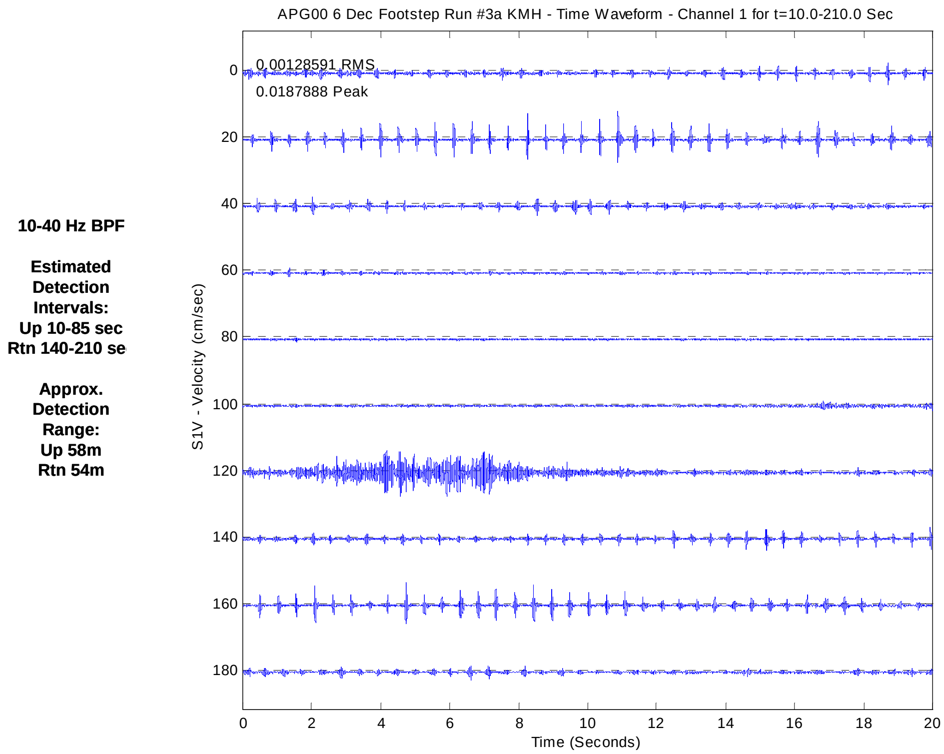


Figure 2
Time Domain Waveform - Standard Walk 6 Dec #3 - Up and Return

The conventional approach to footstep detection is to detect transients corresponding to individual footfalls, and then possibly associating the arrival times to classify the transients as human-based. We feel this is an error-prone approach, because many real-world signals unrelated to human locomotion look like transients. Even Gaussian noise will appear as many transient spikes if it is sufficiently broad-band. Because individual transients can occur from a variety of sources, or even background noise, transient-based footstep detection will suffer from high false alarm rates, or will be insensitive because detection thresholds must inevitably be set to very conservative values.

3.1 Modified Spectrum Analysis

Figure 4 shows the general processing approach that was used for footstep detection. The approach is spectrum analysis-based as opposed to transient-based. The seismic signals are bandpass filtered, envelope-detected, downsampled to a 40 Hz sampling rate (a decimation factor of 30), and spectrum-analyzed using conventional Fast Fourier Transform (FFT) techniques and a Hanning window.

An example of the resulting spectrogram of the envelope data appears in Figure 5. It may be seen that a family of footstep-related harmonic lines occur for much of the run, with a fundamental frequency of approximately 1.8 Hz. It may also be seen that the pickup truck pass at around 140 seconds creates a broadband envelope which is significantly different in character from the footstep harmonic lines, and the background noise at around 100-120 seconds is generally free of tonals in its envelope.

After applying a split-window 2-pass normalizer (a conventional spectrum analysis algorithm) on a line-by-line basis, a spectrogram of signal-to-noise values is obtained (Figure 6). Again the footstep harmonic lines appear very strongly, often at signal-to-noise ratios (SNRs) greater than 15 dB. The pickup truck's broadband signal is effectively removed by the normalization. At the same time, however, the pickup truck is observed to completely mask the footstep signals.

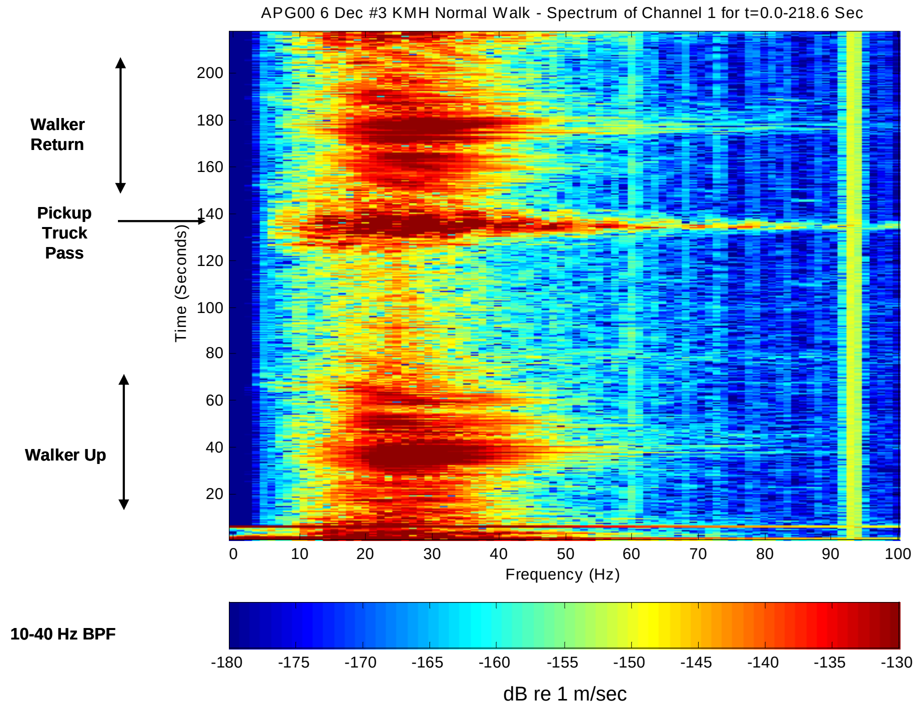


Figure 3
Conventional Spectrogram - Standard Walk - 6 December Run 3

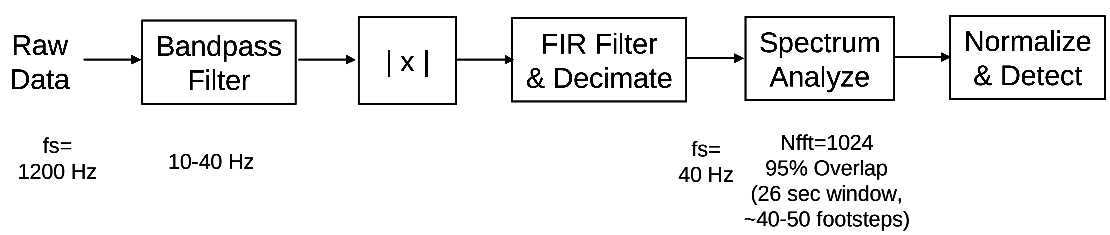


Figure 4
Footstep Detection Processing Chain

The envelope detection (absolute value) operation is critical to the success of this approach. The footsteps can be looked upon as a series of impulses passed through a time-varying bandpass filter. The received footstep impulses have essentially random phases. Even if the impulses were to occur exactly at a certain frequency f_0, spectrum analysis would fail to detect a periodicity at f_0 because the impulses would fail to sum coherently. The absolute value operation demodulates the bandpass signal and removes the effect of the random phase, allowing the footstep periodicities to be detected.

The spectrum analysis approach has several advantages over a conventional transient detector. First, it takes advantage of the natural periodicity of walking, which should be distinct from other potential sources of interference. This should help to specifically identify walkers and reduce false alarms. Second, it obtains significant SNR gains though integrating over a considerable time window (26 seconds or 40-50 footsteps for this analysis), which improves detectability. In addition, the spectrum analysis algorithm should be readily implemented on a digital signal processor (DSP), especially since similar algorithms are already used in UGS for vehicle detection and classification.

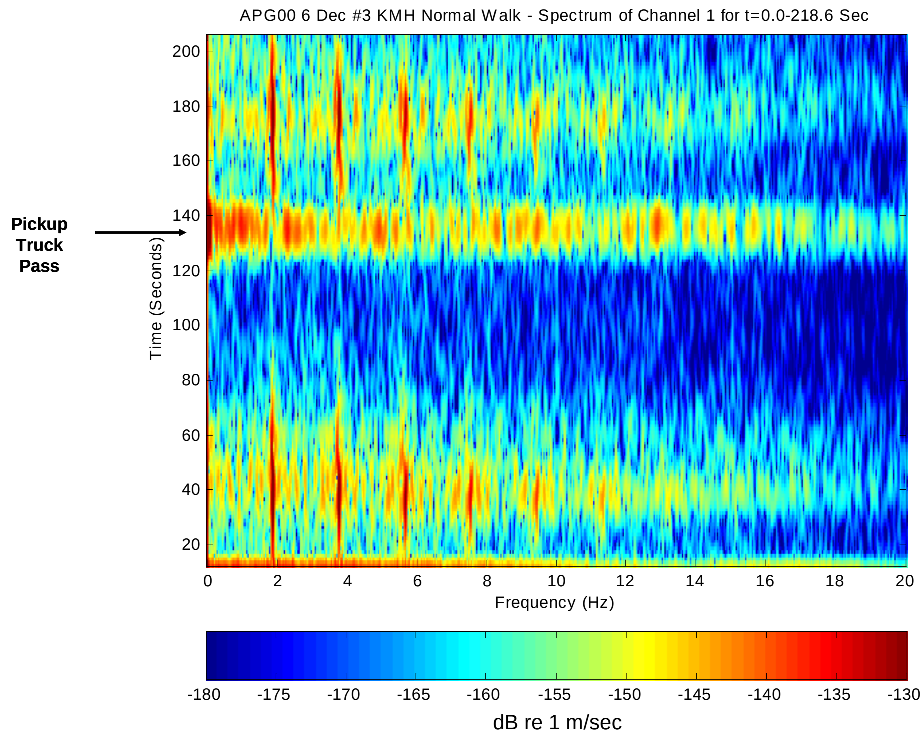


Figure 5
Spectrogram of Envelope Data - Standard Walk - 6 December Run 3

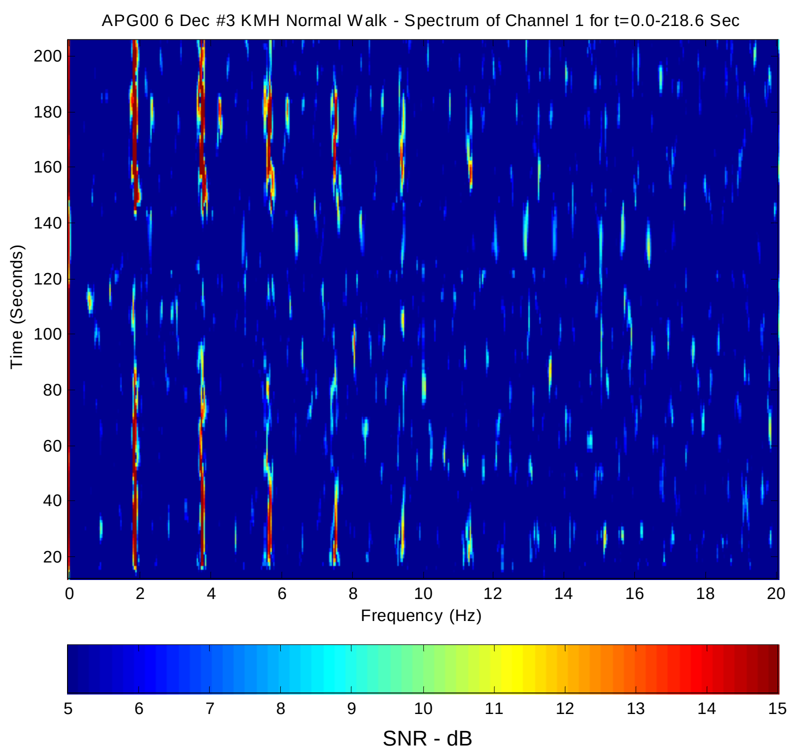


Figure 6
Normalized Spectrogram - Standard Walk - 6 December Run 3

3.2 Autodetector

An algorithm to automatically detect footsteps from normalized spectrograms was developed. Detection was performed on a line-by-line basis, meaning that a detection decision was made every time a new spectrum was computed. For the 95% overlap used, this amounts to a new line each 1.28 seconds. In spite of considerable overlap in the input time series (each new line uses 1 second "new" data and 25 seconds "old"), each new line was treated independently with regard to decision-making.

The detection rules were very simple: 1) a primary frequency must occur in the 0.5 to 3.0 Hz Range, 2) the primary frequency must have a second or third harmonic present, and 3) the primary must be greater than 11 dB SNR and the harmonic greater than 7 dB, or vice versa. While these rules were found to be effective, they are still somewhat *ad hoc* and could be optimized in the future.

4. RESULTS

4.1 APG2000 Detection Range Results

The key results for the above run are summarized in a triple plot shown in Figure 7. The top plot shows the range to each sensor versus time for the round trip, for a total of 10 sensor curves. The curve is shown if a detection occurs, and masked if a detection has not occurred. The second plot shows SNR vs time. Again the SNR is masked out if no detection occurs. The third plot shows the estimated background noise level vs. time.

It may be seen that detections occur for most of the run, even out to 70-80 meters range. However, two significant gaps occur: one at around 100-110 seconds, and another over 120-140 seconds. The gap at 100-110 seconds occurs near the turnaround, where range is greatest. This gap appears to be simply due to signal levels dropping with range and SNR going under the threshold. The gap at 120-140 seconds corresponds to the pickup truck pass, which raises background noise levels by up to 35 dB. Here the SNRs drop due to the greatly increased background noise levels. The pickup truck pass disturbs a wider span of time than might be expected, because of the relatively wide span of the spectrum analysis window (26 seconds).

The gait frequency estimate is shown in Figure 8. It may be seen to be quite consistent over all sensors. A few outlyers are seen in the 100-120 second interval. Some correspond to exactly half of the primary frequency (a minor problem involving fundamental frequency estimation), and another spurious set of frequencies at about 0.6 Hz, presumably corresponding to an interfering target.

A plot of probability of detection versus range appears in Figure 9, based upon histograms of the detection data. The lower curve gives the P_D vs. range for the entire run, including all data. The upper curve shows P_D vs. range when the cases involving high background noise levels are excluded from consideration, corresponding in this case to the pickup truck passby. The upper curve has been found to be a more consistent measure between similar runs. For reference, a third curve (lower) corresponds to results recently reported in the literature [1] over the same period at Spesutie Island, though at a location approximately 200 meters away.

It may be seen that for this run, there is a high probability of detection out to 50-60 meters. For discussion purposes, a representative maximum range value might be the range where P_D=50%, which corresponds in this case to 77 meters. This run achieves significantly longer detection range than in [1] (30 meters at P_D=50%), but factors other than signal processing might also explain this.

Other similar plots for normal walking are shown in Figure 10. Table 1 summarizes observed detection ranges. For all individuals, the mean range at P_D=50% for normal walking is 64 meters, but it may be seen that Subject 4 is considerably less detectable.

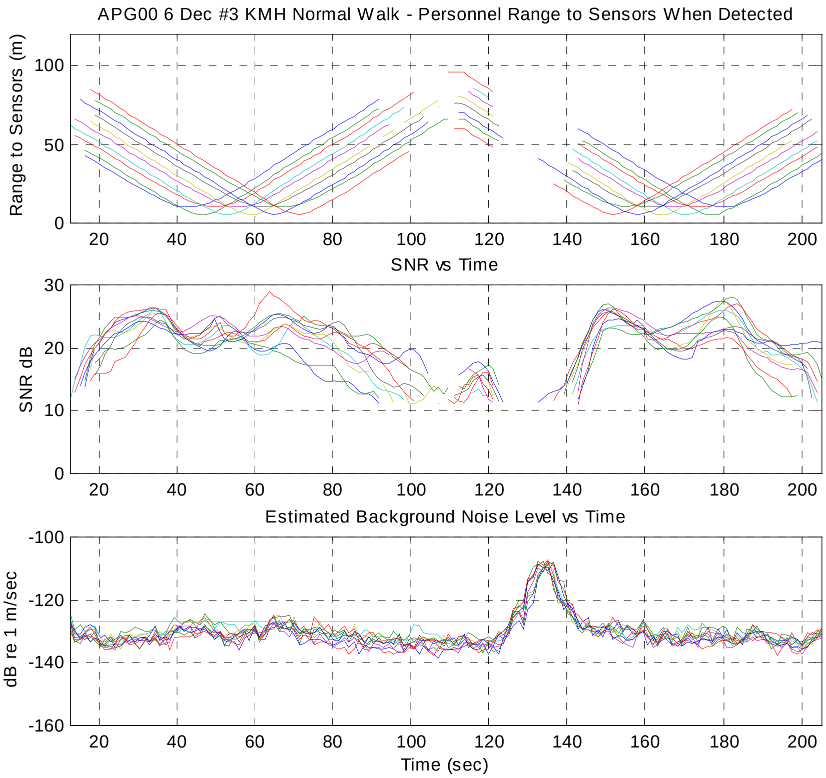


Figure 7
Detection Results for 6 December Run 3

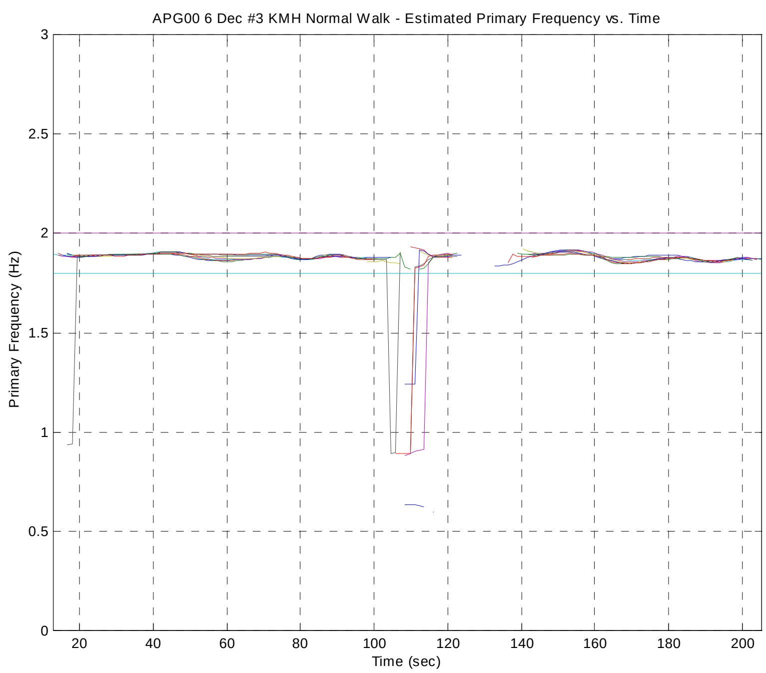
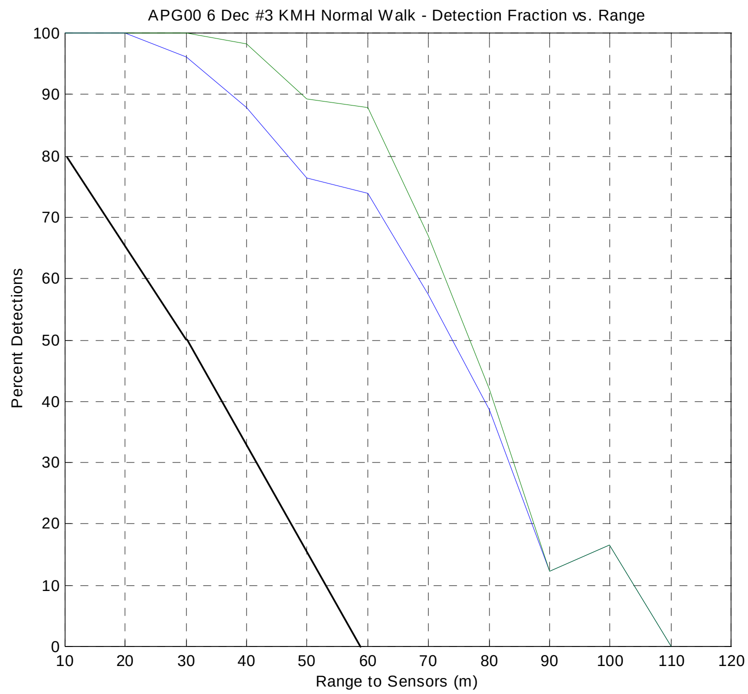


Figure 8
Gait Frequency - 6 December Run 3



Middle curve - results over total run
Upper curve - results after excluding intervals with high background noise levels
Lower line - recent results from literature

Figure 9
P_D vs. Range for 6 December Run 3

Similar detailed results for stealthy walking are shown in Figure 11. It may be seen that the results for stealthy walking are not nearly so optimistic - in several runs the probability of detection even at close range did not even approach 50%. Stealthy walking remains a considerable problem.

Results for multiple walkers are given in Table 1. Detection ranges are similar to those for single walkers, although somewhat less. From examining time domain data, the transients from two individuals walking side-by-side appear to interfere with each other so as to degrade the character of the pulse envelopes. This can cause significant problems for time-domain detectors. A spectrogram for 2 walkers side-by-side at 1 meter separation appears in Figure 12. Interestingly, multiple harmonic line families do not appear. We suspect that there is a tendency for multiple walkers to unknowingly "fall into step", so that multiple walkers may be synchronous and hard to separate using simple spectral techniques. Bandwidth of spectral lines, or variability of primary frequency may provide clues that multiple walkers are present, however.

Results for running appear in Table 1. Runners are very detectable. The mean 50% detection range for 4 runs was 84 meters.

4.2 Simulations for P_D and P_{FA} Estimation

Background runs were conducted at APG to estimate false alarm rates, but were inconclusive because walkers were present during portions of the run. Instead, simulations were performed to estimate false alarm rates. When combined with simulations of footstep signals plus noise to estimate probability of detection, we can start to define points of a ROC (Receiver Operating Characteristic) curve.

				Estimated Range at Pd - meters		
Walk Type	Subject	Date	Run #	Pd=80%	Pd=50%	Pd=20%
standard walk	Subject 1	6-Dec	1	60	64	68
single walker	"	6-Dec	2	71	76	81
"	"	6-Dec	3	63	77	87
"	"	7-Dec	2	54	70	93
"	"	7-Dec	3	58	81	90
"	"	7-Dec	12A	55	90	100
"	"	7-Dec	12B	62	76	87
"	"	Mean Values		**60**	**76**	**87**
"	Subject 2	6-Dec	9	32	47	65
"	"	6-Dec	10	33	46	58
"	"	6-Dec	12	34	58	84
"	"	6-Dec	13	48	72	87
"	"	6-Dec	20	35	52	67
"	"	6-Dec	21A	35	50	70
"	"	7-Dec	14A	30	38	50
"	"	7-Dec	14B	23	35	47
"	"	Mean Values		**34**	**50**	**66**
"	Subject 3	7-Dec	6	48	76	92
"	"	7-Dec	7A	73	82	90
	"	Mean Values		**61**	**79**	**91**
"	Subject 4	7-Dec	8A	33	44	60
"	"	7-Dec	8B	27	38	49
"	"	Mean Values		**30**	**41**	**55**
"	Subject 5	7-Dec	10A	41	58	69
"	"	7-Dec	10B	56	76	87
"	"	Mean Values		**49**	**67**	**78**
"	Subject 6	7-Dec	11A	55	91	98
"	"	7-Dec	11B	62	81	89
"	"	Mean Values		**59**	**86**	**94**
"	All	Mean Values		**47**	**64**	**77**

				Estimated Range at Pd - meters		
Walk Type	Subject	Date	Run #	Pd=80%	Pd=50%	Pd=20%
standard walk	Subjects 1&2	6-Dec	21B	42	58	70
2 walkers	"	6-Dec	21C	42	57	68
"	"	Mean Values		**42**	**58**	**69**
standard walk	Subjects 3-6	7-Dec	9A	47	71	90
4 walkers	"	7-Dec	9B	52	62	75
"	"	7-Dec	9C	44	67	89
"	"	7-Dec	9D	n/a	65	88
"	"	Mean Values		**n/a**	**66**	**86**
stealthy walk	Subject 1	6-Dec	5	45	65	82
single walker	"	6-Dec	6	30	41	56
"	"	7-Dec	4	38	53	70
"	"	7-Dec	5	40	62	79
"	"	7-Dec	13A	32	48	59
"	"	7-Dec	13B	19	38	50
"	"	Mean Values		**34**	**51**	**66**
"	Subject 2	6-Dec	14	n/a	23	43
"	"	6-Dec	15	n/a	28	40
"	"	7-Dec	14C	n/a	n/a	10
"	"	7-Dec	14D	n/a	n/a	13
"	"	Mean Values		**n/a**	**n/a**	**27**
"	Subject 3	7-Dec	7B	n/a	n/a	26
"	Subject 4	7-Dec	8C	n/a	n/a	n/a
"	Subject 5	7-Dec	10C	n/a	19	n/a
"	Subject 6	7-Dec	11C	n/a	n/a	n/a
run	Subject 1	6-Dec	7	50	73	104
"	"	6-Dec	8	64	91	108
"	"	Mean Values		**57**	**82**	**106**
"	Subject 2	6-Dec	16	n/a	85	99
"	"	6-Dec	19	52	88	98
"	"	Mean Values		**n/a**	**87**	**99**
"	All	Mean Values		**n/a**	**84**	**102**

Table 1
Detection Range Summaries - APG2000 Data

Simulated white Gaussian noise with a bandpass spectrum identical to the observed background spectrum (approximately 18-40 Hz at -10 dB points) was run into the detector over several 30 minute trials. It was found that the 11 dB fundamental/7 dB harmonic detection threshold used for the APG data was somewhat aggressive, in that a P_{FA} of 1.6% resulted, or 1 false alarm every 80 seconds. While larger than desired, this could be managed with additional post-processing, such as requiring several detections in a row for low-level detections. When the threshold was raised to 14 dB fundamental/8 dB harmonic, the observed false alarms over 30 minutes dropped to zero, implying $P_{FA} < .07\%$. This reduced false alarm level represents a 3 dB tradeoff against detection range.

Several probability of detection runs were performed at various signal levels. When a simulated footstep signal with a peak amplitude of 5 was combined with additive noise of unit standard deviation, or Peak/(RMS Background)=5, the observed P_D was 100%. (Incidentally, time domain detectors typically have thresholds in the vicinity of 4-5 times the noise standard deviation, limiting detectable Peak/RMS to approximately 4-5.) With Peak/RMS=3, the observed P_D was virtually 100% (99.9%) for the 11 dB threshold and 76% for the 14 dB threshold. With Peak/RMS=2.5, the observed P_D was still 85% for the 11 dB threshold, but dropped to 25% for the 14 dB threshold.

The above suggests that while time domain detectors are limited to a Peak/RMS range of 4-5, the envelope spectrum technique still works down to the 2.5-3 Peak/RMS range. This means that the envelope spectrum detector should have roughly 3-6 dB advantage in minimum detectable signal. Assuming simple cylindrical spreading (20 log R), this should translate into a factor of 1.4 to 2.0 greater detection range. In addition, the envelope spectrum detector should be much less susceptible to false triggers due to rapid variations in the background level, such as when a vehicle passes.

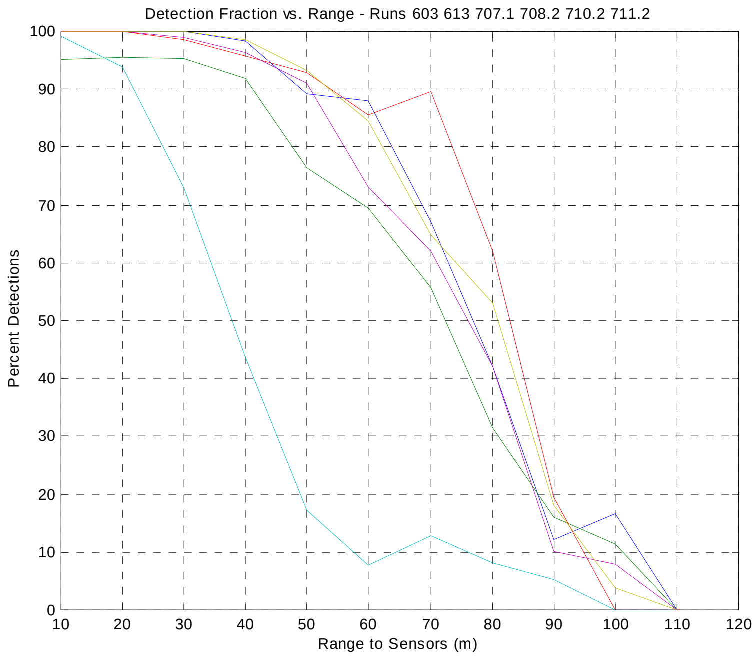


Figure 10
Representative P_D vs. Range - Normal Walk

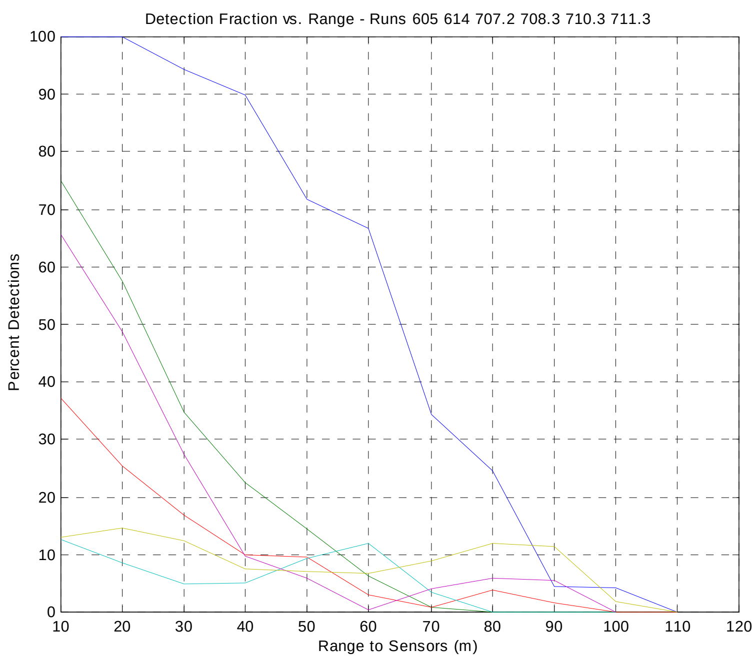


Figure 11
Representative P_D vs. Range - Stealthy Walk

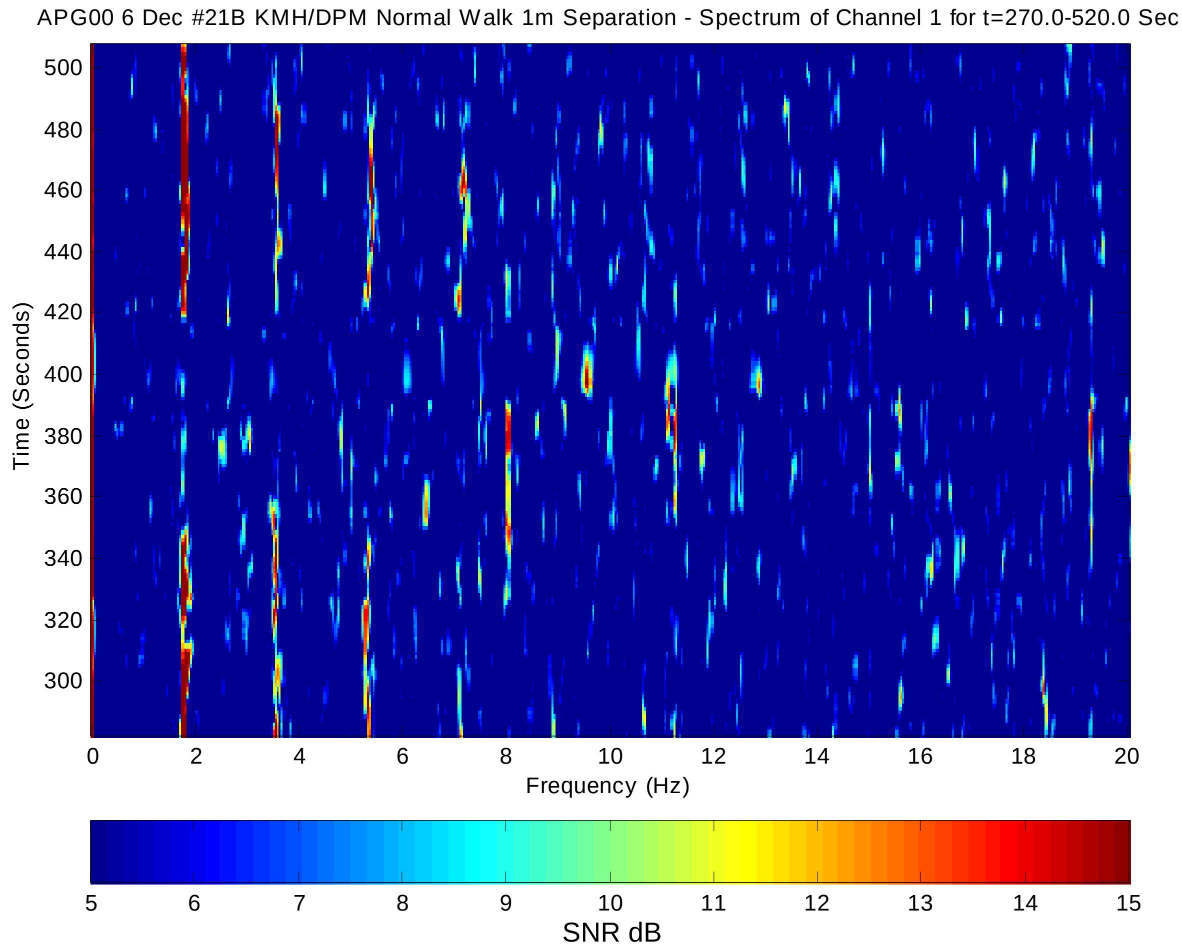


Figure 12
Normalized Spectrogram - 2 Walkers Side-by-Side

5. CONCLUSIONS AND AREAS FOR FUTURE INVESTIGATION

We believe that our approach to footstep detection is new, and shows promise. Since the information in the footstep signal resides primarily in the regular pattern of impulse arrival times and not in the impulses themselves, spectrum analysis may be naturally applied. Targeting periodicities in the arrival times is not only useful for detection, but the frequency information may also be useful for classification and discrimination against other seismic sources (both broadband and narrowband). In particular, gait patterns and their corresponding signatures may help discriminate between human intruders and animals. We believe that this technique may yield a significant improvement in detection range - we observed up to 70-80 meters in some cases for normal walkers for the APG data set - but clearly more data sets are needed.

Detectability of stealthy walkers (creepers) is a serious issue. If someone is determined to walk very slowly and quietly along a considerable distance, there is very little seismic signal to detect. This raises the question: are there complementary sensors which could exploit creepers? To creep one must move very slowly and carefully, so that one would be exposed to other sensors over a considerably longer time (perhaps a factor of 2 longer than a normal walk).

Even with seismic sensors alone, eluding detection would not be simple - one would need to know the locations of all sensors, and begin creeping at least 80-100 meters away. It would be easy to make a mistake and be detected.

We also note that the detector is susceptible to masking from other seismic sources, such as passing vehicles, and like other envelope-based algorithms, a hard threshold effect is observed (much like an FM radio signal tends to "break up" catastrophically in areas of marginal reception). Therefore, to protect a perimeter from intruders, it is especially important to place sensors away from roadsides or other sources of seismic noise.

In the future, additional data sets need to collected and processed for walking, creeping and running. Crawling would also be useful to include. New data sets should examine a range of geological and environmental conditions, and should record enough background signals so as to reliably establish false alarm rates.

Various algorithm improvements can be envisioned. Detection parameters need to be optimized. Time did not permit examination of the direction of travel, which can be observed by estimating bearing using the three-axis seismic sensor and well-established techniques. Likewise, the number of intruders should be readily estimated based upon bearing tracking.

REFERENCES

[1] Richman, M.S., Haney, P.J., Deadrick, D.S., "Performance of a Method for Real-Time Personnel Tracking Using Seismic Sensors", 2001 Meeting of the MSS Specialty Group on Battlefield Acoustic and Seismic Sensing, October 2001.