ARMY RESEARCH LABORATORY

Data Collection and Analysis for Personnel Detection at a Border Crossing

by Thyagaraju Damarla, Tom Walker, and Ronald Sartain

ARL-TR-5426 January 2011

NOTICES

Disclaimers

Army Research Laboratory
Adelphi, MD 20783-1197

ARL-TR-5426 **January 2011**

Data Collection and Analysis for Personnel Detection at a Border Crossing

Thyagaraju Damarla, Tom Walker, and Ronald Sartain
Sensors and Electron Devices Directorate, ARL

REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED (From - To)
January 2011	Final	

4. TITLE AND SUBTITLE Data Collection and Analysis for Personnel Detection at a Border Crossing	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Thyagaraju Damarla, Tom Walker, and Ronald Sartain	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory ATTN: RDRL-SES-A 2800 Powder Mill Road Adelphi, MD 20783-1197	8. PERFORMING ORGANIZATION REPORT NUMBER ARL-TR-5426
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

There is considerable interest in detecting people crossing the border with fewer false alarms and high confidence. This capability requires understanding the phenomenology of various sensor modalities and developing algorithms based on the phenomenology. In an effort to develop this capability, U.S. Army Research Laboratory scientists went to the southwest border to collect data using acoustic, seismic, passive infrared (IR), profiling, electric field, magnetic field, radar, sonar, visible, and IR imaging sensors. In this report, we discuss the data collection effort and resultant data, phenomenology of various sensor modalities, and robust detection algorithms. In the future, the acoustic sensor data will be processed to determine the characteristic features of human voice (formants, etc.), the seismic data will be processed using the ground transfer function to determine the cadence of the person walking (as opposed to an animal), and the radar and ultrasonic data will be processed to determine the Doppler frequency resulting from various limb movements.

15. SUBJECT TERMS

Border crossing, data collection, signature analysis, personnel detection

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Thyagaraju Damarla
Unclassified	Unclassified	Unclassified	UU	42	19b. TELEPHONE NUMBER (*Include area code*) (301) 394-1266

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Contents

List of Figures

List of Tables

1. Introduction

Detection of people is one of the important tasks in Intelligence, Surveillance, and Reconnaissance (ISR) missions. For example, for perimeter protection, one would like to detect intruders both during day and at night, so security can be alerted for appropriate action. In urban operations, one would like to ensure that once a building is evacuated, no one re-enters the building—this implies that sensors need to detect people entering the building. The Department of Homeland Security has a requirement to detect illegal immigrants crossing the border. There are numerous other applications where personnel detection is important.

Detecting people is a challenging problem. For example, acoustic sensors may analyze sound to determine if human voices are present; however, if people are not talking, the acoustic sensors will not be able to detect people based on voice analysis alone. Other sensors may be combined with acoustic sensors such as seismic, non-imaging passive infrared (PIR), sonar, ultrasound, radar, magnetic, and electric field sensors. Multiple sensing modalities are beneficial since no single sensor can detect the presence of humans in every situation and circumstance. There is an emphasis on non-imaging sensors because they require lower power, last longer, and generally are less expensive than imaging sensors. Imaging sensors require higher power and frequent replacement of batteries—hence, there is a higher chance of compromising the mission.

Traditionally, personnel detection research concentrated on footstep analysis using seismic sensors. When a person walks, the person's foot impacts the ground causing vibrations, which are detected by the seismic sensors. In general, a person walks with a rhythm and has a cadence frequency of approximately 1.5 Hz. One objective of the research was to detect and estimate this cadence frequency to distinguish between a person and other targets, such as animals. However, when there are several people walking in a group, it is difficult to estimate the cadence of an individual person and, in fact, it is quite difficult to distinguish between people and animals walking. In order to aid in differentiating people from animals, a multimodal sensor suite was used. Each sensor has unique characteristics that complement other sensing modalities in conducting ISR; section 2 provides a detailed description of the sensors used in this experiment.

2. Sensor Suite

2.1 Acoustic

The acoustic sensors used for this experiment were piezoelectric microphones. Acoustic sensors are low-cost sensors used to detect sound energy generated by people, animals, or machines. Unlike other sensors, these sensors are omnidirectional and do not require line of sight to a target. If more than one microphone is employed, these acoustic sensors can provide a line of bearing to the source of the sound. Figure 1 shows the tetrahedral array of microphones used in collecting the data. The microphones used for this experiment were three Knowles microphones (part number [P/N] BL-1994) with a frequency response of 20 Hz to 20 kHz placed at the base of the tetrahedron array, and a Bruel & Kjaer (B&K) ½-in-diameter microphone (P/N 4191) with a frequency response up to 50 kHz placed on the *z*-axis of the tetrahedron. Each B&K microphone also required a preamplifier (P/N 2669) and power supply (P/N 5939L). The data were collected at 10 K samples per second, providing an effective bandwidth of 5 kHz, which allows capture of both voice and (audible) footstep signatures with sufficient fidelity to detect personnel.

Figure 1. Single microphone and an array (tetrahedral) of microphones with windscreens.

2.2 Seismic

Seismic sensors are similar in operation to acoustic sensors and are used to capture vibrations in the ground caused by footfalls from people or animals walking, or by vehicles traveling in the vicinity, among other sources. The geophone seismic sensors used during our experiment were manufactured by Geospace (P/N GS-3C) and they measure vibrations in all three axes. They were oriented towards magnetic north and were buried about 15 cm deep to increase coupling with the seismic signals (figure 2 shows a photo of the sensor). The sensitivity and frequency response of seismic sensors generally vary depending on design and manufacturer and are typically purchased taking mission requirements into account.

Figure 2. Tri-axis seismic sensor.

2.3 Passive Infrared (PIR)

These non-imaging devices are inexpensive sensors that detect the nearby presence of a warm body, e.g., a human. The field of view (FOV) of the sensor is determined by the lens in front of the actual sensing element. Two different PIRs were employed, one with an FOV of 15° and one with 60°. In addition, the PIR sensors have plates that are charged differentially; they are charged positively or negatively depending on the direction the person is traveling. Hence, it is possible to determine the direction of motion of a target. The sensors reliably detect targets, but do not distinguish whether the target is human, animal or a warm inanimate object. It only records the thermal signature generated by the target. Figure 3 shows a photo of the PIR sensor that was fabricated at the U.S. Army Research Laboratory (ARL) and used for the experiment.

Figure 3. Picture of PIR sensor.

2.4 Magnetic (B-field)

These sensors can be used to detect ferromagnetic materials carried by people, e.g., keys, firearms, and knives. For the experiment we used Model 1540 three-axis fluxgate magnetometers from Applied Physics Systems. They have a sensitivity of 30 μV/nT and are used to detect low frequency components up to 5 Hz. The data from the fluxgate magnetometer were collected at 10 samples per second. Figure 4 shows a photo of the emplaced fluxgate magnetometer.

Figure 4. Picture of fluxgate magnetometer.

2.5 Electrostatic

The sensor used for the experiment was an ARL-built E-field sensor. The sensor consists of two parallel plates with the lower plate grounded with a spike driven into the ground. The plates are charged and when a person having a static E-field (due to rubbing of clothes, etc.) walks nearby the plate potential is affected. The sensor output was recorded at 10 K samples per second. Figure 5 shows a photo of an emplaced E-field sensor.

Figure 5. Picture of E-field sensor.

2.6 Modified Toy Radar

This is a stock Mattel Hot Wheels Radar Gun with a transmit frequency of 10.525 GHz that displays the velocity of the target in km/hr (or mi/hr) that was modified to provide the Doppler frequency of the target (f_d=2v/λ). The toy radar used during the data collection is shown in figure 6.

Figure 6. Mattel Hot Wheels radar gun.

2.7 ARL Compact Radar

The ARL compact radar is a Doppler-based, linear frequency modulated, low-power radar system with an electrically scanned patch-array antenna that allows azimuth and elevation control of the radar beam. The radar system provides sufficient resolution to detect movement of individual arms and legs on humans or animals walking or running—the limb movement velocity information is used to differentiate between humans and animals. Figure 7 shows a photo of the ARL compact radar.

Figure 7. ARL compact radar.

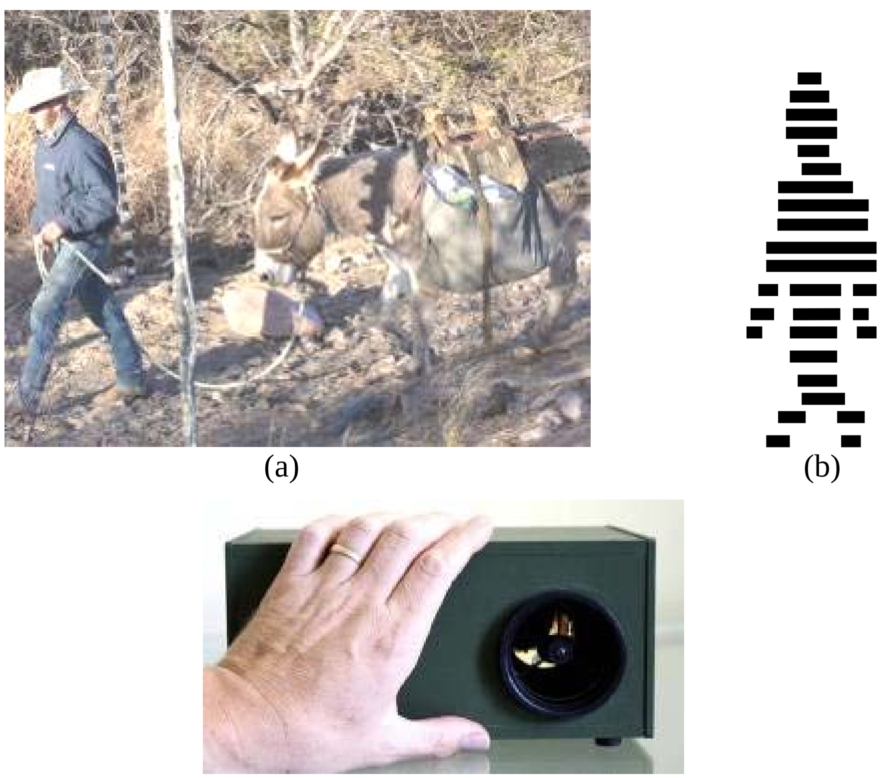
2.8 Ultrasonic

This sensor transmits an acoustic tone at 40 kHz and receives the signals scattered by the target, both active and passive ultrasonic measurements were conducted. For the passive method, a narrowband ultrasonic microphone receiver (UR) was used to measure ultrasonic emissions from footsteps. This UR had a resonance frequency of 25.5 kHz and a bandwidth of 1 kHz at –6 dB, the directivity at –6 dB was 60°. For the active method a 40-kHz ultrasonic continuous-wave (CW) Doppler sensor (UDS) was employed. The sensor was assembled from two 40-kHz ultrasonic transducers (MATSU/PAN EFR-RCB40K 54). These transducers have a typical bandwidth at –6 dB of 2 kHz and a directivity pattern at –6 dB of 55°. One of the transducers, acting as a transmitter, emitted an ultrasonic wave, while the other acted as a receiver. Signals from the UR and the UDS were simultaneously recorded using a 12-channel, 24-bit at 1 V data acquisition board (DAQ) (Echo AudioFire12) and a laptop computer with Loud Technologies software (Tracktion 2). The DAQ, having a sampling rate of 96 kHz, acquired signals from the sensors. These signals were stored on the laptop computer in a .wav format. The UR and UDS were attached to a 1.2-m tall tripod. In the test configurations, the beam pattern of the UR and UDS were oriented along the walking track. Figure 8 shows the ultrasonic sensor used.

Figure 8. Ultrasonic sensor.

2.9 Profiling

This sensor records the silhouette of the target rather than the image of the target. One implementation of the profiling sensor is shown in figure 9a with two vertical poles consisting of IR transmitters mounted on one pole and the receivers mounted on the other. A sample human silhouette is shown in figure 9b. A more covert type of profile sensor built by Brimrose that can be emplaced some distance from the trail is shown in figure 9c.



(a) (b)

(c)

Figure 9. (a) Two-pole profiling sensor, (b) typical human silhouette, and (c) Brimrose profiling sensor.

2.10 Visible Imaging

Each ARL sensor suite also included a Kodak Zi8 video color camera to record ground truth for each data run; the video/audio data were stored on 32-GB SanDisk memory cards. The video camera has a resolution of 1920x1080 pixels at 30 frames per second using a 6.3-mm f/2.8 fixed focus lens. The camera also records audio. Figure 10 shows a picture of the visible video camera set up along the trail and a close-up view.

Figure 10. Picture of daylight video camera set up along trail and close up.

2.11 Visible and Infrared Imaging

These imagers are commonly used in the ISR realm based on the adages that a "picture is worth thousand words" or "seeing is believing." The dual imager used for this experiment came from a Tactical Remote Sensor System (TRSS) and it contains both a visible and IR camera. The visible color video camera has a resolution of 768x494 active pixels, ¼-in charge-coupled device (CCD), and has approximately 450 TV lines. The FOV is approximately 25°. The IR camera used is an uncooled long-wave (8–12 micron) microbolometer with FOV of 25° and a focal plane array resolution of 320x240. The data were collected at 30 frames per second and recorded using an ARL integrated four-channel digital video recorder consisting of four Datavideo 120-Mbyte hard drives and associated control circuitry. Figure 11 shows the emplaced TRSS dual imager and ARL recording equipment used for the experiment, along with a close up of the TRSS imager.

Figure 11. Picture of emplaced TRSS dual imager and ARL data recorder, plus a close-up shot of imager.

2.12 Meteorological Station

The air temperature, wind speed and direction, dew point, barometric pressure, and humidity along with a global positioning system (GPS) time stamp were recorded once every minute using a Vantage Pro 2 Weather Station from Davis Instruments for the duration of the experiment at each test site. At the end of each day, the meteorological data were retrieved from the Vantage Pro Remote Controller and downloaded onto a laptop and stored in a text file. Figure 12 shows a picture of an emplaced Vantage Pro 2 Weather Station.

Figure 12. Picture of Vantage Pro 2 weather station.

3. Data Collection

In order to collect data in a real-world situation, the ARL team went to the U.S. southwest border. Two trips were made: the first visit was to consult with the Department of Homeland Security, which faces the illegal immigration problem on a daily basis, and determine the actual test sites where the experiments would be conducted. After discussions with the border security division and watching surveillance videos, it was determined the experiment would occur at three different types of locations, namely a wash, a trail, and a choke point. Figures 13a–c show pictures of a wash, trail, and choke point (respectively) that are typically found along the southwest border.

Figure 13. (a) Photo of a wash, (b) a trail, and (c) a choke point.

3.1 Data Collection Objectives

Several objectives were envisioned for the field test experiment on the southwest border, these included the collection of personnel, animal, and vehicle signatures using an array of sensors for the purpose of understanding target phenomenology and providing signatures for accomplishing the following:

- Developing multi-sensor fusion algorithms
- Developing detection and classification algorithms for single- and multi-sensor systems
- Supporting target counting and direction of travel algorithms
- Supporting algorithm development to determine if payloads are being carried by humans or animals

3.2 Participating Teams

The following lists the teams that participated in the experiment and what tasks they handled:

- ARL
  - Networked Sensing and Fusion Branch
    - Acoustics, seismic, PIR, E and B-field, and digital video (truth data)
  - Radar Branch
    - Compact radar
- Armament Research and Development Center (ARDEC)
  - Test support
- University of Mississippi
  - Acoustic, seismic, active and passive ultrasonic, and toy radar
- University of Memphis
  - Profiling sensors (parallel optical tripwire and microbolometer)
- Brimrose Co.
  - Thermopile profiling sensor
- Night Vision and Electronic Sensors Directorate (NVESD)
  - Pyroelectric profiling sensor

3.3 Sensor Placement

The experiment used four ARL sensor suites placed approximately 50 m apart along the prescribed travel path. Each sensor suite consisted of acoustic, seismic, PIR, magnetic, E-field, and toy radar sensors. Figure 14 shows a typical deployment of the entire sensor ensemble at a test site and figure 15 shows a photo of an individual ARL sensor suite. The ARL compact radar was placed at a location in-line with the trail that allowed good coverage of the subject movement along the entire travel path, while the TRSS visible and infrared imager was placed at a vantage point off to one side of the trail.

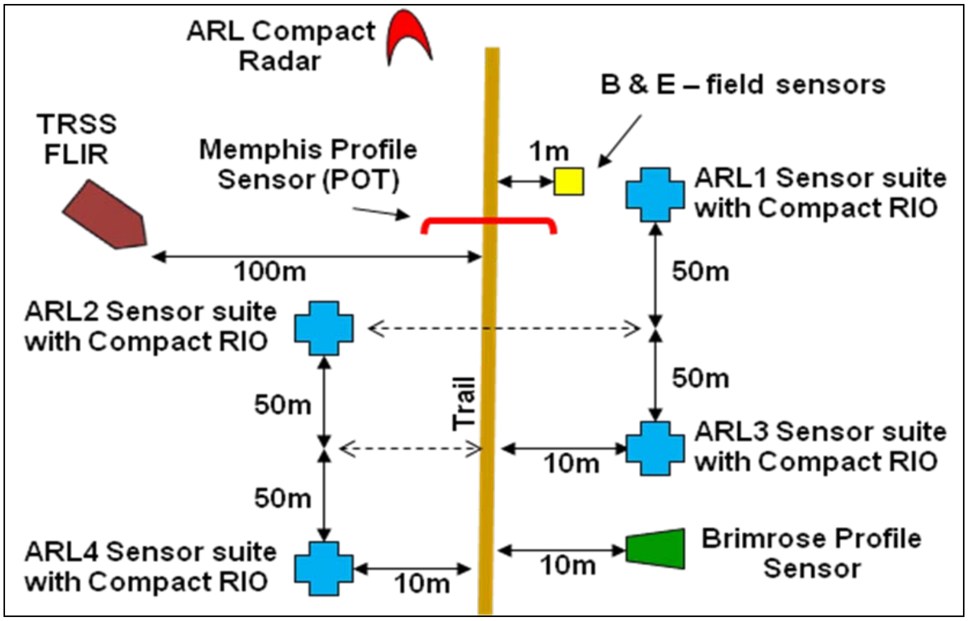


Figure 14. Typical sensor layout.

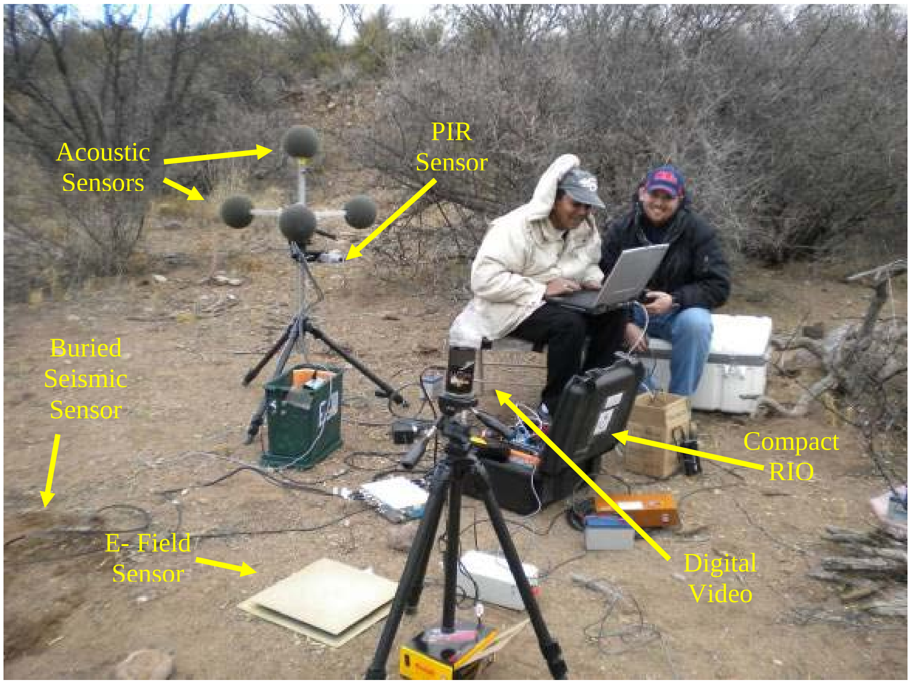


Figure 15. Typical ARL sensor suite.

3.4 Data Collection Equipment

Each ARL sensor suit used a 12-channel, 16-bit National Instruments CompactRIO control and data acquisition system for capturing the various sensor signals. Major advantages of this recording system include low power consumption; small size and operation from 12-V automotive batteries for portability; low noise operation (no cooling fan) that produced very little acoustic and electrical noise that might otherwise corrupt sensor signals; and the inclusion of a GPS receiver that accurately time stamped all the recorded data. The partitioning of the 12 CompactRIO channels and the sampling rate for the sensors are shown in table 1. Each ARL sensor suite also included a Kodak Zi8 daylight video camera to record ground truth that was stored on 32-GB SanDisk memory cards.

Table 1. Apportionment of CompactRIO channels and sampling rate.

Sensor Type	No. Channels	Sampling Rate	Resolution
Acoustic	4 – Analog	10000	16 bit
Seismic	3 – Analog	10000	16 bit
PIR	1 – Analog	10000	16 bit
E-field	1 – Analog	10000	16 bit
Toy Radar	1 – Analog	10000	16 bit
Magnetic	1 – Digital (3 axis)	10	24 bit

3.5 Data Collection Scenarios

The following data collection scenarios were used for the experiment. For the cases where a small animal was used, the handler walked behind the animal. For the large animals, the handlers walked in front.

Run #1: Pre-test checkout of equipment to make sure sensors and recording equipment were operating properly

- Acoustic Sensors: We applied a 1-kHz signal to microphones using an acoustic source (B&K P/N 4230).
- Seismic Sensors (oriented magnetic north): Dropped a 6.5-kg steel weight from 1-m height at 1, 5, and 10 m due north from sensor.
- PIR Sensors: One person walked through FOV of sensor at 1, 5, and 10 m from sensor.
- Magnetic Field Sensors: A person walked past the sensor with a 1-m ferrous metal pipe (5 cm diameter) at 1, 5, and 10 m from sensor.
- E-field Sensors: We used a piezoelectric sparker (from a butane lighter) at 1, 5, and 10 m from sensor.
- ARL compact Radar: One person walked from 1 to 30 m away from the radar at constant velocity and then back towards the radar.

Run #2: One man walking (figure 16)

- We noted the GPS time at the beginning and end of the data run.
- We collected background ambient data for 2 min.
- A person walked from beginning to end of designated path, waited 10 s, then returned along same path and stood still for another 10 s when finished.
- While walking, the person was instructed to talk, sing, hum, etc.

Figure 16. Run #2.

Figures 17 through 20 illustrate Runs #3 though #26. Runs #3 though #26 followed the same data collection procedures as Run #2; they only varied in the participants and activities performed.

Figure 17. (a) Run #3: one man walking with a 40 lb backpack, (b) Run #4: one man running, (c) Run #5: one woman walking, (d) Run #6: one woman walking with 20-30 lb backpack, (e) Run #7: one man and one woman walking, and (f) Run #8: two women walking.

(a) (b) (c) (d) (e) (f)

Figure 18. (a) Run #9: two men running, (b) Run #10: two men running with backpacks, (c) Run #11: three men walking, (d) Run #12: two men and one woman walking, (e) Run #13: three men running, and (f) Run #14: two men and one woman running.


(a) (b)


(a) (b)


(a) (b)

Figure 19. (a) Run #15: three men running with backpacks, (b) Run #16: four men and three women walking, (c) Run #17: one dog with one woman walking, (d) Run #18: one horse with handler walking, (e) Run #19: one horse and one mule with handlers walking, and (f) Run #20: one horse, one mule, and one donkey with three handlers walking.

(a)

(b)

(c)

(d)

(e)

(f)

Figure 20. (a) Run #21: one horse, one mule, and one donkey with three handlers walking, (b) Run #22: one horse with payload with handler walking, (c) Run #23: one horse and one mule with payloads with two handlers walking, (d) Run #24: one horse, one mule, and one donkey with payloads with three handlers walking, (e) Run #25: one ATV going 5 mph, and (f) Run #26: another ATV going 10 mph.

Tables 2–7 provide information on sensor locations and test schedules. All times listed are local mountain standard time (MST); individual test subjects abbreviated as M1 (man 1), M2 (man 2), W1 (woman 1), etc.

Table 2. Sensor locations for test site 2, Tuesday, December 8, 2009.

Sensor Type	Elevation (ft)	Waypoint Name	Site Photo (Y or N)	Notes
MET Station	4423	Wpt 002	y	
Compact RIO #2A	4417	Wpt 003	y	Site also contained radar gun and digital video camera
Compact RIO #3A	4416	Wpt 004	y	Site also contained radar gun and digital video camera
Compact RIO #5A	4440	Wpt 005	y	Site also contained radar gun
TRSS	4459	Wpt 006	y	
ARL Compact Radar	4443	Wpt 009	y	Radar mounted on top of vehicle
Brimrose PFx and Memphis FLIR	4447	Wpt 008	y	
Memphis PFx	4437	Wpt 007	y	

Table 3. Test scenarios and data collection start and end times for test site 2, Tuesday, December 8, 2009.

Run No.	Test Scenario	Start time	Stop time	Notes
2	One man walking	11:52:00 AM		M1
3	One man walking with 40-lb backpack	12:00:00 Noon	12:05:00 PM	M2
4	One man running	12:07:00 PM	12:10:00 PM	M2
5	One woman walking	12:11:00 PM	12:18:27 PM	W1
6	One woman walking with 20-lb backpack	12:19:49 PM	12:18:27 PM	W2
7	One man and one woman walking	12:26:15 PM		M3, W3
8	Two women walking			W1, W2
9	Two men running	12:47:24 PM	12:52:21 PM	M4, M2
10	Two men running with 40-lb backpacks	12:54:00 PM		M2, M3
11	Three men walking	1:00:10 PM	1:06:38 PM	M3, M4, M11
12	Two men and one woman walking	1:08:01 PM	1:14:54 PM	M4 with large iron pipe, M11, W1
13	Three men running	1:16:04 PM	1:20:35 PM	M2, M5, M3
14	Two men and one woman running	1:21:43 PM	1:27:20 PM	M13, M2, W3
15	Three men running with 40 lb backpacks	1:43:10 PM	1:48:48 PM	M2, M1, M4, Compact RIO 2A stopped working
16	Four men, three women, and one dog walking	1:54:48 PM	2:02:04 PM	M1, M2, M4, M6, W1, W2 with dog, W3. Stopped test for lunch break.
17	One dog with one woman walking	2:50:00 PM	2:55:01 PM	W2
22a	Man leading horse with payload	2:56:00 PM	3:02:04 PM	M7
23a	Two men leading horse and mule with payloads	3:04:11 PM	3:10:08 PM	M7, M8
24a	Three men leading horse, mule, and donkey with payloads	3:11:00 PM	3:17:00 PM	M7, M8, M9

Table 3. Test scenarios and data collection start and end times for test site 2, Tuesday, December 8, 2009 (continued).

Run No.	Test Scenario	Start time	Stop time	Notes
21a	Three men walking beside horse, mule, and donkey with payloads	3:17:55 PM	3:24:24 PM	M7, M8, M9
18	Man leading horse	3:36:50 PM	3:42:26 PM	M7
19	Two men leading horse and mule	3:43:52 PM	3:49:58 PM	M7, M8
20	Three men leading horse, mule, and donkey	3:50:18 PM	3:55 PM	M7, M8, M9
22	Man leading horse with saddle pack, 100 lb load	4:00:00 PM	4:04:51 PM	M7
23	Two men leading horse and mule with saddle packs, 100 lb loads	4:05:23 PM	4:11:00 PM	M7, M8
24	Three men leading horse, mule, and donkey with saddle packs, 100 lb loads	4:11:19 PM	4:17:10 PM	M7, M8, M9

Table 4. Sensor locations for test site 2, Wednesday, December 9, 2009.

Sensor Type	Elevation (ft)	Waypoint Name	Site Photo (Y or N)	Notes
MET station	4423	Wpt 002	y	Same location as day 2
Compact RIO #2A	4447	Wpt 010	y	Site also contained radar gun and digital video camera
Compact RIO #3A	4445	Wpt 011	y	Site also contained radar gun
Compact RIO #5A	4439	Wpt 012	y	Site also contained radar gun
TRSS	4459	Wpt 006	y	Same location as day 2
ARL compact radar	4437	Wpt 013	y	Radar pointed due west
Brimrose PFx and Memphis FLIR	4438	Wpt 017	y	Site also contained FLIR and two linear array pyro PIR’s, all pointed 340°
Memphis PFx	4437	Wpt 007	y	Same location as day 2
Digital movie camera	4447	Wpt 014	y	Two digital movie cameras used during the test
Mississippi ultrasonic and radar	4413	Wpt 015	y	
Black body radiator	4438	Wpt 018	y	Used to calibrate FLIR sensors

Table 5. Test scenarios and data collection start and end times for test site 2, Wednesday, December 9, 2009.

Run No.	Test Scenario	Start time	Stop time	Notes
25	1 ATV traveling ~5 mph	12:15:45 PM	12:20:13 PM	Yamaha Grizzly 750 FI
26	1 ATV traveling ~10 mph	12:24:17 PM	12:27:44 PM	Yamaha Grizzly 750 FI
27	1 ATV traveling ~5 mph with man running behind	12:30:15 PM	12:34:38 PM	Yamaha Grizzly 750 FI and M2 running
27a	1 ATV traveling ~5 mph with man running behind	12:38:17 PM	12:42:27 PM	Yamaha Grizzly 750 FI and M2 running
28	2 ATV’s traveling ~10 mph	12:46:15 PM	12:49:52 PM	2 Yamaha Grizzly 750 FI
29	3 ATV’s traveling ~10 mph	12:52:55 PM	12:57:54 PM	2 Yamaha Grizzly 750 FI and 1 Yamaha Kodiak Ultramatic 400 (all single-cylinder engines)

Table 5. Test scenarios and data collection start and end times for test site 2, Wednesday, December 9, 2009 (continued).

Run No.	Test Scenario	Start time	Stop time	Notes
2	One man walking	1:02:05 PM	1:08:29 PM	M1, helicopter noise
3	One man walking with 40-lb backpack	1:11:10 PM	1:17:18 PM	M2
4	One man running	1:19:50 PM	1:24:17 PM	M2
5	One woman walking	1:27:08 PM	1:34:52 PM	W1 (unsure of trail path), ATV started during ambient data period, added another minute, ATV and bird noise during run.
6	One woman walking with 20-lb backpack	1:37:31 PM	1:43:59 PM	W2
7	One man and one woman walking	1:45:47 PM	1:52:28 PM	W3, M3
8	Two women walking	1:53:54 PM	2:00:49 PM	W1, W2
9	Two men running	2:02:52 PM	2:07:53 PM	M4, M2, noise from Memphis gazebo as it flapped in strong wind
10	Two men running with 40-lb backpacks	2:10:51 PM	2:16:11 PM	M12, M2, helicopter noise during run
11	Three men walking	2:18:25 PM	2:25:04 PM	M3, M4, M11
12	Two men and one woman walking	2:26:24 PM	2:32:50 PM	M4 with large iron pipe, M11, W1
13	Three men running	2:42:41 PM	2:47:26 PM	M12, M2, M5, ATV noise in background
14				Skipped this test run
15	Three men running with 40-lb backpacks	2:51:00 PM	2:56:13 PM	M4, M13, M2. Dog barked at end of run.
16	Four men, three women, and one dog walking	2:57:25 PM	3:04:29 PM	M1, M2, M4, M6, W1, W2 with dog, W3
17	One dog with one woman walking	3:05:59 PM	3:12:01 PM	W2
18	Man leading horse	3:17:09 PM	3:23:18 PM	M7, Memphis gazebo making noise flapping in wind
19	Two men leading horse and mule	3:24:16 PM	3:30:19 PM	M7, M8, ATV horn beeped 3:26:10PM.
20	Three men leading horse, mule, and donkey	3:34:40 PM	3:41:08 PM	M7, M8, M9
21				Skipped this test run
22	Man leading horse with saddle pack, 100 lb load	3:51:35 PM	3:57:19 PM	M7
23	Two men leading horse and mule with saddle packs, 100-lb loads	3:59:00 PM	4:04:56 PM	M7, M8, cell phone rang 3:59:10, Memphis gazebo flapping noise 4:00:05, walkie talkie call ringer 4:02:40, jet passed overhead 4:03:31.
24	Three men leading horse, mule, and donkey with saddle packs, 100-lb loads	4:07:14 PM	4:12:56 PM	M7, M8, M9
22a	Man leading horse with payload	4:37:00 PM		M7
23a	Two men leading horse and mule with payloads	4:38:00 PM		M7, M8
24a	Three men leading horse, mule, and donkey with payloads	4:40:00 PM		M7, M8, M9
22b	Man leading donkey with payload	4:42:00 PM		M9

Table 6. Sensor locations for test site 3, Thursday, December 10, 2009.

Sensor Type	Elevation (ft)	Waypoint name	Site Photo (Y or N)	Notes
MET station	4477	Wpt 021	y	
Compact RIO #2A	4471	Wpt 023	y	
Compact RIO #3A	4462	Wpt 025	y	
Compact RIO #5A	4439	Wpt 026	y	
TRSS				Did not set up TRSS on day 4
ARL compact radar	4440	Wpt 028	n	Raju's camera battery died
Brimrose PFx and Memphis FLIR	4413	Wpt 029	n	
Memphis PFx	4477	Wpt 022	n	
Mississippi ultrasonic and radar	4455	Wpt 024	y	
Trail start			n	GPS receiver battery died
Trail end	4433	Wpt 027	y	

Table 7. Test scenarios and data collection start and end times for test site 3, Thursday, December 10, 2009.

Run No.	Test Scenario	Start time	Stop time	Notes
0	Two border patrol agents	12:01:59 PM	12:08:32 PM	1 agent with M16 rifle, both with sidearms and small backpacks
18	Man leading horse	12:12:58 PM	12:19:23 PM	M7, small airplane flew over 12:17:00
19	Two men leading horse and mule	12:22:28 PM	12:28:46 PM	M7, M8, red tail hawk called from above
20	Three men leading horse, mule, and donkey	12:31:45 PM	12:38:12 PM	M7, M8, M9
21				Skipped this test run
22	Man leading horse with saddle pack, 100-lb load	12:48:32 PM	12:54:35 PM	M7, heard ATV and walkie talkie call ringer
23	Two men leading horse and mule with saddle packs, 100 lb loads	1:00:08 PM	1:06:30 PM	M7, M8
24	Three men leading horse, mule, and donkey with saddle packs, 100-lb loads	1:08:59 PM	1:15:20 PM	M7, M8, M9
22a	Man leading horse with payload	1:22:59 PM	1:28:59 PM	M7, crow called in background
23a	Two men leading horse and mule with payloads	1:30:52 PM	1:37:33 PM	M7, M8
24a	Three men leading horse, mule, and donkey with payloads	1:41:40 PM	1:47:45 PM	M7, M8, M9
2	One man walking	1:52:00 PM	1:57:08 PM	M10
3	One man walking with 40-lb backpack	2:00:06 PM	2:05:30 PM	M4
4				Skipped this test run
5	One woman walking	2:07:18 PM	2:13:22 PM	W1
6	One woman walking with 20-lb backpack	2:15:44 PM	2:21:20 PM	W2
7	One man and one woman walking	2:23:49 PM	2:29:53 PM	W3, M4
8	Two women walking	2:43:43 PM	2:49:50 PM	W1, W2
9				Skipped this test run
10				Skipped this test run
11	Three men walking	2:52:23 PM	2:58:30PM	M1, M4 with large iron pipe, M11

Table 7. Test scenarios and data collection start and end times for test site 3, Thursday, December 10, 2009 (continued).

Run No.	Test Scenario	Start time	Stop time	Notes
12	Two men and one woman walking	3:00:42 PM	3:06:54PM	M4, M11, W4, jet noise overhead 3:04:00
13				Skipped this test run
14				Skipped this test run
15				Skipped this test run
16	Four men, three women, and one dog walking	3:11:04 PM	3:17:39 PM	M1, M12, M4 with large iron pipe, M6, W4, W3, W2 with dog
16a	Background ambient noise test	3:20:49 PM	3:24:00 PM	Radio talk 3:21:18, voices and radio talking 3:22:15, crow called 3:23:20

4. Data Analysis and Algorithm Development

4.1 Acoustic Sensor Data Analysis for Personnel Detection

The analysis of the acoustic sensor data is primarily concentrated on three aspects: (1) human voice detection by way of formant detection (*8*), (2) spread of energy of human voice in various spectral bands (*7, 8*), and (3) footstep detection for estimation of cadence.

4.1.1 Detection of Formants

Humans generate their speech sounds by modulating the vocal cords and appropriately opening and closing their vocal tract. In general, there are several frequencies associated with voice and they are called formants. A small segment of speech signal is shown in figure 21. One would notice from figure 21 that whenever a word is spoken a burst of high frequency signal appears along with the background noise. This high frequency signal is called the formant and it varies from person to person and also on the word spoken. In general, the frequency lies between 200–800 Hz for the people we tested. Figure 22a shows an expanded version of the first segment of the voice signal shown in figure 21, and figure 22b shows the Fourier transform of the segment. Clearly, one can see the dominant frequency around 300 Hz. The objective of the signal processing is to detect and determine this frequency. As mentioned previously, the carrier frequency (formant) is amplitude modulated whose representation may be given as

$$s(t) = (A_c + A_m \sin(2\pi f_m t))\cos(2\pi f_c t) \quad (1)$$

where "f_c" and "f_m" represent the carrier and modulating frequencies and "A_c" and "A_m" denote their magnitudes, respectively. The signal has three distinct frequency components, namely, f_c, $f_c + f_m$, and $f_c - f_m$. The spread (see figure 22b) of frequency is then $\pm f_m$ around the carrier. The algorithm for detection of human voice consists of estimating the formant (carrier frequency) and the spread. If the spread is above some threshold, we declare it is a human voice. Statistical analysis is performed on various speech signals in order to determine the threshold value.

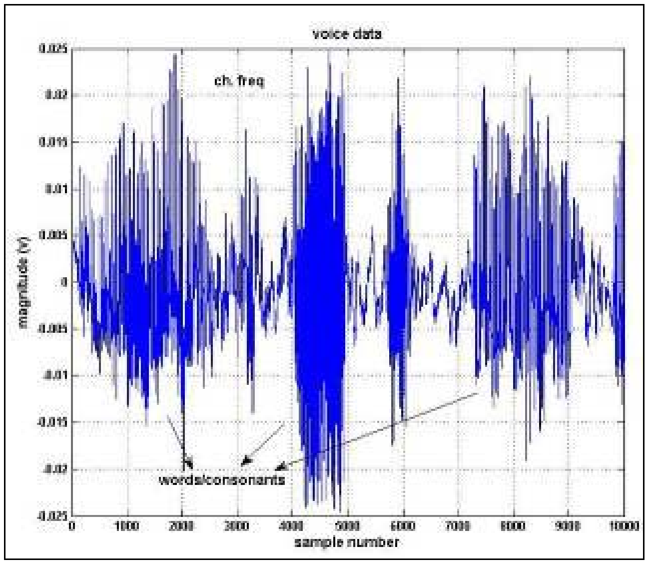


Figure 21. Sample voice data.

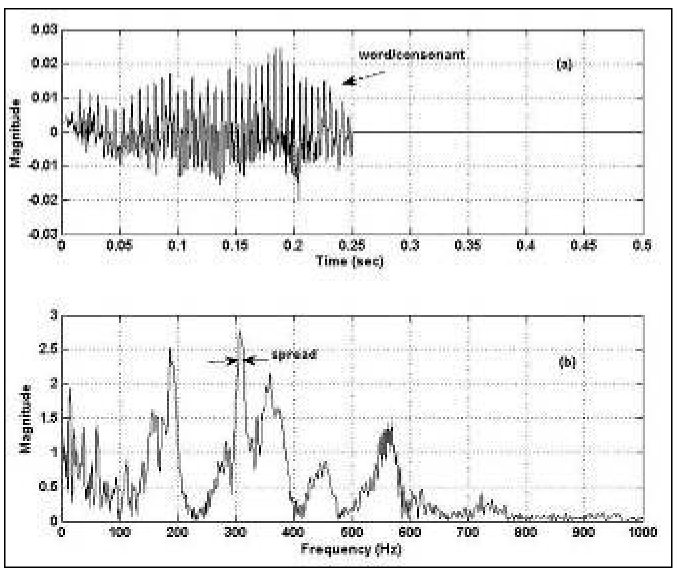


Figure 22. (a) Portion of voice signal in figure 16 and (b) its spectrum.

4.1.2 Detection of People Using Energy in Several Bands

It is known (*8*) that the human voice spans 50 Hz–20 kHz frequency range; however, most of the energy is concentrated in four bands, as can be seen in figure 22b. These bands are 50–250, 251–500, 501–750, and 751–1000 Hz. The energy levels in these bands are the features and designated by the feature vector $X = \{x_1,x_2,x_3,x_4\}$, where x_i is the energy in band 'i'. The feature vectors are used to classify whether they belong to human voice or not using a multivariate

Gaussian (MVG) classifier, as described in reference 7. For the sake of continuity, we present a short description of the MVG classifier. We assume the energy levels in each band are statistically independent and have the Gaussian distribution given by

$$p(X_i) = \frac{1}{(2\pi)^{1/2} |\Sigma_i|^{1/2}} \exp\left\{ -\tfrac{1}{2} (X_i - M_i)^T \Sigma^{-1} (X_i - M_i) \right\}, \tag{2}$$

where M_i and Σ_i denote the mean and variance respectively and T denotes the transpose. Then, the likelihood that a person is present or not is given by

$$p(X \mid H_j) = \prod_{i=1}^{N} p(X_i \mid H_j)\ p(H_j), \quad j = \{0,1\}, \tag{3}$$

where H_0 and H_1 are the hypotheses that correspond to a person is not present and a person is present, respectively. Then, the posterior probability of human presence is given by

$$p(H_1 \mid X) = \frac{\prod_{i=1}^{N} p(X_i \mid H_1)\ p(H_1)}{\prod_{i=1}^{N} p(X_i \mid H_0)\ p(H_0) + \prod_{i=1}^{N} p(X_i \mid H_1)\ p(H_1)}. \tag{4}$$

Assuming the priors $p(H_0) = p(H_1) = 0.5$, we can compute the posterior probability of a human present given X. If it exceeds a particular threshold value, we declare that a human is detected. The algorithm is given as follows:

Algorithm 1:

1. Let $s(t)$ correspond to 1-s data
2. $S = fft(s)$ is the Fast Fourier transform of the signal $s(t)$.
3. Compute the energy in each band. These energies become the feature vector $X = \{x_1,x_2,x_3,x_4\}$. Compute the mean and variances for feature x_i for all i.
4. Use equations 2 and 4 with appropriate means and variances for noise and statistics collected on people to compute the posterior probability $p(H_1|X)$
5. Use the posterior probability for fusion and declare that a person is detected if $p(H_1|X) > 0.6$.

An additional component of the acoustic data analysis is footstep detection. This is the same as footstep detection using seismic sensor data and is covered in the next section. Figure 23 shows the block diagram for acoustic data analysis for personnel detection.

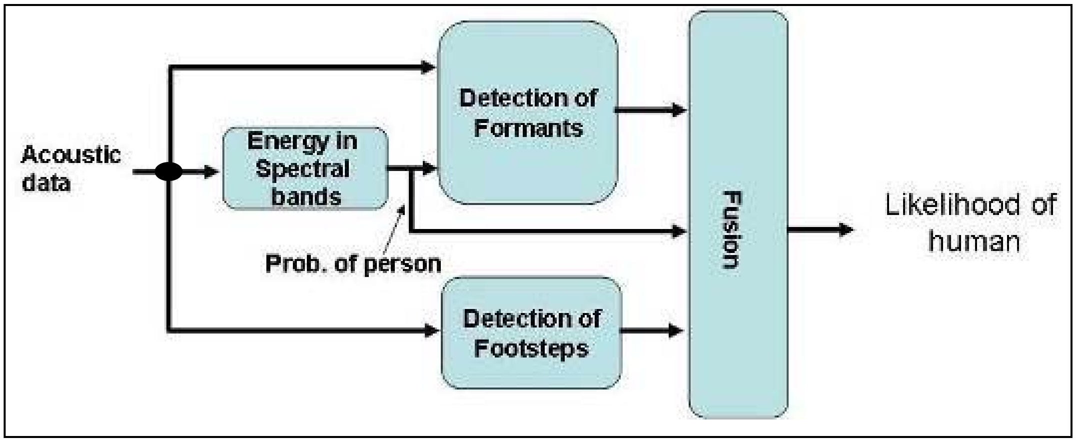


Figure 23. Acoustic data processing.

4.2 Seismic Data Analysis

The main purpose of seismic sensor is to detect footfalls of humans walking within the receptive field of the sensor. There is a considerable amount of literature (*1–6*) in footstep detection. Traditionally, they focused on estimation of cadence. However, if multiple people are in the vicinity of the sensor and walking, it is difficult to estimate the cadence of an individual person. Moreover, if there are animals present, it is difficult to differentiate multiple people walking and animals walking by observing the footfalls. However, multiple footfalls superpose one another resulting in a frequency of "*c*" Hz (where "*c*" is the cadence of a person) along with several harmonics of "*c*." So, seismic algorithms would look for harmonics of cadence or several strong frequency components between 2 to 15 Hz. The seismic algorithm is similar to that of algorithm 1, once the feature set is determined. For the feature set, we first compute the spectrum of the envelop (*1, 7*) of the seismic signal accumulated for a period of 6 s (to encompass several footfalls). Then, the feature set consists of amplitudes of the frequency bins from 2 to 15 Hz. These amplitudes become the feature set $X = \{x_1, x_2, \cdots, x_n\}$. Then, algorithm 1 is used to estimate the posterior probability of footsteps present.

As mentioned earlier, the algorithm only determines whether there are footsteps or not. However, in order to determine the presence of humans, it is necessary to determine whether these footsteps belong to a human or an animal. For this, we invariably turn to acoustics. If there is voice, it can be detected and identified as human voice based on the formants as described in section 4.1. In order to distinguish between people and animals, we analyze the sound generated by the animals walking. When the hoofs of a horse hit the ground, they make a distinct sound. Figure 24a shows the signature of a horse walking (for a period of 6 s) and figure 24b shows the signature with the noise removed. The noise removal is performed using empirical mode decomposition (*4, 6*) of the original signal into various component signals. From figure 24, it is clear that there are three peaks uniformly distributed in each time interval of one second. This indicates the cadence of the horse to be approximately 2.8 to 3 Hz. Since the cadence of a person is around 1.5 to 2 Hz, one can infer the presence of animals.

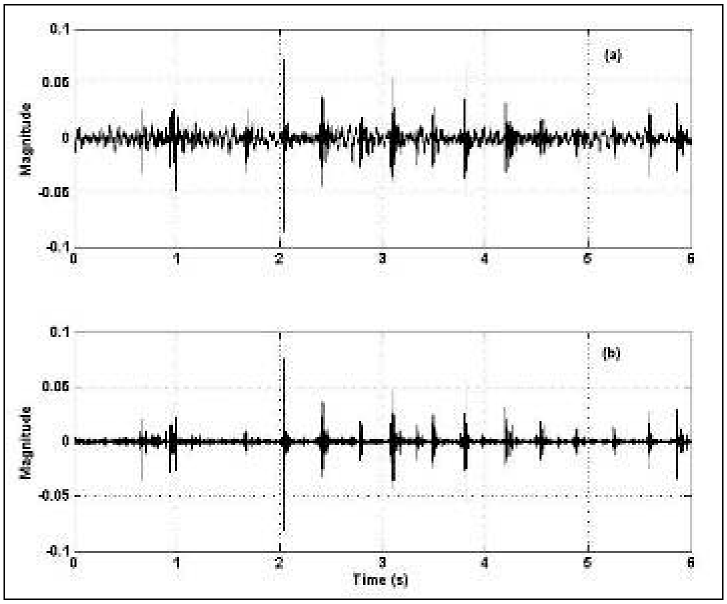


Figure 24. (a) Hoof signature (b) hoof signature after noise removal.

In this section, we process the ultrasonic data. This is primarily analyzed to distinguish the characteristic arm and leg movements by observing the micro-Doppler pertaining to these limbs. Typical micro-Doppler frequencies from moving portions (arms, legs, chest, etc.) of a person walking for the active ultrasonic sensor are shown in figure 25. Ideally, the micro-Doppler signatures from humans will be sufficiently different from animals to enable target classification. However, since the analysis of the micro-Doppler signatures is still ongoing, it remains to be seen if this capability can be realized. Here, we are able to process the ultrasonic data to count the number of targets in the vicinity using the energy content in the micro-Doppler return. Figure 26 shows the flow chart for the algorithm used in counting the number of targets. For processing the ultrasonic data, a 1-s interval of the sampled data is used, and the algorithm shown in figure 26 is used to find the energy in each band. Then a sliding window is used, which covers 10,000 samples (approximately 0.1 s), and next set of data is obtained and processed.

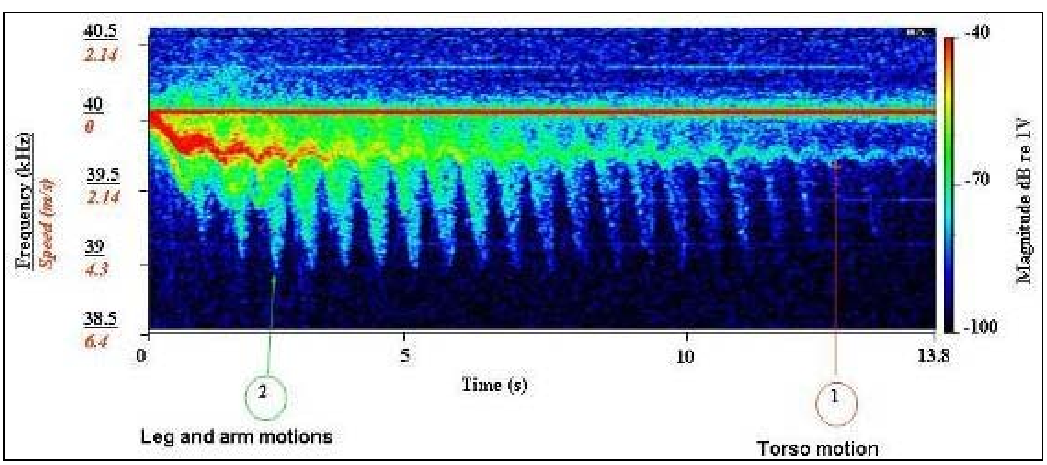


Figure 25. Micro-Doppler signature of a person walking for the active ultrasonic sensor.

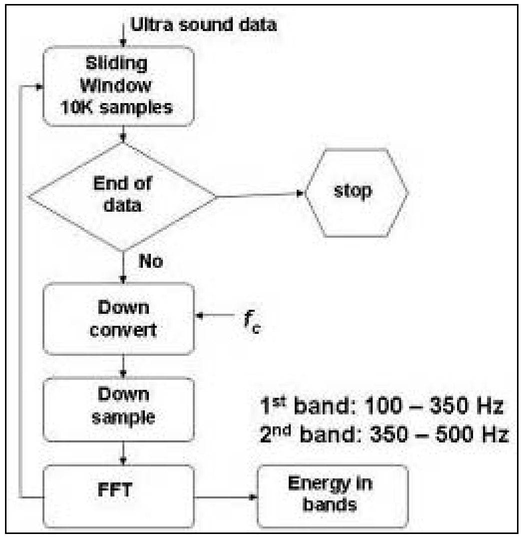


Figure 26. Flow chart for ultrasonic data processing.

In section 5, we describe the data collection scenarios used and show some of the results of various algorithms on real data collected at southwest border.

5. Data Collection and Algorithm Results

In order to collect data in a realistic environment, we traveled to the U.S. southwest border and performed the experiments on routes typically used by smugglers. We selected three types of common travel routes used by illegal immigrants crossing the border:

1. A wash, a flashflood river bed with fine grain sand interspersed with rocks
2. A trail, a worn path through the shrubs and bushes usually heading towards a pick-up destination
3. A choke point, a valley between two mountains or large hills

During the data collection experiment, we used several sensor modalities: acoustic, seismic, PIR, magnetic, E-field, active and passive ultrasonic, IR and visible imagers, and video sensors. Each sensor suite was alternately placed along the selected travel path about 50 m apart. Some of the scenarios used for data collection experiment included (1) a single person walking with and without a back pack, (2) two people walking, (3) multiple people walking, (4) one person leading an animal, (5) two people leading animals, and (6) three people leading animals with and without payloads. A total of 26 scenarios with various combinations of people, animals and payload were run and data were collected for the three chosen test sites. The data were collected over a period of three days, at a different site and different environment each day. At times, there was wind and other times it was still and quiet.

5.1 Voice Analysis and Algorithm Results

Acoustic data was analyzed for the presence of formants pertaining to human speech. The algorithm results are shown in figure 27a for a segment of data collected during the experiment. Figure 27b is a bar chart showing the detections of humans. The results of the analysis are verified by playing back the recorded audio ground truth and listening for the human voices. The detection at time period "9 s" is clearly a false alarm.

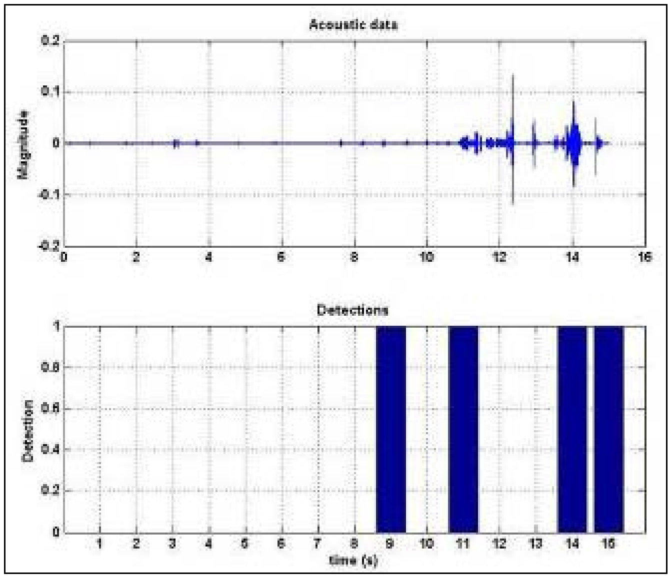


Figure 27. (a) Acoustic data and (b) detections.

5.2 Seismic Data Analysis and Algorithm Results

The seismic data was analyzed for footstep detection, as described in section 4.2, and the results are shown in figure 28a. In figure 28b, we find that the detection algorithm did not detect initial footsteps for about 8 s as the amplitudes of the footsteps are very weak. Once the footsteps are detected, the algorithm continued to detect until the footsteps faded away. We also notice there are a few misdetections. The initial lapse is due to the fact that 6 s worth of data is needed to analyze the foot step detection. The misdetections could be due to the training data.

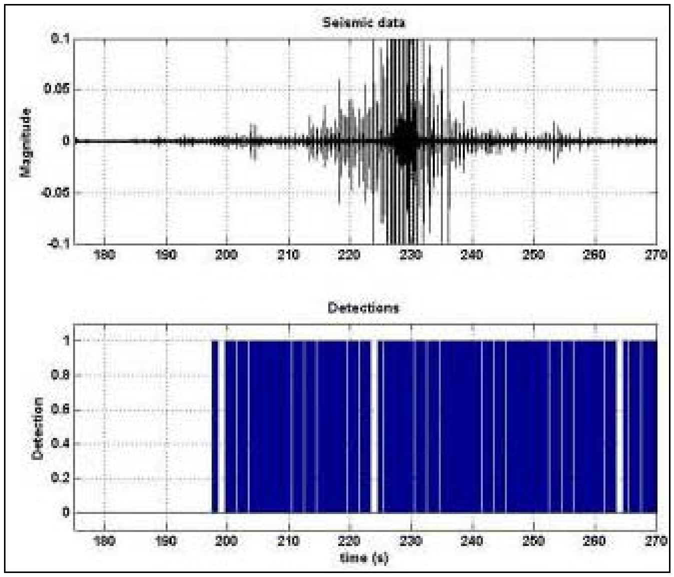


Figure 28. (a) Seismic data and (b) detections.

5.3 Ultrasonic Data Analysis for Counting Number of Targets

The ultrasonic data was analyzed for counting the number of targets using the algorithm shown in figure 26. The results are shown in figure 29. Each subfigure in figure 29 corresponds to one of the scenarios enacted during the data collection test. These figures show how many people and animals are walking as analyzed by the ultrasonic sensor. The *x*-axis of each subfigure corresponds to the number of iterations the algorithm uses; for each iteration, the data set is time shifted by 0.1 s. The number of distinct peaks in each subfigure shows the number of targets.

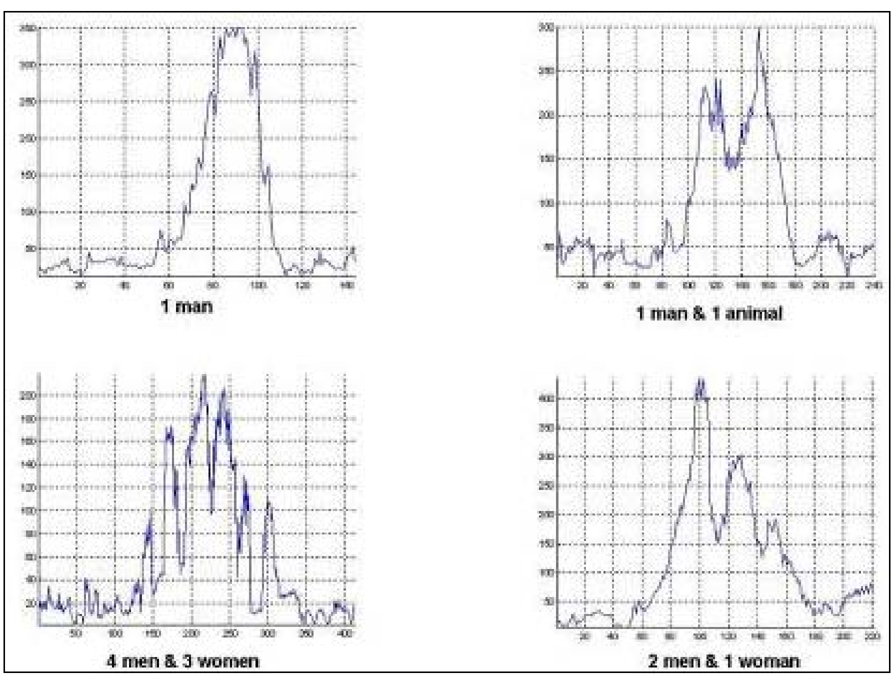


Figure 29. Results of ultrasonic data processing.

6. Conclusion

The goal of the experiment was to collect personnel, animal, and vehicle signatures at active southwestern U.S. border crossing locations using an array of multimodal sensors. The resulting data set allows ARL researchers to analyze and better understand target phenomenology, to provide signatures for the development of multi-sensor fusion algorithms, and to enable the creation of detection and classification algorithms (for single and multi-sensor systems) and target counting algorithms. An added benefit of the research will be the determination of which sensors are best suited to work in concert, and which algorithms and sensors maximize the probability of correctly classifying humans versus animals versus vehicles for tomorrow's unattended ground sensor systems. The initial research findings using border crossing multimodal data show great promise in the development of sensor fusion algorithms for target discrimination, and likely will continue to be a focus of researchers at ARL and academia in the near future.

7. References

1. Houston, K. M.; McGaffigan, D. P. Spectrum Analysis Techniques for Personnel Detection Using Seismic Sensors. *Proc. of SPIE* **2003**, *5090*, 162–173.

2. Sabatier, James M.; Ekimov, Alexander. Range Limitation for Seismic Footstep Detection. *Proc. of SPIE* **2008**, *6963*, 69630V-1.

3. Ekimov, Alexander; Sabatier, James M. Passive Ultrasonic Method for Human Footstep Detection. *Proc. of SPIE* **2007**, *6562*, 656203.

4. Sunderesan, A.; Subramanian, A.; Varshney, P. K.; Damarla, T. A Coupula Based Semi-parametric Approach for Footstep Detection Using Seismic Sensor Networks. *Proc. of SPIE* **2010**, *7710*, 77100C.

5. Bland, R. E. Acoustic and Seismic Signal Processing for Footstep Detection. Master's Thesis, Massachusetts Institute of Technology, Department of Electrical Engineering and Computer Science, 2006.

6. Iyengar, S. G.; Varshney, P. K.; Damarla, T. On the Detection of Footsteps Based on Acoustic and Seismic Sensing. *in Conference Record of the Forty First Asilomar Conference on Signals, Systems and Computers* **4–7 Nov. 2007**, *ACSSC 2007*, 2248–2252.

7. Damarla, Raju; Ufford, David. Personnel Detection Using Ground Sensors. *Proc. of SPIE* **2007**, *6562*, 656205.

8. Encyclopedia of Acoustics, Vol. 4, Edited by Malcolm J. Crocker, Published by John Wiley & Sons, Inc. New York, NY, 1997.

List of Symbols, Abbreviations, and Acronyms

ARDEC	Armament Research and Development Center
ARL	U.S. Army Research Laboratory
B&K	Bruel & Kjaer
CW	continuous-wave
DAQ	data acquisition
GPS	global positioning system
FOV	field of view
ISR	Intelligence, Surveillance, and Reconnaissance
MVG	multivariate Gaussian
NVESD	Night Vision and Electronic Sensors Directorate
P/N	part number
PIR	passive infrared
TRSS	Tactical Remote Sensor System
UDS	Doppler sensor
UR	microphone receiver

NO. OF COPIES	ORGANIZATION
1 ELEC	ADMNSTR DEFNS TECHL INFO CTR ATTN DTIC OCP 8725 JOHN J KINGMAN RD STE 0944 FT BELVOIR VA 22060-6218
1 CD	OFC OF THE SECY OF DEFNS ATTN ODDRE (R&AT) THE PENTAGON WASHINGTON DC 20301-3080
1	US ARMY RSRCH DEV & ENGRG CMND ARMAMENT RSRCH DEV & ENGRG CTR ARMAMENT ENGRG & TECHNLGY CTR ATTN AMSRD AAR AEF T J MATTS BLDG 305 APG MD 21005-5001
1	PM TIMS PROFILER (MMS-P) AN/TMQ-52 ATTN B GRIFFIES BUILDING 563 FT MONMOUTH NJ 07703
1	US ARMY INFO SYS ENGRG CMND ATTN AMSEL IE TD A RIVERA FT HUACHUCA AZ 85613-5300
1	COMMANDER US ARMY RDECOM ATTN AMSRD AMR W C MCCORKLE 5400 FOWLER RD REDSTONE ARSENAL AL 35898-5000
1	US GOVERNMENT PRINT OFF DEPOSITORY RECEIVING SECTION ATTN MAIL STOP IDAD J TATE 732 NORTH CAPITOL ST NW WASHINGTON DC 20402
1	US ARMY CERDEC ATTN: ROBERT FORESTA INTELLIGENCE & INFO WARFARE DIR BLDG 6003 APG MD 21005

NO. OF COPIES	ORGANIZATION
1	US ARMY RSRCH LAB ATTN RDRL CIM G T LANDFRIED BLDG 4600 APG MD 21005-5066
25	US ARMY RSRCH LAB ATTN IMNE ALC HRR MAIL & RECORDS MGMT ATTN RDRL CIM L TECHL LIB ATTN RDRL CIM P TECHL PUB ATTN RDRL SES A R DAMARLA (5 COPIES) R SARTAIN T WALKER (5 COPIES) N SROUR J HOUSER (5 COPIES) K BENNETT L KAPLAN T PHAM ATTN RDRL SES E M THIELKE ATTN RDRL SER M JOHN CLARK ADELPHI MD 20783-1197
3	US ARMY ARDEC ATTN SHAFIK QUORAISHEE ATTN DAVID GRASING ATTN SACHI DESAI FUZE PRECISION ARMAMENT TECHNOLOGY DIVISION PICATINNY ARSENAL NJ 07806
1	US ARMY NIGHT VISION LAB ATTN JOHN HUTCHISON ROBOTICS URBAN & GROUND SENSORS FORT BELVOIR VA 22060-5806
1	UNIVERSITY OF MISSISSIPPI ATTN JAMES M. SABATIER NATIONAL CTR FOR PHYSICAL ACOUSTICS 1 COLISEUM DR. UNIVERSITY MS 38677

NO. OF COPIES	ORGANIZATION
5	UNIVERSITY OF MEMPHIS ATTN DR. SRIKANT KRISHNASWAMI CHARI ATTN R. KENNY REYNOLDS ATTN JEREMEY BENJAMIN BROWN ATTN JASON MICHAEL BROOKS ATTN FORREST ALBERT SMITH 206 ENGINEERING SCIENCES BLVD MEMPHIS TN 38152

TOTAL:44 (1 ELEC, 1 CD, 42 HCS)