Low-frequency signals detection and identification as a key point of software for surveillance and security applications

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ABSTRACT

Various passive as well as active surveillance and security systems try to detect and identify very low frequency signals. Diversity of such real time working systems is very broad. Those are seismic, acoustic, hydroacoustic, IR, ultrasound, etc. systems. Detected target spectrum is also broad: from human motion on the ground surface and under water to low-noise submarines. In real application corresponding signals have poor signal-to-noise ratio, unstable shape and amplitude, short duration, and even missing parts of the signal. This paper describes test records of some raw seismic, acoustic, acoustic-seismic, hydroacoustic, and IR signals with proper characteristics. We investigate those signals specifics and possible approach to target oriented reliable signal processing that allows drastically increasing detection range and reducing false alarm rate. We also report on the preliminary field-testing that was implemented with active ultrasonic detector.

Keywords: Signal detection, signal identification, signal processing, low frequency, surveillance, security.

1. INTRODUCTION

The real success of various surveillance and security systems depends on using effective signal processing that typically includes signal detection and identification. This issue can be quite easy solved, if the signal frequency is relatively high. But the situation becomes much worse, if the signal frequency is low and has a value less than ten hertz. The signal processing algorithm design does not have simple and standard solutions for systems that use such low frequency physical fields and signals. Corresponding difficulties exist for various passive as well as active systems, but for passive systems those difficulties become crucial.

Existing signal processing procedures do not work well in such situations because in real applications corresponding signals have poor signal-to-noise ratio (SNR up to 2:1 or even 1:1), arbitrary and unstable shape and amplitude, short duration (4-12 sec), and even missing parts of the signal (up to 1-2 sec). Additional limitation of using standard procedures can be caused by using a simple micro controller with limited power supply and therefore with limited processing abilities for signal processing in real time. Strong requirements to low false alarm rate (not higher than 10^{-6}) also create serious difficulties.

Security&Defense Research (S&DR) Company has broad experience in dealing with low frequency signals processing. Corresponding signals include: seismic, acoustic, acoustic-seismic signals, passive hydroacoustic and IR signals, active ultrasonic detector response signals after detection and smoothing, etc.

In this paper we will describe test records of some mentioned above signals with proper characteristics. We present results of the investigation of those signals features and possible approach to target oriented reliable signal processing that allows drastically increasing detection range and reducing false alarm rate of the surveillance and security systems. We illustrate our results for detection ability of typical unattended ground and underwater sensors in possible and real tactical situations. Presented results can be a very useful guidance to both designers and consumers.

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2. RESULTS AND DISCUSSIONS

2.1 Real signal characteristics

For successful solving of many signal processing issues, it is very important to find some general and relatively universal approach to design of target detection and identification algorithms. This can be possible only if we can find any universal features of low frequency signals that can be generalized and used as a base to the design of effective and robust signal processing procedures and algorithms. Below we present some of the test records in real environment conditions for various physical fields that Security&Defense Research Company uses in its projects.

2.1.1 Seismic signals

Seismic signals are typical representatives of the low frequency signals that are used in surveillance and security application especially for footstep detection. Raw seismic signal record and corresponding signal envelope for almost ideal environment conditions with low background noise level are shown in Figures 1 and 2 below. The distance between a standard GS-20DX geophone and a walking person for the shown signal is nine meters [1].

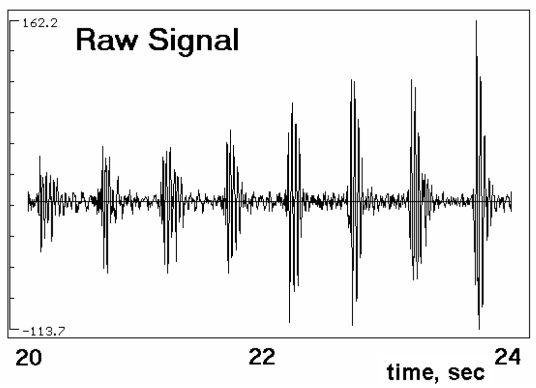

Figure 1. Raw seismic signal record in case of low background noise level. Distance between geophone and walking person is nine meters.

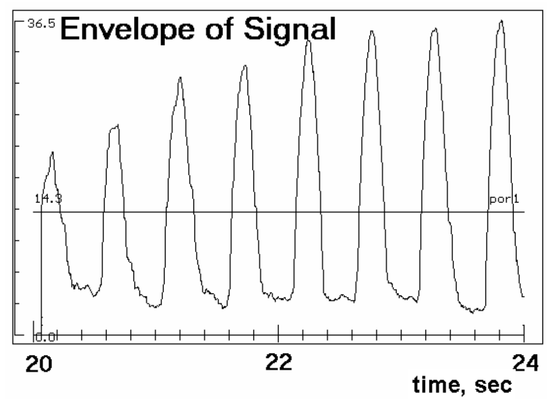

Figure 2. Envelope of signal shown in Figure 1.

Envelope of seismic signals is typically used for footstep detection because it represents the main and most informative characteristics of a person's footstep. Unfortunately, in real conditions especially at maximum distances where footstep detection is possible, the envelope pattern is much worse. An example of such envelope is presented in Figure 3, when distance between a walking person and a GS-20DX geophone is about 30-35 meters with a low background noise level [2]. We have the same ambiguous footstep signal envelope in case of using a seismic string instead of single geophone. Figure 4 presents the signal envelope when distance between an eight-geophone seismic string and a walking person is about 8 meters [1]. The distance between GS-20DX geophones in the string is 15 meters. The level "por1" in Figures 2-6 shows the value of the raw signal root-mean-square. Figures 3 and 4 clearly show that in a real situation even with relatively low background noise level conditions, the envelope pattern is very unstable. Estimation error of the footstep peak's time increases. Some "spikes" of footstep signal can be missed. Signal to noise level is low and may be close to 2:1 or even 1:1. Any attempts to use standard approaches to detect such footstep signal very often fail or have very low reliability and as a result lead to high and practically unacceptable false alarm rate.

2.1.2 Acoustic signals

Acoustic sensors (various microphones and microphone arrays) that are placed in air medium are used in surveillance and security applications for footstep detection [3, 4, 5]. For such sensors, an acoustic signal pattern situation is actually the same like the one described in paragraph 2.1.1 for seismic sensors. The main difference is only in a value of a "carrier" frequency that is modulated (actually manipulated) by a footstep pattern. That frequency is determined by characteristics of various elastic mediums. However, the signal envelope for acoustic footstep signals is actually the same as the signal envelope for seismic footstep signals with all those envelope characteristics and difficulties for detection described in paragraph 2.1.1.

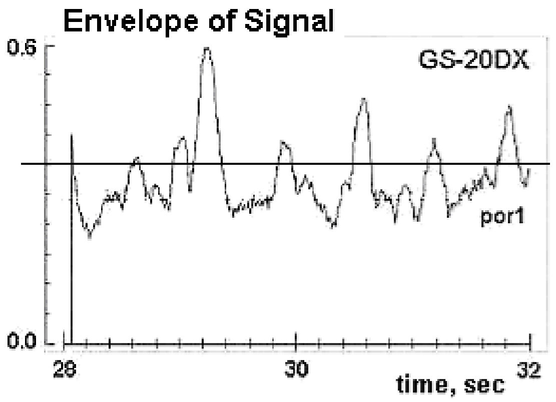

Figure 3. Footstep signal envelope for distance between single GS-20DX geophone and walking person about 30-35 meters.

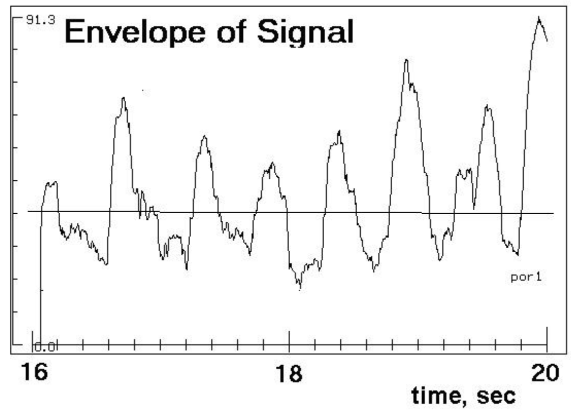

Figure 4. Footstep signal envelope for distance between seismic string and walking person about 8 meters.

2.1.3 Acoustic-seismic signals

Acoustic-seismic signals are very important for surveillance and security applications because they allow providing long range detection for some very interesting targets like, for example, submarines by using seismic sensors. Example of the raw seismic record of towboat noise made by a single GS-20DX geophone placed at the river bank is shown in Figure 5 below. The distance between a moving towboat and a geophone was about 500-600 meters.

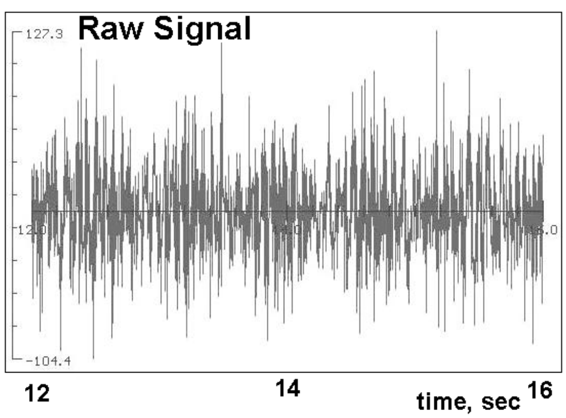

Figure 5. Towboat acoustic-seismic signal record made by GS-20DX geophone.

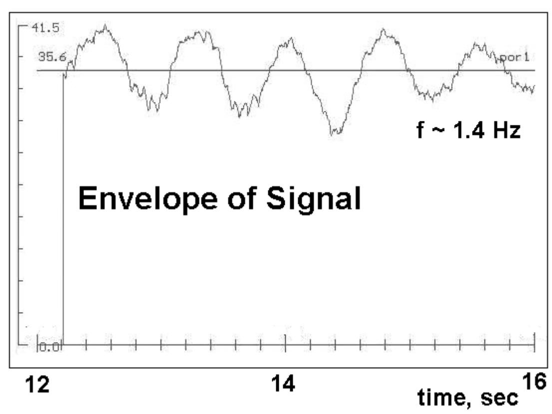

Figure 6. Envelope of towboat seismic signal presented in Figure 5.

Figure 6 presented the envelope of the towboat seismic signal shown in Figure 5. A signal with low frequency (approximately 1.4Hz) is clearly seen in Figure 6 and represents the most important characteristic for target classification of the acoustic-seismic signal. It is interesting and very important that amplitude spectrum of the raw towboat seismic signal from Figure 5 does not allow recognizing the low 1.4Hz frequency. (See Figure 7 below.) The lowest frequency that can be recognized at the amplitude spectrum is much higher and is equal to about 7Hz. Therefore, special processing procedures have to be used for detection and recognizing of such signal and for reliable target detection of specific classes at long detection range.

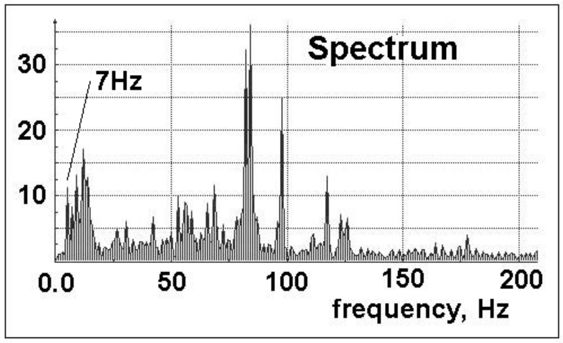

Figure 7. Amplitude spectrum of towboat raw signal presented in Figure 5.

2.1.4 Hydroacoustic signals

The big contemporary underwater targets (for example submarines) usually have a very low noise level that is comparable to the natural sea noise level. That low noise level is achieved by using new low noise regularly working machines inside of the target/submarine, by using special sound absorbing cover materials, by using special noise reduction devices, etc. That fact makes a passive hydroacoustic detection of such objects at reasonable and desirable detection range very difficult and sometimes impossible. The only way to solve this problem is to use a very low frequency sound caused by the target moving that can not be eliminated.

Figure 8 below shows amplitude spectrum of the raw hydroacoustic signals of two different underwater targets (marked as # 1 and # 2). Amplitude spectrum of the envelope of those hydroacoustic signals of two different underwater targets is presented in Figure 9. Figure 8 clearly shows that spectral analysis of the raw signals does not allow to recognize presence of frequency around 1Hz. The envelope spectrum (Figure 9) has spectral lines 0.5Hz, 1Hz, 2.3Hz with amplitude level that is close to the natural sea noise level and does not allow do use automatic procedures for the spectral lines detection and recognition. The low frequency spectral lines recognition is especially difficult for the underwater target # 2 because of the broad width of those lines.

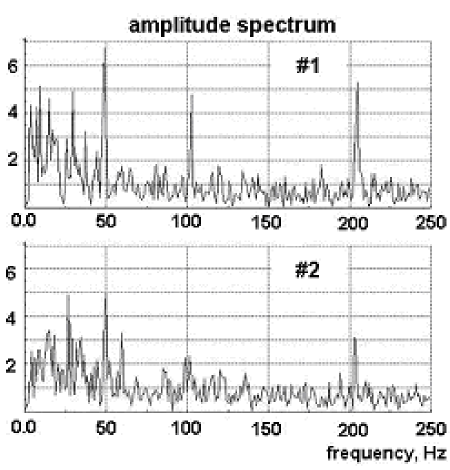

Figure 8. Amplitude spectrum of raw hydroacoustic signals of two different underwater targets

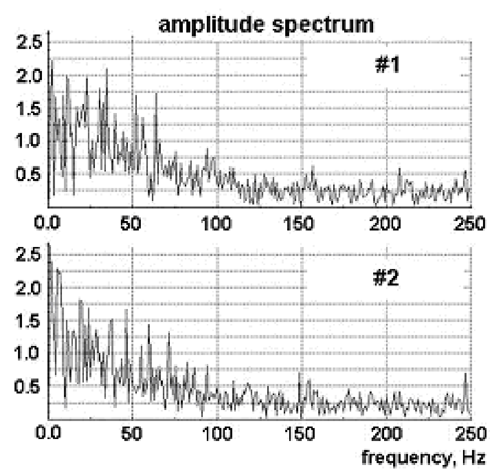

Figure 9. Amplitude spectrum of raw signals envelope of two different underwater targets

The envelopes of the raw signals for both underwater targets are presented in Figure 10 and Figure 11 below. Those envelopes clearly show the presence of frequency around 1Hz in the original hydroacoustic noises of targets. Pattern of those envelopes is very similar to that of the footstep seismic signals shown in Figures 3 and 4 above. That fact allows using the same approach and sometimes almost the same or similar algorithms for footstep and underwater target detection.

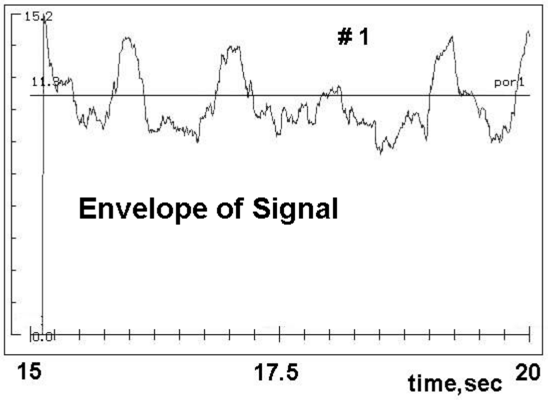

Figure 10. Envelope of raw signal for underwater target # 1.

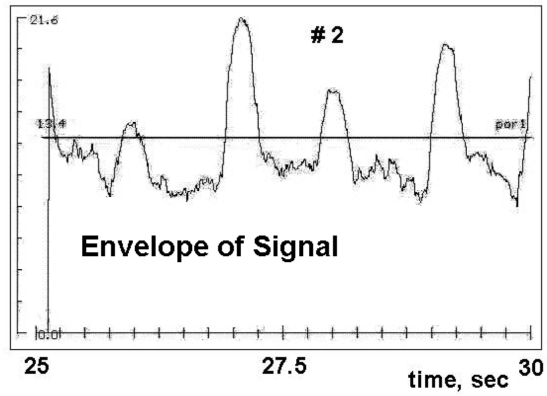

Figure 11 Envelope of raw signal for underwater target # 2.

The results of the trickier preprocessing of raw signal for the underwater target # 2 are shown in Figure 12. Data from Figure 12 allows recognizing the frequency about 0.5Hz with very high reliability and using for that recognition S&DR proprietary automatic procedures. The pattern of those data shows interesting character of corresponding raw signal like pulsations. The recognition of those pulsations can be crucial for target recognition in many tactical situations.

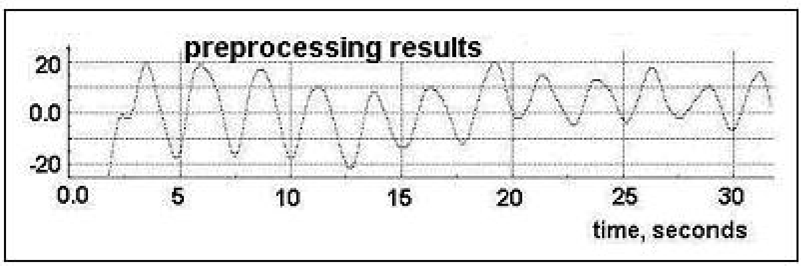

Figure 12. Raw signal preprocessing results for underwater target # 2.

2.1.5 Infrared (IR) signals

All signals that were mentioned in previous paragraphs are the periodical signals. Quite similar algorithms can be used for their detection and recognition. Very often they can differ only in some processing/tuning parameters. Now we will consider the non-periodic signals. Typical representative of such signals is the response of passive infrared sensors to the moving across sensors beam target. Examples of corresponding signals presented in Figures13-16 below. For all presented records PIR325 pyroelectric infrared (PIR) sensor and FL 65 (Focal Length=0.65 inches) long range single element Fresnel Lense were used [6].

Figure 13 shows the IR sensor signal caused by vehicles crossing the sensor beam from the right and from the left. Distance from the sensor to the moving at about 30mph speed vehicles is 30 meters. All responses are actually non-periodic with relatively short length of about 1 sec. The main point is that the phase of the signal strongly depends on the side from which a vehicle is crossing the sensor beam. That fact can be easily used to recognition of the vehicle or any other target side moving. The two-beam IR sensors in such situation generate almost identical signals that are slightly shifted to each other. This shifting allows measuring a speed of the vehicle (or other moving target) if distance between a sensor and a moving vehicle is known. The vehicle's speed and signal duration allow to roughly estimate the "size" (or "class") of a vehicle and make 100% reliable discrimination between a vehicle and a walking person.
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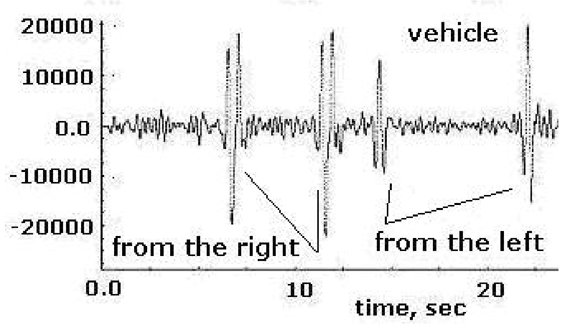

Figure 13. IR sensor signal that is caused by vehicles crossing the sensor beam from the right and from the left.

Figure 14. IR sensor signal that is caused by walking person crossing the sensor beam from the right and from the left. Distance between sensor and person is 30m.

Figures 14-16 show the IR sensor signals that are caused by a walking person crossing the sensor beam from the right and from the left. Distance between a sensor and a person in those Figures 14-16 is 30, 40 and 50 meters respectively. In addition to "typical" IR sensor response, in all Figures14-16 we can see a signal amplitude modulation that is caused by the walking person rhythmic moving with footstep frequency of about 2Hz. The presence of such footstep frequency modulation allows making reliable recognition of a walking person among other slow speed targets. Figure 16 shows that even at long distance when the signal level is low and the background noise amplitude is high, the person detection and recognition can be reliable after rejection of all frequencies below 1Hz. (See low part of Figure 16.)

Figure 15. IR sensor signal that is caused by walking person crossing the sensor beam from the right and from the left. Distance between sensor and person is 40m.

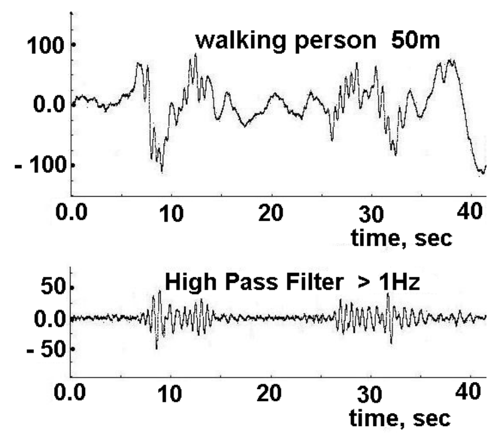

Figure 16. IR sensor signal that is caused by walking person crossing the sensor beam from the right and from the left. Distance between sensor and person is 50m.

2.1.6 Active ultrasonic detector response signals

Active ultrasonic detectors also generate non-periodic signal after high-frequency preprocessing. An input signal for the decision making part of the software is a digitized delay between a sounding signal and an echo signal. When a target crosses a sensor beam that delay changes smoothly. The pattern of that non-periodic changing and its parameters are used for the target detection, recognition, and speed measurement.

Figure 17 below presents the 2-channel record of a moving vehicle. In presented test the active ultrasonic detector and passive IR detector are used simultaneously. Both sensors are above monitoring road and pointed vertically down. The first channel presents the sounding signals and echo signals of the ultrasound detector after the high frequency preprocessing. We can see in Figure 17 that the echo signal delay becomes lower between points marked by #1 and #12 signs. The second channel (IR sensor record) shows that at that time a vehicle crosses the sensors beams. A vehicle placement in Figure 17 just illustrates an idea of how the echo signal delay is changed.

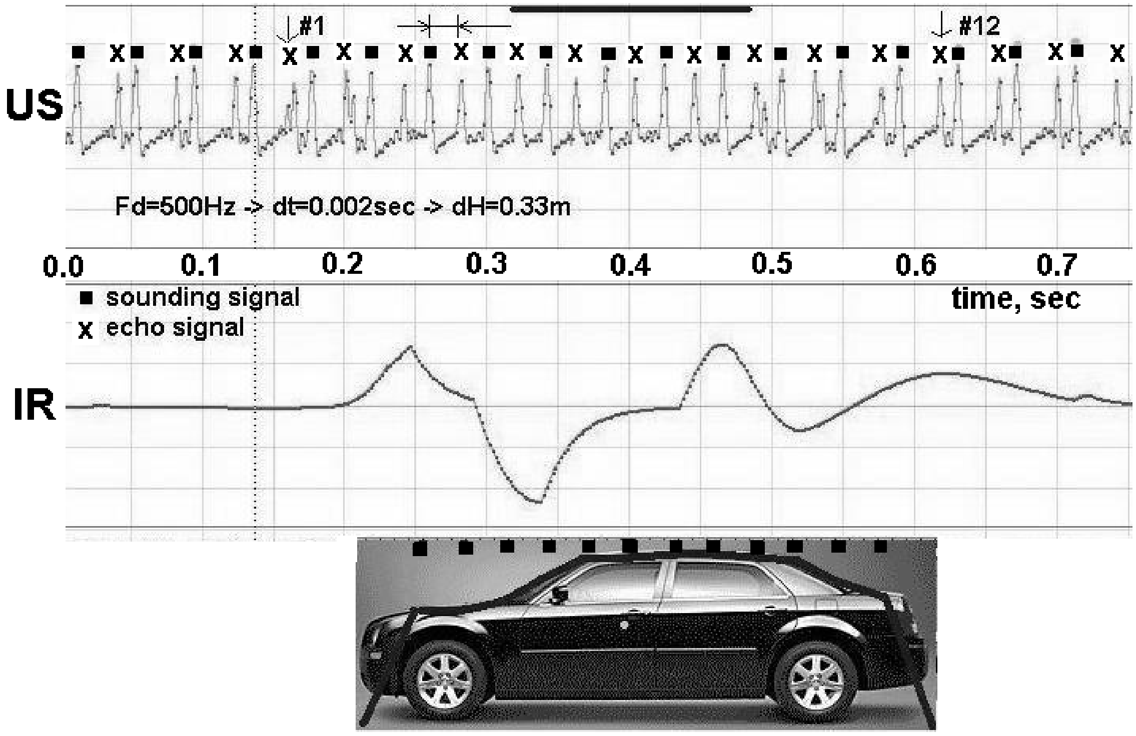

Figure 17. Response of the active ultrasound detector and passive IR detector to moving vehicle.

2.2 General characteristics of low frequency signals

Generalizing the characteristics of all the signals mentioned above that are interesting for surveillance and security applications, we can summarize the following. Periodical signals that have to be processed typically have:

- Low frequency or low frequency amplitude modulation (manipulation) below 3-10Hz.
- Poor signal-to-noise ratio (SNR up to 1:3 or lower).
- Arbitrary and unstable shape and amplitude.
- Short duration of the processing record (sometimes not more than 4-12 seconds).
- Missing part/parts of the signal (up to 1-2 seconds).

Non-periodical signals that have to be processed typically have:

- Short duration (typically not more than 1-10 seconds).
- Low number of signal amplitude changing. (Typically not more than 3-5.)
- Arbitrary and unstable shape and amplitude.
- A-priori known kind of signal pattern.

Sometimes signals that have to be processed have characteristics of both periodical and non-periodical signals. In certain cases a non-periodical signal can be modulated by a short duration periodical signal. All the aforementioned signals have to be processed in real time and very often by a simple microcontroller with limited power consumption and therefore with limited processing ability. Processing results have to provide a low False Alarm rate (about 10^{-6}).

2.3. Some techniques for low frequency signals processing

Security&Defense Research LLC uses a comprehensive set of unique and proprietary processing and decision making techniques that can solve core problems of almost all security, intelligence, surveillance and reconnaissance systems that work with low frequency physical fields. For a periodic signal, the crucial point of processing is time processing that includes estimation of frequency or period of signals and position of signal specific points on the time line. Additional amplitude and phase processing allows increasing the probability of target detection and reducing the False Alarm rate. The processed signal is analyzed in parts and as a whole.

For a non-periodic signal, the main point of processing is phase and amplitude processing. Additionally we use estimation of signal time length and position of signal specific points on the time line. If a non-periodic signal is modulated by a short duration periodic signal (like in case of a passive IR detector in paragraph 2.1.5) we also use estimation of frequency or period of that periodic signal.

In case of processing the multi-channel records in addition to the above mentioned techniques, we use the estimation of possible signal delay between channels. In some tactical situations, it allows estimating bearing toward the target or just the side of target approach to the sensor. Multi-channel processing can also increase the probability of target detection and reduce the False Alarm rate. In case of multi-channel processing the best results in terms of detection ability and low False Alarm can be achieved if various physical fields are recorded and analyzed simultaneously.

3. CONCLUSIONS

A broad variety of sensors and detectors used in many surveillance and security applications requires processing of low frequency signals for target detection and identification. Those signals can be directly generated by any sensor itself or can be a result of any preprocessing transformation like filtering, smoothing, detection, etc. Generally, usage of passive surveillance and security systems leads to necessity of low frequency signals processing, but sometimes active systems also require such solutions at the final stages of signal processing. In this paper, the low frequency signal examples of both passive and active systems were presented and discussed. Various physical fields were considered.

In many applications, low frequency signals are periodical but sometimes they are non-periodical. Some of the signals have periodical and non-periodical features simultaneously. Important characteristics of both kinds of signals were presented and considered in this paper. In its projects, Security&Defense Research LLC uses a comprehensive set of unique and proprietary procedures for low frequency signals detection and identification. Those techniques are based on specific time, amplitude and phase processing. General features of corresponding techniques and procedures were also presented in this paper. These procedures can be implemented even in microcontrollers with relatively limited computing ability. In many applications, usage of mentioned procedures drastically increases detection range and reduces False Alarm rate.

In the future, we are planning to implement our low frequency signals procedures in a variety of existing and new surveillance, reconnaissance and security systems in order to improve their performance, reliability and usefulness.

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