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The application of unattended ground sensors to stationary targets

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ABSTRACT

The unattended sensing of stationary (i.e. non-mobile) targets is important in applications ranging from counter-proliferation to law enforcement. With stationary targets, sources of seismic, acoustic, and electro-magnetic emissions can potentially be used to detect, identify, and locate the target. Stationary targets have considerably different sensing requirements than the traditional mobile-target unattended ground sensor applications. This paper presents the novel features and requirements of a system for sensing stationary targets. In particular, issues associated with long-listen time signal processing for signal detection, and array processing techniques for signal localization are presented. Example data and signal processing outputs from a stationary target will be used to illustrate these issues. The impact on sensor, electronic signal processing, battery subsystem, and communication requirements will also be discussed. The paper will conclude with a detailed comparison between mobile-target and stationary-target unattended ground sensor architectures.

Keywords: sensors, unattended ground sensors, seismology, acoustics, signal processing, electro-magnetics

1. INTRODUCTION

Unattended ground sensors (UGS) are used for remote sensing in a variety of applications ranging from industrial monitoring to military information gathering. As the name implies, an UGS is a device which is placed on the ground, automatically gathers sensor data on a remote "target", interprets the data, and communicates information back to some other location. UGS are capable of gathering and interpreting data on the remote target without interaction from a human operator. A key element of an UGS is the lack of direct physical contact with the target. Rather, it is set at some stand-off distance from the target and monitors emissions from the target. The types of emissions that may be sensed include acoustic, seismic, electro-magnetic waves (optical, infra-red, ultraviolet), electro-magnetic fields, chemical, and nuclear radiation. The particular sensing modality depends on the application and the target(s) of interest. A simple example of an UGS is a microphone sensor (sound pressure sensor) coupled with an automatic acoustic signal processor and a telemetry system. Such an acoustic UGS could then be used, for example, to detect and report the sound of an aircraft flying overhead. This simple example represents the traditional applications of UGS; the monitoring, detection, and reporting of mobile targets (e.g. a moving aircraft). A similar, but functionally different application of an UGS involves the monitoring, detection, and reporting of stationary targets. As a simple example of a stationary-target UGS, consider a autonomous device based on a radio-frequency sensor. Such a radio-frequency UGS could be used, for example, to remotely monitor and report unauthorized radio transmissions from a roof-top antenna.

In this paper, we discuss the unique application of unattended ground sensors to stationary targets. The stationary target problem offers new opportunities for autonomous sensing, and as such, deserves treatment as an independent problem. Although in some situations, an UGS platform may be applicable to both mobile and stationary targets, there are unique aspects of both that would need to be considered to optimize the UGS for a particular application. It is these similarities and differences that are borne out in this paper.

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2. OBJECTIVES OF STATIONARY TARGET SENSING

The objective of a stationary target UGS is to remotely monitor a target which is fixed in space. The target is presumed to emit some form of energy which can be remotely sensed. For purposes of this paper, we limit our scope to sensors that measure some form of propagating wave (e.g. acoustic, electromagnetic, seismic waves). As such, we exclude from our discussion scalar sensors which rely on some transport mechanism to create a measurable signal at some remote location. Examples of scalar sensors include radiation, chemical, and environmental sensors. Hence, we are focusing on remotely monitoring a stationary target by sensing waves that have been emitted by the target and are propagated through the local medium to the UGS.

The UGS senses propagating waves and characterizes the target by determining the presence of emissions, the lack of emissions, or time-varying characteristic of the emissions. The specific objectives of the UGS will depend on the particular application, but will include one or more of the following functions:

- the detection of the emissions; to determine the presence or state of the target
- the identification of the source of the emissions; to infer the device or phenomenon generating the emissions
- the location of the emissions; to pinpoint in space (bearing, range, and elevation) the source of the emissions

An essential feature of a stationary target UGS is that it must discriminate between emissions from the potential target and those waves that have been propagated from other interfering sources. The discrimination of target emissions from interfering sources is essential so that a high probability of detection can be achieved while simultaneously maintaining a low probability of false alarms. This usually requires that the stationary target UGS have some *a-priori* knowledge of the wavefields and signatures that would be emitted from a potential target. That *a-priori* knowledge is then used by the signal processor to enhance target emissions relative to interfering sources.

Another important objective of an UGS is its ability to remain unattended and to report important sensor information back to some distant location. This implies that the UGS must have both an internal energy source and a telemetry system. Energy sources depend on the mission requirements and the expected operational modes but range from conventional chemical batteries to solar cells. Telemetry requirements are also mission dependent and can range from simple optical indicators to full duplex satellite transceivers.

3. SIGNAL MODEL FOR STATIONARY TARGETS

For stationary target applications, a general purpose model to represent the sensed signals is depicted in Figure 1. With this model, the source is located at position (x_0, y_0, z_0) and emits a signal represented by the time-varying waveform $u(t, x_0, y_0, z_0)$. The source signal is coupled to the local media and can be modeled as a source-coupling function $c(t, x_0, y_0, z_0)$. As the signal propagates through the medium, it undergoes both temporal and spatial modifications due to effects such as frequency-dependent attenuation, reflections, refractions, and scattering, that can be represented as a medium-dependent function $m(t, x, y, z)$. The UGS sensor is located at some position (x_s, y_s, z_s) and is coupled to the medium through the coupling function $s(t, x_s, y_s, z_s)$. The signal recorded by the sensor, $r(t, x_s, y_s, z_s)$ can then be represented as the convolution of the source signal with the coupling functions and the medium dependent function as;

$$r(t, x_s, y_s, z_s) = u(t, x_0, y_0, z_0) * c(t, x_0, y_0, z_0) * m(t, x, y, z) * s(t, x_s, y_s, z_s) + n(t, x_s, y_s, z_s) \quad (1)$$

where $*$ denotes the convolution operation and $n()$ represents interfering noise sources. If we consider the combination of $u()$, $c()$, $m()$ and $s()$ to represent the *in-situ* received sensor signal, and furthermore separate out the direct waveform arrival¹, then Eq. 1 may be represented more simply as

$$r(t) = q_0(t-T_0) + n(t) + \sum_{I=1}^N q_i(t-T_i) \quad (2)$$

where $r(t)$ is the received sensor signal, $q_0()$ is the received direct wave, T_0 is the propagation time from the source to the unattended ground sensor, and $n(t)$ is the additive interfering noise source. The term represented by the summation models interfering time-delayed wavelets that correspond to reflections and mode conversions in the media. If we furthermore model the direct wave as having propagated through a homogeneous, isotropic medium, then we can express the direct wave arrival time, T_0 , as:

$$T_0 = \text{sqrt}((x_s - x_0)^2 + (y_s - y_0)^2 + (z_s - z_0)^2) / c_d \quad (3)$$

where c_d is the nominal propagation velocity of the direct wave.

Based on the signal model described above, the objectives of an UGS can be re-phrased as:

- given $r(t)$, detect $u(t)$ in the presence of noise, interference, and propagation effects
- identify the target class from the signal properties of $u(t)$
- and given $r(t)$, locate the position of the target, x_0, y_0, z_0 .

There are also some key features of the signal model which are worth mentioning;

- because both the target and sensor are fixed in space, there are no motion effects such as Doppler shift.
- estimating the location of the target from unattended sensor measurements is an inverse problem. Multiple sensors, at multiple locations will be needed to estimate the source position.
- some further assumptions such as *a-priori* information about the coupling functions and the propagation are needed. Otherwise, the detection and classification of targets would be extremely sub-optimal.

4. DATA ACQUISITION AND SIGNAL PROCESSING

An unattended ground sensor houses one or more sensors, supporting data acquisition electronics, and computational element(s) for digital signal processing. The data acquisition circuitry consists of pre-amplification, analog filtering, optional multiplexing, and analog-to-digital conversion. The computational element is responsible for autonomously analyzing the digital signals obtained from the data acquisition circuitry. Thus, the computational element must be capable of performing the core digital signal processing functions. As described in the previous sections, the signal processing functions are application specific, but involve some aspect of signal detection, source identification, and source localization. These core functions must operate under some prescribed real-time constraints and be presented to the telemetry system for reporting. The remainder of this section will discuss the specific signal processing operations performed for the stationary target application.

The detection of the target involves the processing of the sensor signals to determine the presence of $u(t)$. For optimal detection, the received signal $r(t)$ would be processed using a matched filter based on $u(t)$. In general, some features of $u(t)$ would be known, from which a near optimal digital signal enhancement filter can be applied. However, it is also important to apply correction effects for source coupling, signal propagation, and receiver coupling in order to achieve acceptable detection results.

The identification of the target also involves processing the received signal $r(t)$ to determine the type of target that is generating the emissions. For optimal identification, the received signal $r(t)$ would be processed using a bank of matched filters followed by an M-ary classification process. Again, it is essential that the features of the suspected targets be known so that near-optimal filters can be applied. As for detection, correction for propagation and coupling effects is essential.

The location estimation of the target is a unique inverse problem. There are two general approaches to location estimation: Array processing using multiple UGS sensors; and/or signal feature extraction from multiple UGS. Both approaches generally tend to rely on arrival time measurements and apply an inverse relationship as per Eq.3. Because

the signal is stationary, multiple observations at multiple locations can be made of arrival times. Thus, if the application so permits, a desirable location accuracy can be achieved through a multiplicity of spatial and temporal UGS measurements.

An important function of a stationary-target UGS is the integration of multiple measurements over long listen times. Because the target is stationary, multiple observations of the emitted wavefields can be averaged to reduce the effect of incoherent noise. This technique is of great value when attempting to detect very weakly emitted wavefields.

5. SYSTEM ISSUES FOR STATIONARY TARGETS

The stationary target problem places some important constraints on unattended ground sensors. First and foremost, the general location of the target should be known *a-priori*. This constraint comes from the fact that the UGS relies on the measurement of emitted wavefields to characterize the target. These wavefields generally have finite propagation ranges, so very wide area searches using UGS is generally not possible. The second constraint is that *a-priori* information on the signatures of the emitted wavefields must also be available. To optimally detect and identify the target, the full time-varying source signature, source/receiver coupling characteristics and wavefield propagation effects would need to be known. In general, however, reasonable estimates of target features and the coupling/propagation effects will result in acceptable target detection and identification.

In order to accurately locate a stationary target using an UGS, multiple deployment locations are generally required. This impacts the system design since accurate deployment locations and accurate timing references must be available. Furthermore, due to the potentially long listen times associated with the stationary targets, the power subsystem must be able to provide either adequate resources or use some form of power management. A final system consideration is that the use of multiple UGS against a target requires some means of multi-point telemetry.

6. ILLUSTRATIVE EXAMPLE OF STATIONARY TARGET APPLICATION

In this section, we present a simple example to illustrate the typical functions of a stationary-target UGS. Consider an application where one is trying to determine the unauthorized transmission of radio signals. Let us denote this as the Radio UGS. One could set out one or more Radio UGS in the general vicinity of where the unauthorized operator is suspected. The UGS consist of radio receivers tuned to the interfering frequency, a signal processor, and a communications link to some central location. This application is illustrated in Figure 2. The first function of the system is to detect the presence of radio transmissions in the frequency band of interest. The system must automatically monitor around-the-clock for the presence of radio transmissions. If the system fails to detect transmissions, then the system would assume that there are no unauthorized transmissions within the monitoring range of the sensors. If on the other hand, the UGS detects transmissions, it would report such transmissions. However, such transmissions could be generated by a licensed operator. Hence this UGS must also perform the second function: signal identification. The UGS would process the received radio signals, and apply a signal processing algorithm to determine whether they are characteristic of a licensed operator or an unauthorized operator. Such an algorithm could use a variety of feature extraction methods to identify the legality of the source; signal energy, pattern matching, speech or data recognition, etc. Once the system declares the presence of unauthorized communications, then the UGS would execute the localization objective.

To further illustrate this application, consider that the unauthorized operator transmits digital information at a rate of 38.4 kBaud. Figure 3 represents a digital serial waveform of the ASCII message "Dave" at this Baud rate. Suppose the unauthorized operator (Dave) transmits this message using amplitude modulation (A.M.) with a carrier frequency of 3.84 MHz. Figure 4 illustrates an example of the signal that would be sensed by the Radio UGS. Note both the presence of noise and the lack of a clearly recognizable ASCII serial string.

For our example, the Radio UGS has been given *a-priori* knowledge that the unauthorized transmissions are at a carrier frequency around 3.8 MHz. Using this *a-priori* knowledge, the Radio UGS applies a signal enhancement digital filter that suppresses noise and enhances signals at the assumed carrier frequency. The output of the signal enhancement filter is shown in Figure 5. This enhanced signal is furthermore applied to an adaptive threshold algorithm, and the detected

signal is illustrated in Figure 6. Thus, Figure 6 represents a detection of a radio transmission at the *a-priori* carrier frequency, and would cause the Radio UGS to send an alarm message.

Having detected a possible unauthorized radio transmission, the second function of the UGS is to identify the characteristics of the transmission. In our example, the Radio UGS has been given *a-priori* information that the unauthorized operators name is "Dave". As such, the Radio UGS implements an algorithm which continually checks for the "Dave" message at the 38.4 Kbaud rate. An optimal approach for identifying the presence of the "Dave" message is to apply a digital matched filter. The output of a matched filter for the noisy message of Figure 4 is shown in Figure 7. Note the high signal output of the matched filter when the "Dave" message is present versus the very low output in the presence of noise. Hence, the matched filter output provides a robust means for detecting and identifying Dave.

The third and final step for the Radio UGS signal processing algorithm is to locate the source of the unauthorized transmissions. The preferred method for locating the source is to utilize multiple UGS. In this manner, each UGS is used to measure a propagation time, and a triangulation algorithm applied to fix the source in space, as per Eq. 3. Relative propagation times can be measured using a variety of algorithms. We illustrate in Figure 7 the use of the matched filter output to directly determine the relative propagation time. Note that the peak of the matched filter output is a very precise measurement of the start of the transmission of the "Dave" message. Multiple UGS would, in a similar manner, compute relative propagation times, and these would be combined to arrive at a location estimate of the unauthorized transmissions.

7. COMPARISON OF MOBILE TARGET AND STATIONARY TARGET APPLICATIONS

In this section, we provide a detailed comparison between mobile-target and stationary-target unattended ground sensor architectures. The primary feature that differentiates a stationary target UGS is the long listen time associated with the data acquisition, signal processing, and concept of operations. The long listen time results from three aspects of stationary target sensing:

- 1.) Since the target is stationary, characterizing the target is usually a non-time-critical operation
- 2.) Due to its fixed location, the target emissions are often time invariant; this is used to increase signal-to-noise for detection, identification, and localization
- 3.) The fixed location of both target and UGS allows better use of *a-priori* information such as propagation effects, target emission signatures, and measurement biases.

These issues have important implication on the architecture of the stationary target UGS. A comparison of stationary target UGS with mobile target UGS is summarized in Table 1.

Table 1
Comparison of stationary and mobile UGS

Feature	Stationary-target UGS	Mobile-target UGS
Primary Mission	Intelligence, Targeting, BDA	Rapid Targeting, Mobility Assessment
Communications Needs	Usually low-bandwidth	High bandwidth, fast response
Time-critical reporting	Not usually	Yes
Doppler Shifted Signals	No	Yes
Long listen time enhancement	Yes	No
Ability to detect low SNR signals	Yes	Limited
Ability to accurately locate target	Yes	Limited

8. CONCLUSIONS

In this paper, the application of unattended ground sensors to the stationary target problem has been investigated. The objectives, requirements, and system features of stationary target unattended ground sensors have been described in detail. In particular, we have developed a signal model for wavefields emitted from stationary targets and sensed by an UGS. Using the signal model, a methodology for data acquisition and signal processing has been described. The data acquisition and signal processing requirements were used to develop the system features for a stationary target UGS. A unique aspect of the stationary target UGS is its ability to take advantage of long-listen time signal processing. An example of a stationary target UGS and representative data were used to illustrate the signal processing and system features. Furthermore, a detailed comparison between stationary target and mobile target unattended ground sensors was made. In conclusion, the application of unattended ground sensors to stationary targets requires a unique system architecture and signal processing methodology.

9. REFERENCES

- ¹ D. Middleton, "A statistical theory of reverberation and similar first-order scattered fields - part I: waveforms and the general process," IEEE Transactions on Information Theory, Vol. IT-13, No. 3, pp. 372-392, July 1967.

Figure 1: Model used to represent the stationary target sensing problem.

Figure 2: Illustrative example of a stationary target unattended ground sensor (UGS). The UGS is used to detect, identify, and locate radio transmissions from Dave.

Figure 3: Digital waveform representation of the ASCII serial message "Dave" at 38.4 kBaud

Figure 4: Representative A.M. radio signal of the "Dave" message as sensed by the Radio UGS

Figure 5: UGS-enhanced radio signal

Figure 6: UGS-detected radio signal

Figure 7: Matched filter output of UGS for identifying and locating the "Dave" transmission