Zero False Alarm Seismic Detection and Identification Systems

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ABSTRACT

General Sensing Systems (GSS) has achieved outstanding and verifiable results in the design and development of various seismic detection and identification systems. These results include, in particular, new seismic miniature sensor design and seismic signal recording and research for many traditional and nontraditional targets—walking, running and jumping persons, heavy and light vehicles, helicopters and aircraft, ships, trains, etc. These results also include the hardware design for up-to-date unattended seismic detection and identification systems. The main outcome of our effort is detection and identification algorithms and corresponding software for personnel and vehicle detection and identification which were tested in real environment conditions. These algorithms provide a zero false alarm rate with no target missing and can be used for many real and important military and homeland security applications. We also report on future seismic detection and identification systems for various military and civil applications.

Keywords: Zero false alarm, seismic systems, sensors, signals, detection and identification.

1. INTRODUCTION

Seismic detection and identification systems have a very broad spectrum for the homeland security, military and civil security applications. Performance capabilities of such systems strongly depends on many factors and components. The most important are: seismic sensors (geophones); seismic signal processing algorithms/procedures; and amplifying and computing hardware (seismic amplifiers and micro controllers). During the past five years, GSS has achieved remarkable and verifiable results in the design of all the above mentioned components for many purposes and applications [1, 2, 4-7, 9-14, 16-19]. In addition, GSS has researched seismic signal characteristics for a complete set of various targets, including walking, running and jumping persons, light and heavy vehicles, helicopters, aircrafts, ships etc. [3, 8, 15].

In this paper, we report and summarize our general results. In particular, we report on GSS's small, inexpensive and highly sensitive seismic sensor. This sensor displays much better characteristics according to laboratory and field seismic testing in various conditions than, for example, the commercial GS-14-L3 and GS-20DX geophones produced by Geo Space Corporation [20]. We describe the capability and field-testing results of our software versions that were specifically designed for detection and identification of personnel and light and heavy vehicles. The software and corresponding algorithms allow to detect targets at a high detection range with actually zero false alarm rate and without missing targets. Various versions of such software were designed and tested for all set of the micro controllers for seismic signal processing and detection-identification decision making in up-to-date unattended seismic detection and identification modules with various limitation in terms of power supply, size and so on. Corresponding modules can be used in many very useful and reliable seismic detection and identification systems for security and military applications. Such systems can be wired or wireless, mobile and autonomous or stationary, etc.

We also report on prospective design ideas and the future of seismic detection and identification systems for various homeland security, military and civil-security applications.

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2. RESULTS AND DISCUSSIONS

2.1 New miniature seismic sensor

GSS has designed a new, extremely small, inexpensive and very sensitive seismic sensor, based on using electret materials. GSS's new electret-based sensor (GSS-EBS) was described in our papers and in US patents [6, 7, 9-14, 17]. Two examples of the test version of the GSS sensor in comparison with Geo Space's Commercial Geophones GS-14-L3 and GS-20DX are shown in Figure 1. A picture of the GSS sensor with the middle replaceable mass, which was used during testing described below, is shown in Figure 2. The special board shown in Figure 2 was used for attaching GSS-EBS to a vibration stand (lab test) or to a land case of a standard geophone (field test). For our final lab testing and for the all field-testing GSS-EBS and both GS-14-L3 and GS-20DX geophones were installed in standard land cases.

Figure 1. Two examples of the test version of the GSS sensor in comparison with Geo Space's Commercial Geophones GS-14-L3(in the middle) and GS-20DX (on the right)

Figure 2. GSS sensor with middle replaceable mass on a board for securely attaching to a vibration stand (lab test) or to a land case of a standard geophone (field test)

The broad comparison testing of the represented in Figure 1 geophones has shown that the new GSS geophone has significant advantages, including small size, lower weight, and lower cost. These characteristics are represented in Table 1 below (we used the GS-14-L3 and GS-20DX characteristics according to manufacturer's data [20]).

Table 1. Basic characteristics of the geophones

	GSS-EBS	**GS-14-L3**	**GS-20DX**
Volume, cm³	~1.33	3.77	16.72
Mass, g	2.2 g	20-27 g	87 g
Price, $	~ $3-5	~ $50	~ $25-35

Table 1 data shows that:

- The GSS sensor has a volume about 3 times less than that of GS-14-L3 and 12 times less than that of GS-20DX
- The GSS sensor has a mass about 9-12 times less than that of GS-14-L3 and 40 times less than that of GS-20DX
- The GSS sensor may potentially have a price 10-15 times less than that of GS-14-L3 and 5-8 times less than that of GS-20DX

In addition, the new sensor has:

- Much broader spectrum bandwidth both for strong and weak seismic signals
- Significantly higher sensitivity
- Lower sensitivity threshold (real sensitivity)
- Higher detection range

The amplitude spectrums of the compared geophones for strong and very weak seismic signal are shown in Figure 3 and Figure 4 below.

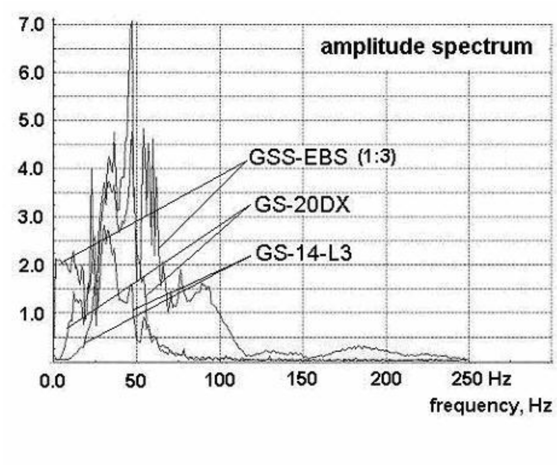


Figure 3. The amplitude spectrum of the strong seismic signals recorded by the GSS-EBS, GS-14-L3 and GS-20DX geophones

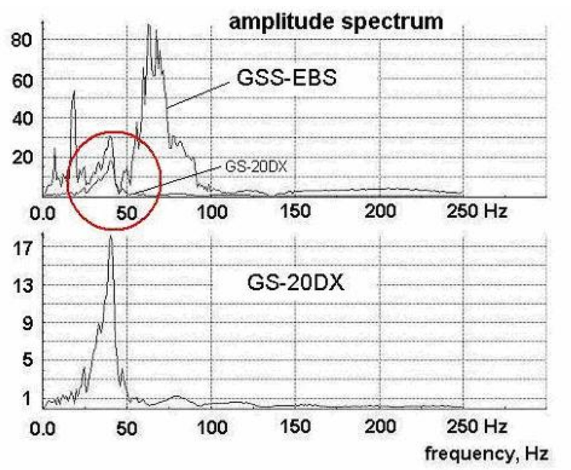


Figure 4. The amplitude spectrum of the weak seismic signals recorded by the GSS-EBS and GS-20DX geophone

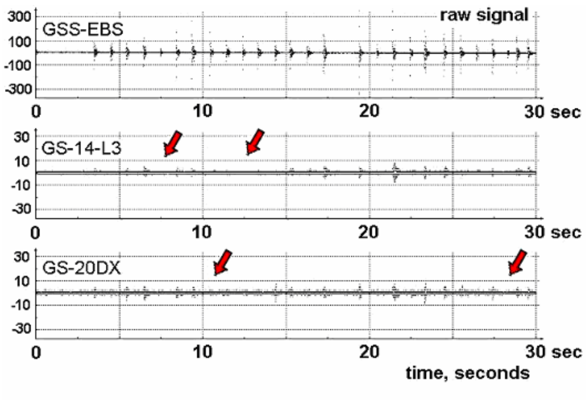
During corresponding testing equal strong or weak impacts were exerted on all sensors placed in the land cases. For more obvious comparison, the GSS-EBS's signal for strong impact was reduced by using an attenuator (1:3). A weak impact exerted on all sensors' land cases was amplified with a gain of about 10,000 for all geophones.

The GSS-EBS shows a much better response to low and high frequency signals than either the GS-14-L3 or GS-20DX geophones. The GSS-EBS performs better than the GS-14-L3 below 20-24Hz and above 40Hz frequencies and better than the GS-20DX geophone below 10-12Hz and above 50Hz frequencies. Note that the spectral responses of both the GS-14-L3 and GS-20DX geophones are in accordance with the manufacturer's data for these geophones [20].

It is interesting that at frequencies 25-50Hz, amplitude spectrum of the all sensors have similar shape. Therefore, if we trust the manufacturer's data and assume a linear response curve for the GS-14-L3 and GS-20DX commercial geophones, these results confirm a linear response curve of the GSS-EBS at frequencies 25-50Hz.

The represented amplitude spectrum shown in Figure 4 above indicate that for low amplitude signals, the GSS-EBS has significant sensitivity advantages versus the GS-20DX, the best commercial geophone at the present time (note the vertical scale in Figure 4). These sensitivity advantages are very clear especially at frequencies below 24-25Hz and crucial at frequencies above 45-50Hz. As in the case of the strong impact, Figure 4 shows that the GSS-EBS has a linear response curve by weak impact at frequencies 25-50Hz because the shapes of both amplitude spectrum are similar at these frequencies. However, Figure 4 shows that at frequencies above 50Hz by weak impact, the existing commercial sensors actually do not have a response and cannot be comparable with the new GSS-EBS which has a much better response to very small amplitude signals at both high and low frequencies. Since, in the real environment, the footstep signal magnitude is very low, this point is significant for real signal interpretation in heavy noise environments and is a significant advantage of the GSS-EBS's performance in comparison to that of the GS-14-L3 and GS-20DX.

The amplitude spectrum of the seismic signals shown above in Figure 3 and Figure 4 indicate that for all types of signal, the GSS sensor has significant sensitivity advantages among other sensors and these sensitivity advantages are crucial in many cases. An example of one of such cases is shown in Figure 5.



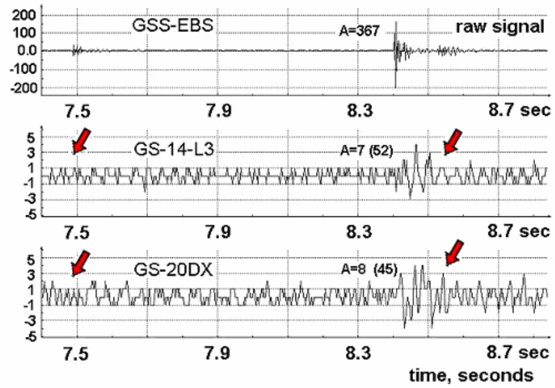


Figure 5. Records of the same weak seismic signal by the GSS electret-based sensor and two different geophones GS-14-L3 and GS-20DX

Figure 6. Highlight of an area with weak GS-14-L3 and GS-20DX response from Figure 5

All sensors were placed in one area of vibrating surface as before. Impacts on sensors were weak. While the GSS electret-based sensor has high response signal, both the GS-14-L3 (especially) and the GS-20DX geophones have very poor or even no response signals. The red arrows in Figure 5 point to such areas. Figure 6 shows one of these areas.

The GS-14-L3 and GS-20DX geophones in this record do not show a response at time 7.5sec, while the GSS sensor has a good response with amplitude of about 60 (see Figure 6). At 8.4sec, all sensors have a response, but the amplitude of the GS-14-L3 signal is about 52 times less and the amplitude of GS-20DX signal is about 45 times less than the amplitude of the GSS sensor (see Figure 6). These results together with the Figure 3 and Figure 4 data show that the GSS sensor has a sensitivity threshold lower than that of the GS-14-L3 and GS-20DX. Therefore the GSS sensor can pick up a signal in low-level signal situations, where the GS-14-L3 and GS-20DX geophones do not have a response.

At the time 8.55 second, the GSS sensor shows a very clear third signal. However, the GS-14-L3 does not have a response at that time, and the GS-20DX does not show a third signal but shows only a long extended second signal without signal separation. This point is significant for real signal interpretation in heavy noise environments and is a big advantage of the GSS electret-based sensor's performance in comparison to the GS-14-L3 and GS-20DX.

The considered above broader spectrum bandwidth and very high sensitivity of the new sensor provide its great performance characteristics for real environment. We have implemented field-testing in various field conditions. During field-testing all geophones were installed in the same areas right on the ground surface. They were positioned in a triangle with distance between each of about 40 cm. The start position of the human tester was about 4m from the triangle. A person was walking away from the sensors (Figure 7).

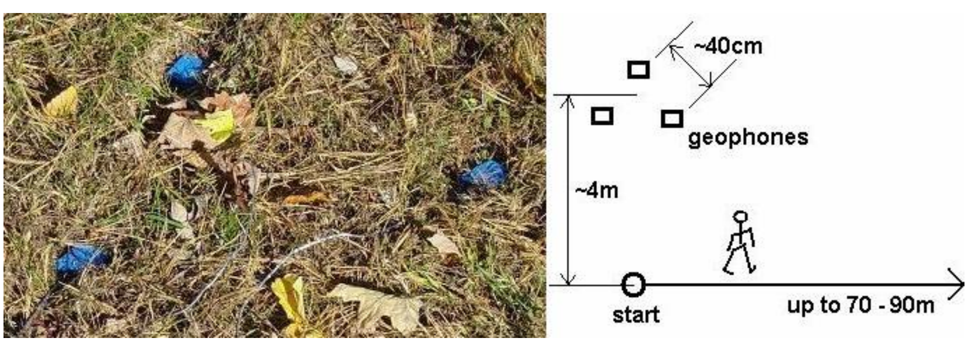


Figure 7. Test layout of geophones used to collect footstep data in all testing areas.

An example of the raw seismic signal records during such experiments is shown in Figure 8 below.
For convenience, Figure 8 shows only the last 45 seconds of the recordings, where the seismic signal amplitude was low and distance to senor was high. A vertical scale was chosen for convenience.

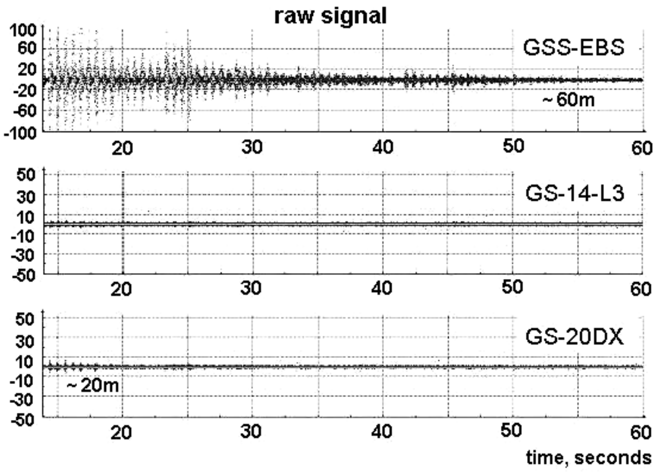


Figure 8. Recordings of the same seismic footstep signal during field-testing.

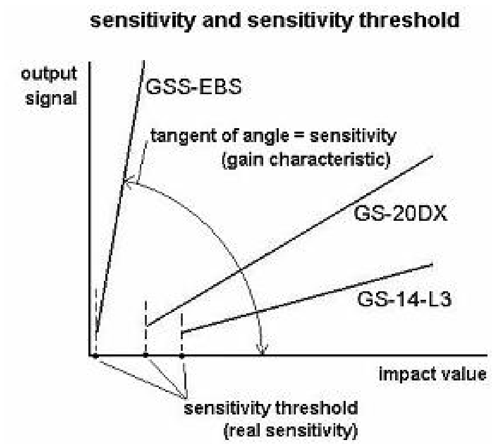


Figure 9. Higher sensitivity and lower sensitivity threshold of the GSS-EBS in comparison with commercial geophones.

The data in Figure 8 clearly shows that the GSS-EBS allows to detect footstep signal by almost 3 times larger distance between the sensor and person—60 meters for the GSS-EBS vs. 20 meters for the GS-20DX (the best geophone among the compared existing commercial geophones).

In addition, according to our testing results, the GSS-EBS shows not only higher sensitivity, but also lower sensitivity threshold especially in low and high frequency bands. Figure 9 shows in correct comparison qualitative scale advantages of GSS-EBS in terms of the sensitivity and sensitivity threshold.

Ultimately, the results of our lab and field testing of the GSS electret-based sensor in comparison with the most popular commercial geophones demonstrated that in all main characteristics the GSS-EBS performs significantly better than the GS-14-L3 and GS-20DX geophones. For tactical applications, the most important characteristic is the GSS-EBS's triple increase in footstep detection range in real environment conditions. This characteristic of the GSS's sensor is much better than characteristics of other up-to-date seismic sensors [21-24].

2.2. Seismic signal processing micro controllers

At the present time, GSS uses in its work the entire set of the GSS micro controllers for seismic signal processing and detection-identification decision making. These micro controllers can be used in up-to-date unattended seismic detection and identification modules with various limitations in terms of power supply, size and so on. Corresponding modules can be incorporated in many very useful and reliable seismic detection and identification systems. Such systems can be wired or wireless, mobile and autonomous or stationary, etc.

In fact, all micro controllers have similar enough and high computing and interface capabilities. The main differences are associated with the power supply (used voltage and current), size and components base. In addition to computing electronic circuitry, corresponding devices have amplifying circuitry. Both circuitries are placed on one or separate boards.

The first GSS micro controller has a power consumption of about 200mW and can be recommended for use in wired detection systems, for example, in perimeter security systems. This micro controller is based on using the high-performance, low-power AVR® 8-bit Micro controller ATMega128. This device has advanced Reduced Instruction Set Computing (RISC) architecture, 128-Kbyte self-programming Flash Program Memory, 4-Kbyte SRAM, 4-Kbyte EEPROM, 8 Channel 10-bit A/D-converter, and up to 16 MIPS throughput at 16 MHz, and 2.7 – 5.5 Volt operations.

The micro controller main board provides programmable comparator circuit for use during sleep mode and watchdog for protection of a seismic detector from specific software or hardware failures that may cause the detector to stop responding and functioning properly. The standard serial interface is used for connection of the main board to laptop for processing parameter loading and for tuning of the whole device by preliminary testing.

The main board has 3 LEDs of various colors (red, green, yellow), which correspond to different classes of a detected target and other overhead information. These LEDs simplify seismic detector tuning and checking its work during installation. Initial signal sampling frequency is 256 Hz. The length of the simultaneous processing signal is 4 sec. The main processing characteristics can be chosen during testing.

Component placement and layout of the seismic amplifier and micro controller boards (top sides) are shown in Figures 10 below. For field tests, breadboards with a battery were placed inside the plastic box. The geophone GS-14LS was used in its standard case (Figure 11).

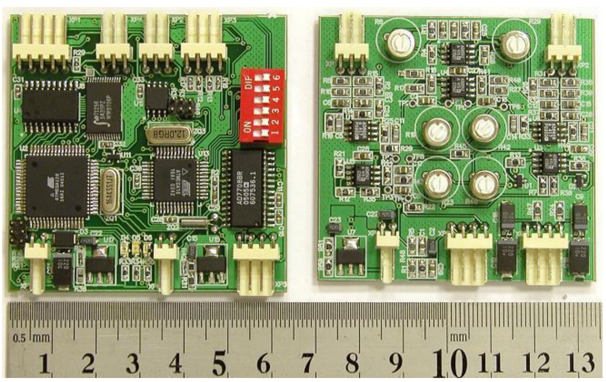


Figure 10. Top sides of the 200mW micro controller and amplifier breadboards

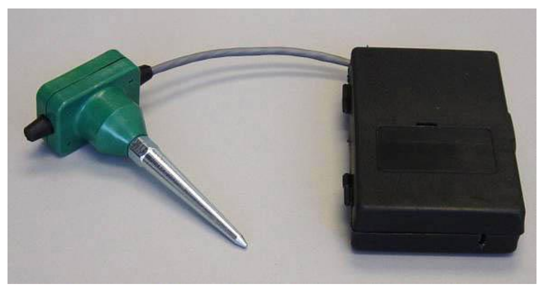
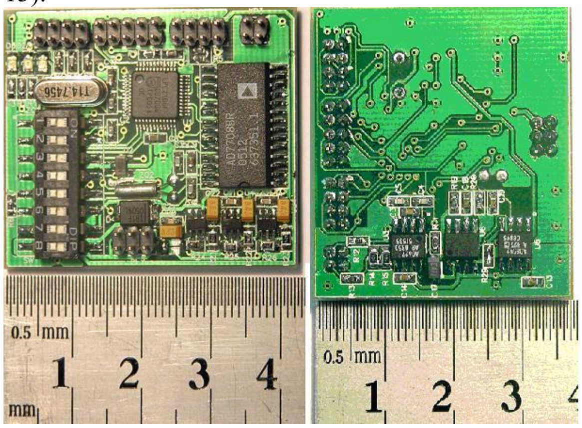


Figure 11. Device used for field tests

The amplifier and controller power supply should be in the range of 6.3-12V. Both boards have internal 5V DC voltage stabilizer. The micro controller's current consumption in data processing mode is 160-180mA. The micro controller's current consumption in idle mode is 40mA. The seismic amplifier has power consumption about 6-10mA per channel. A cable for PC serial connection should be connected to the corresponding connector RS232 on the micro controller board. A RS485 connector is reserved for possible long distance communication in future networks.

The second version of the seismic signal processing micro controller with amplifier has a power consumption of about 45mW and can be recommended for use in both wired and wireless security systems with unlimited or limited power consumption. This module has a single board with both an amplifier and a micro controller electronic circuit on it. This single-board device includes the low voltage supply Philips microchip LPC2106 for micro controller, which has enough memory for the signal processing algorithm and processing data. It is very important since the computing module has to detect and identify at least three or more classes of targets and actually has to realize three or more almost separate detection algorithms. The general view of this board is shown in Figure 12 below.

For lab and field testing, this board was placed in a special box with connectors for geophone attaching, power supply battery, and RS-232 interface providing communication with the computer. The full hardware set includes a detector/processing box, seismic sensor GS-20DX, battery box and an interface cable to laptop. This hardware was used during all lab and field testing of the new target detection and seismic signal record software design (Figure 13).



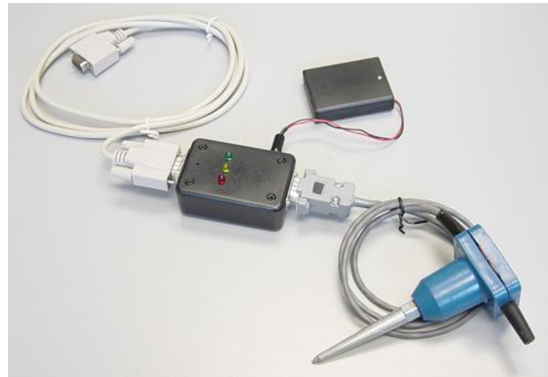


Figure 12. Top and bottom sides of the 45mW micro controller with amplifier on one board

Figure 13. Fully assembled 45mW seismic detector

The third version of the signal processing micro controller has extremely low power consumption of about 4.6mW, which allows to use it in wireless security systems staying very long on position without battery replacement. This micro controller is based on the Philips microchip LPC2148. Component placement and layout on the corresponding board are shown in Figures 14 below. For field tests, the breadboards were placed inside a plastic box (Figure 15). This micro controller has an additional I2C interface and corresponding connector for communication with radio modules. `

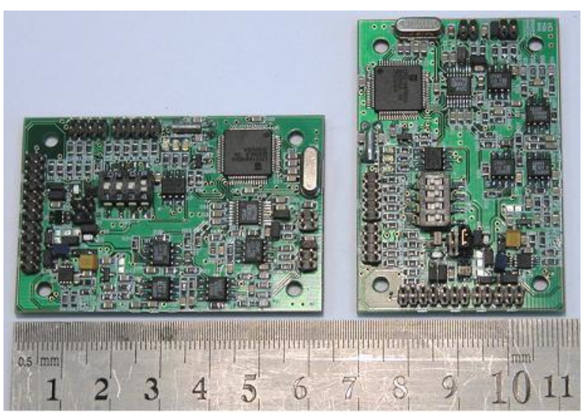


Figure 14. Top side of the 4.6mW micro controller with amplifier on one board

Figure 15. Fully assembled 4.6mW seismic detector

For the third micro controller, the main board power supply should be in the range of 3.7-5V. The board has an internal 3.3V DC voltage stabilizer. The main board's current consumption in the data processing mode is 5.4 mA and corresponding power consumption is 17.8 mW. The main board's current consumption in the idle mode is 1.4 mA and the corresponding power consumption is 4.6 mW. Total power consumption during real work in the field depends on ratio between target presence time and background condition time. That is total power consumption can be calculated as $P_{not\ active} *A + P_{active\ average} *B$ (A, B – part times of active and not active operation).

2.3. Software capability

During the last several years GSS has designed many versions of software for:

- Seismic signal recording in field and lab conditions
- Seismic signal characteristic studying in lab conditions using preliminary signal records
- Seismic signal processing in lab conditions in order to detect and identify various seismic signal producing targets
- Seismic signal processing in real-time field conditions in order to detect and identify various seismic signal producing targets
- Tuning and parameter adjustment of all three micro controllers described above

We investigated the seismic signal of many traditional and nontraditional targets (walking, running and jumping persons, heavy and light vehicles, helicopters and aircrafts, ships, trains, etc.). At the time, we used in our work detection and identification algorithms for such targets as:

- Walking, running and jumping person
- Heavy vehicles (weight more than 10,000 lb)
- Light vehicles (weight lass than 10,000 lb)
- Short strong impact (equal to cannon-shot far away or jumping from fence person)
- Long time high seismic noise (equal to various kind of seismic jamming)

Actually, software for detection and identification of all the mentioned targets can be preloaded in all three kinds of above described processing micro controllers. We try to keep the structure of the software for those micro controllers similar to each other. The detection capabilities of all micro controllers and corresponding detection modules are at the same high level. Some of the mentioned algorithms were described in our previous works [1, 4, 15,16,18,19].

It is clear that the described detection and identification algorithms can be used not only in specialized small size micro controller, but also in full size desktop and laptop computers. This allows to design broad spectrum security systems for various applications.

2.4. Seismic detector testing results

2.4.1. Testing fields description

All the above described software versions were tested in detail in real environment conditions on many testing fields/sites. For our R&D work and testing we use three main testing fields in NY State. In addition to that, we tested our devices in real environment on many testing areas in NC, TX and VA states. One of the our main field test areas was at the Hudson River Bank in Yonkers, NY as described in our paper [15]. That field allows to observe seismic signal from all above mentioned traditional and nontraditional targets and has a high noise level. Our second test field is located in Franklin Roosevelt State Park, Westchester County, NY. General view of environment conditions and satellite picture of this area from [25] is shown in Figure 16 and Figure 17 below.

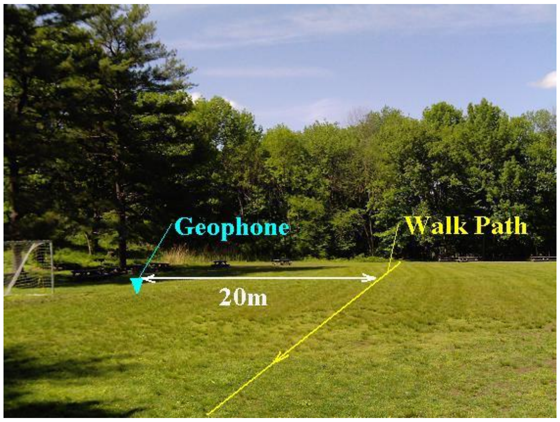


Figure 16. Layout of seismic sensor relative to person walk path in Franklin Roosevelt State Park

Figure 17. General view of testing field in Franklin Roosevelt State Park

This area is sufficiently enough and the distance to the nearest highway (Taconic State Parkway) is about 460 m. We use this area typically for footstep detection algorithm testing. The testing field size is about 120m by 70m. During testing, the person started walking from far away (distance to sensor more than 40m). Then the person went straight by the geophone GS-20DX connected to the seismic detector. The distance between the sensor and the walking path was 5, 10, 15 and 20 meters in the performed tests.

Our third main test area is located in Ward Pound Ridge Reservation, Westchester County, NY. The picture of this testing area is shown in Figure 19 below.

Figure 18. Layout of seismic sensor relative to traffic in Ward Pound Ridge Reservation

Figure 19. General view of testing field in Ward Pound Ridge Reservation

This testing area is also sufficiently quiet and has a dirt and asphalt road that allows to observe heavy and light vehicles on both roads without displacement and reinstallation of the seismic sensor. This is very important for design and testing of the light/heavy vehicle detection algorithm. Real environment conditions and layout of seismic sensor relative to traffic are shown in Figure 18. The distance between the sensor and both dirt and asphalt roads was about 20 meters. This area was also used for footstep detection algorithms.

2.4.2 Seismic footstep signal to noise ratio in real environment

Footstep detection is one of the most important issues for seismic security systems. In real environment, seismic footstep signal levels are low and this level decreases rapidly with increasing distance between a moving person and the sensor. At the same time, the real environment has a continuously high level of seismic noise. Therefore the footstep signal level can be equal to noise level even in the case of a short distance between sensor and walking person. The higher the noise, the shorter the footstep detection range. For practical use, improving a geophone will not lead to an improvement of the signal to noise (S/N) ratio.

The best footstep detection systems are GSS's systems that can work with a (S/N) ratio of about one to one [1, 3, 8]. Examples of relations between the noise level and the footstep detection range of the best systems are given in Table 2 below.

Table 2. Examples of relations between noise level and footstep detection range for the most effective systems

Noise Level	**Mean Value of Range S/N = 1:1**
Very high	2-3 m
High	5-6 m
Medium	10-15 m
Low	25-35 m
Very low	50-70 m
Extremely low	70-90 m

Generally, in the real environment, the noise level is not lower than medium as characterized in Table 2. Therefore the footstep detection range of a single geophone in the best systems in the real environment is not more than fifteen meters. The above must be taken into account when designing and testing systems for practical applications.

2.4.3. Testing results

Wide-ranging field testing has shown that GSS has developed reliable seismic detection modules that can be used for real-time detection. The seismic detectors described in this paper actually do not have false alarms in the mode of the footstep detection during several hours while located in the proximity of the parkway, highway roads or railway. In addition, during many working hours in lab conditions, the footstep detector did not initiate "Alarm" signal.

A possible footstep detection range was estimated during testing in both the high noise (Hudson River Bank) and the quiet area in the park zones (Franklin Roosevelt State Park and Ward Pound Ridge Reservation) of Westchester County, NY. The distance to the nearest road was from 25m in a high noise area to 100m and more in a quiet area.

Typically, if the distance between the sensor and straight walking path was about 5m (see Figure 17), the contact time with the target in a quiet area was about 30-40 seconds. Therefore, a walking person was detected for about 60-80 steps—equal to about 40-55m. In other words, the target was detected and an "Alarm" was initialized in the circuit with a diameter about 20-27m (this diameter represents the typical detection range of surveillance systems). Of course, that circuit was "shifted" from sensor in a walking direction at about 10-12m because the seismic detector needs time for data collection and data processing before decision making. If the distance between the sensor and the walking path was about 20m, the contact time with the target in a quiet area was about 8-12 seconds. The detection was very reliable. The target (walking person) was never missed.

For light and heavy vehicles detection, we keep the distance between the sensor and the road (vehicle path) about 10-30m. This corresponds to the case of suspect road monitoring in a protected area. In all tests, we had 100% detection. The class of vehicles was estimated without error. If we did not have in the surveillance area targets other than walking/running person, light or heavy vehicle, we did not have false vehicle detection.

3. CONCLUSIONS

We reported on the basic results achieved by General Sensing Systems in a wide area of seismic security systems. The presented work shows that at the time a full array of the small-size, autonomous seismic detectors (units) was designed. These units can be used for detection of various seismic signal generating targets. The preloaded in those units software is based on very sophisticated and complex mathematical algorithms for footstep detection, heavy and light vehicle detection. These units also allow to detect and identify seismic events such as cannon shots and other long-term seismic noise shocks (seismic jamming).

The size and power consumption of the presented seismic detector can fit the many possible consumers' requirements [26-31]. The use of the corresponding detectors of the GSS-miniature seismic sensor can improve the autonomous seismic detectors characteristics, especially their detection range in real environment conditions.

Field testing of the represented seismic detector modules was performed in high and low seismic noise environments. Geography, season and weather conditions during testing were also very diverse. Each time testing results were very successful.

We are planning to continue our efforts in all the above mentioned directions. In particular, we increase the number and variety of possible detecting targets. In addition we will add to estimated parameters of detected targets their moving and behavior characteristics. All those improvements will increase tactical capabilities and usefulness of the seismic detection and identification systems in the future.

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