UXO Detection Techniques Using Sonar and Radar

Edmund J. Sullivan

Abstract Several approaches to the detection of Unexploded Ordnance (UXO) in the ground are discussed. Methods exploiting the coupling of sound into the earth are shown to have promise. These approaches can use both linear and non-linear phenomena as clues. Also discussed is the potential of a ground penetrating radar method that is based on a nonlinear phenomenon.

Key words: sonar, acoustic, detection, radar, mines, nonlinear, Laser Doppler Velocimetry, speckle noise

1 Introduction

The general problem of detecting and identifying buried objects has grown more difficult with time. During the second world war, the detection of buried mines was reasonably successful since most mines were metal and thus could be detected with reasonable success by any of several types of metal detectors [1]. The sophistication of mines has increased since then, however. Anti-personnel mines are much smaller than anti-tank mines and many of today's mines are nonmetallic. Other techniques have been tried, such as biological (use of dogs, rats and bees), and infrared techniques. For an overview of these approaches, see reference [1].

A large part of the problem is that, when trying to detect a UXO from, say, a moving vehicle, time is of the essence, so that the issue of false alarms becomes paramount. There has been some recent work which seeks to overcome this problem. In this chapter we will concentrate mainly on seismo-acoustic (SA) methods. Also, a short discussion on a Ground-Penetrating Radar (GPR) method is given.

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2 Detection and Identification

The signal processing practitioner usually separates problems into detection, estimation and identification. The simplest detection problem, the one we will be addressing here, is the binary hypothesis test. That is, we wish to indicate the presence or absence of a target with a reasonably high probability of success. The next level is the estimation problem. For the UXO problem, the estimation of its location is not a major issue since, upon detection, its location is fairly well known. For our purposes, identification is the main issue, since without some means to obtain an approximation of the nature of the contact, the false alarm problem becomes a major issue, since in the case of a UXO buried in a roadway, there likely will be objects of similar size (rocks, discontinuities, etc.) in the same region.

3 Acoustic Methods

The speed of sound for compressional waves in soil is on the order of $200-300m/sec$, as compared to $343m/sec$ in air. This means that to resolve a target with a characteristic size on the order of, say $.25m$, would require wavelengths on the order of $.1m$ or less. Thus, frequencies on the order of $2kHz$ would be necessary. As it turns out, these frequencies are already too high to be of any use, as will be seen in the following.

3.1 Acoustic Properties of Soils

Sound propagation in porous media is well described by the theory developed by Biot [2, 3]. This theory predicts that shear waves and two types of compressional waves are supported in such solids. Of the two compressional waves, sometimes referred to as “fast” and “slow” compressional waves, the slow wave is rapidly attenuated, as is the shear wave. The speeds of the fast and slow waves are actually quite close to each other, differing by only a few 10’s of c/s. There seems to be no general agreement as to which of these compressional waves plays the major role in acoustic UXO detection methods.

Since the sound speeds in soil are significantly less than in air, any sound coupled into the ground can be assumed to refracted downward. Also, since the sound coupling into the soil cannot realistically be thought of as occurring at a well-defined interface, the concepts of reflection and transmission coefficients cannot always be considered to be a realistic model. The phenomenon is usually referred to as *seismo acoustic* or SA coupling, where the interface is viewed as a region of interaction [7]. Generally speaking, it is not the coupling that hinders SA UXO detection methods, but the absorption and false alarm problem.

A study of the behavior of sound waves is soils was carried out by Oelze et al. [4]. They studied six soil compositions with clay content ranging from 2 to 38%, silt content ranging from 1 to 82%, sand content ranging from 2 to 97%, and organic matter ranging from 0.1 to 11.7%. Soils were classified as "loose" to "dense" and water content from dry to saturated. As might be expected, the results varied over wide ranges.

Attenuation coefficients α determined over frequencies of 2 to 6 kHz ranged from 0.12 to 0.96 dB/m/kHz. Lower attenuation tended to be in loose dry samples. Propagation speeds ranged from 86 to 260 m/sec.

The two-way attenuation loss can now be estimated. Figure 1 shows the loss as a function of depth at $2kHz$ for α values of .2, .5, and .8. Here, it can be seen that to expect to detect a buried object at this frequency, at a depth of more than a few tens of centimeters, is unlikely. To complicate the problem, there will likely be a great deal of clutter, leading to a high false alarm rate.

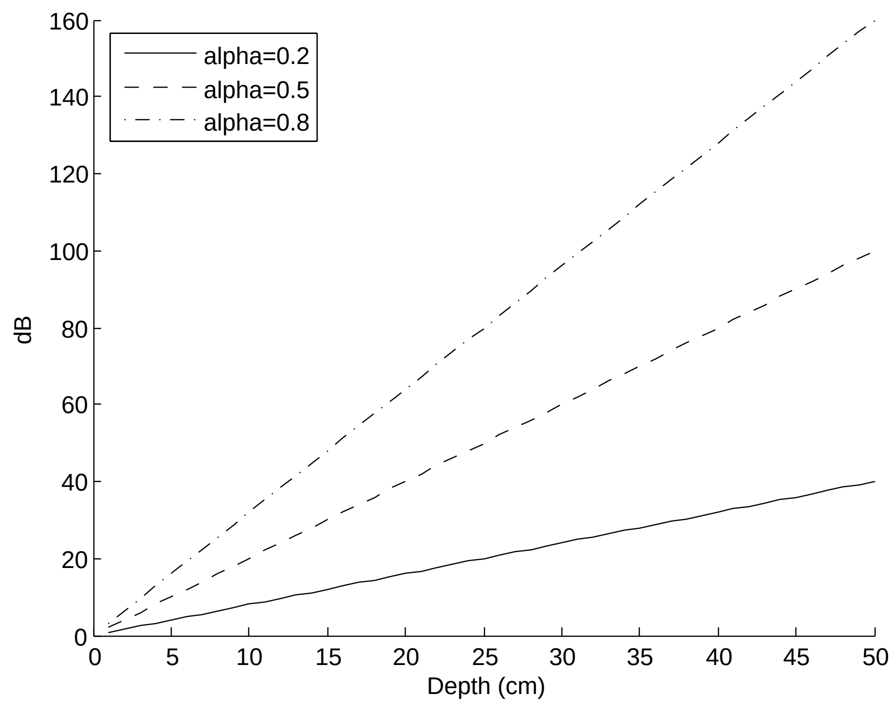

Fig. 1 *Absorption loss in soil. Alpha has units of $dB/m/kHz$.*

3.2 The Nonlinear Approach

There has been some experimental work done in the field of nonlinear detection. In 2002, Donskoy et al. [5] demonstrated that they could detect the nonlinear response of a buried mine-like object by detecting its sum and difference frequencies. The ground was excited with two high-level sound sources, generating acoustic waves in the ground in the region of the objects of interest. The source power levels were on the order of several hundred watts.[1] By using two frequencies, the sum and difference frequencies were detectable by sensing the ground surface vibration with a Laser Doppler Velocimeter (LDV). Interestingly, the nonlinear response is not from the object itself, but arises from the fact that the object is more compliant than the surrounding earth, resulting in a detachment at the interface during the tensile phase of the oscillation.

These results are interesting, since they rely on inducing a resonance in the object, which for anti-personnel mines and anti-tank mines, occurs at frequencies less than a kilohertz, thus ameliorating the absorption problem. In 2004, Korman and Sabatier [6] carried out a series of experiments essentially verifying the work of reference [5] and extending the experiments to include the observation of the effects of nonlinearities on "tuning curves," *i.e.*, the shift of the resonant frequency of the object with amplitude. A major importance of this work is that it shows promise for reducing the false alarm problem, since it is to be expected that the mine will be the most compliant object in the ground.

This work must be considered to still be at the research level, since it is far from being applicable as an operational device.

3.3 The Linear Approach

Another approach, one that also uses a scanning LDV, does show promise of being applicable as an operational device. In this case, the ground is excited by a broadband high-level sound source, which can excite a resonance of the target. Although such a resonance has a low Q, since the object is in the soil, it appears to be sufficient to permit detection of the reradiation of the object by sensing the surface displacement. In 2001, Sabatier and Xiang [7] published a method in which they drove the ground with a broadband signal with a reasonably flat spectrum between 80 and 300 Hz, with a sound pressure level on the order of $90-130 dB(C)$ [2] and interrogated the surface with a scanning LDV. By using a correlation detector, they were able to successfully detect VS 2.2 and M21 anti-tank mines at a depth of 7.5 cm. The VS 2.2 is a roughly cylindrical plastic mine with a diameter of 24 cm, and the M21 is a

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[1] It is difficult to translate these numbers into sound pressure level since the sources are in the near field.

[2] Unlike underwater acoustics, where the sound reference level is 1 μPa, the conventional reference in air is 20 μPa, which is approximately at the hearing threshold. C refers to the frequency weighting, which is essentially flat over a band of 63 Hz to 4 kHz.

metallic mine with a diameter of 22 cm. In these cases, surface velocities on the order of $50\mu m/sec$ at frequencies on the order of $150Hz$ were encountered. The laser light has a wavelength of approximately $.6\mu m$, so that for vibrational speeds of this order, Equation 6 indicates displacements on the order of 50 nanometers. Generally speaking, the plastic mines showed a greater response than the metallic ones.

In a later work, Valeau et al. [8] were able to improve the detection performance by using a time-frequency approach which was able to remove much of the speckle effects.

The importance of this approach is that it holds promise for the development of an operational system, since the scanning LDV allows the processing to be carried out at acceptable speeds, as opposed to the so-called "stop and stare" method, where the LDV is used in a point by point method.

3.4 Principle of the Laser Doppler Velocimeter

The laser Doppler velocimeter is a device that uses the Doppler shift imparted by a moving (vibrating) surface on the reflected energy of an incident laser beam to estimate its instantaneous velocity. The approach used by Sabatier and Xiang [7] is based on the heterodyne method, where the incident beam is modulated by a Bragg cell, sometimes called an Acousto-Optic modulator or A/O modulator, which imparts a frequency shift (usually in the megahertz range) on the optical frequency. This frequency shift plays the role of a carrier frequency which is then frequency modulated by the vibratory motion. For example, if the laser frequency is ω_0 and the modulation frequency is ω_m, then when a beam of amplitude A_i with this frequency is scattered from a surface, and mixed in an interferometer with a reference beam of amplitude A_r and frequency ω_0, the intensity of the sum is given by

$$I_s = |A_i e^{i(\omega_0+\omega_m)t} + A_r e^{i\omega_0 t}|^2 = |e^{i\omega_0 t}|^2 |A_i e^{i\omega_m t} + A_r|^2. \tag{1}$$

Equation 1 now reduces to

$$I_s = I_1 + I_r + 2A_i A_r cos(\omega_m t), \tag{2}$$

with $|A_i|^2 = I_i$ and $|A_r|^2 = I_r$. The result, after removing the DC terms, is simply

$$I_s = A_i A_r cos(\omega_m t). \tag{3}$$

Now suppose the reflecting surface is vibrating with amplitude A_v at radian frequency ω_v. Then there will be a time dependent phase term added to $\omega_m t$ equal to

$$\phi(t) = \left(\frac{2\pi}{\lambda}\right) 2A_v sin(\omega_v t), \tag{4}$$

where λ is the wavelength of the laser light. Thus, Equation 3 becomes

$$I_s = 2A_iA_r cos(\omega_m t + \phi(t)). \tag{5}$$

The output of the LDV photodetector is a current proportional to I_s which can then be demodulated to extract the velocity. That is,

$$v(t) = \frac{\phi'(t)}{4k} = \omega_v A_v cos(\omega_v). \tag{6}$$

The prime indicates the time derivative.

3.4.1 Speckle Noise

The LDV suffers from a limitation commonly referred to as “speckle” noise. This is a consequence of the fact that the laser light is highly coherent, so that the phase front of reflected laser light is extremely grainy and non-stationary in time. This can be viewed as a coherent addition of a multiple of spherical wavefronts, arriving from different points on the surface, coherently interfering at the observation point. From a statistical point of view, even though it is deterministic, it can be considered to be a realization of a random process.

If the undulations of the scattering surface have a characteristic deviation greater than the laser wavelength, then the phase structure of the wavefront can be considered to be a zero-mean random process, uniformly distributed from $-\pi$ to π, and its autocorrelation function is sharply peaked with a width on the order of a wavelength. Also, it is reasonable to consider the complex field at an observation point on an observation plane to be complex Gaussian.

In the case of the LDV, the difficulty is that the speckle noise takes the form of random spots that are rapidly moving in the observation plane. These spots have a characteristic size that is strongly dependent on the optical aperture involved. This is a consequence of the fact that highly localized scatterers are not resolvable beyond the capability of the viewing aperture. Thus, the narrower this aperture, the larger the correlation length, and therefore the larger the apparent size of the speckle spots. For a scanning LDV then, the speckle noise emanating from the LDV has a “bursting” type behavior as these speckle spots move past. This noise is difficult to remove. As mentioned above, some progress has been made in dealing with this by Valeau et al. [8] where a space-time representation of the velocity field is used for the detection statistic.

An excellent discussion of speckle is in the book by Barrett and Myers [9].

4 Ground-Penetrating Radar

Ground Penetrating Radar (GPR) techniques have been highly developed in the recent past [10] and have resulted in several commercial devices. It has applications in a number of fields. It is used to make geological measurements, nondestructive testing of large structures and pavements, and locating pipes and other buried objects. It is also extensively used in archaeology.

In spite of its successes however, it has some severe limitations. It performs poorly in any medium that has a high conductivity, such as clayey and moisture laden soils. Also, there is the fact that absorption of electromagnetic energy increases with frequency, whereas high frequency is necessary when resolution of small objects is desired. This means that there are severe depth constraints in such cases. In the case of mine hunting or UXO detection, as with the SA methods, it can suffer from poor detection statistics due to clutter. More information on GPR can be found in reference [10].

4.1 Nonlinear Detection

Here we propose a nonlinear approach that may have application to cases where some form of electronic circuitry is contained. As an example, a typical cell phone receives on a carrier on the order of 850 MHz. If we choose a radar signal of this frequency to drive the input, then we should expect that the circuitry itself will have induced currents due to the high field strength. Since these circuits are highly nonlinear, we could expect reradiated frequencies to exhibit spectral components that lie outside of the carrier frequency's band. This means that, even if the reradiated field levels are low, they will have a favorable signal to noise ratio.

In the following example, we consider a clipped sine wave. In Figure 2 we show a $1kHz$ unit amplitude sine wave that is clipped to half of its amplitude. Figure 3 depicts the power spectrum of this signal. As can be seen, along with the $1kHz$ line, there are several strong lines at odd multiple frequencies.

The exact nature of the nonlinearities and their ability to produce such spectra would most easily be determined by experiment. Clearly, one drawback of this approach is that frequencies of $800-900kHz$, depending on the soil makeup, may not penetrate deeply into the ground. In many cases however, such high frequencies usually can detect at depths on the order of $1-2ft$. For UXO devices buried at such depths, this offers an interesting possibility.

5 Conclusions

The capabilities of seismo-acoustic coupling and ground penetrating radar have been discussed. Due to the absorption of high-frequency ($> 1kHz$) sound waves by the soil, direct imaging of a buried object appears to be out of the question.

The exploitation of nonlinear effects shows promise in mitigating the false alarm rate, but they are still at the research stage. The linear approach, which uses SA coupling into the ground to excite the object of interest, shows promise of being

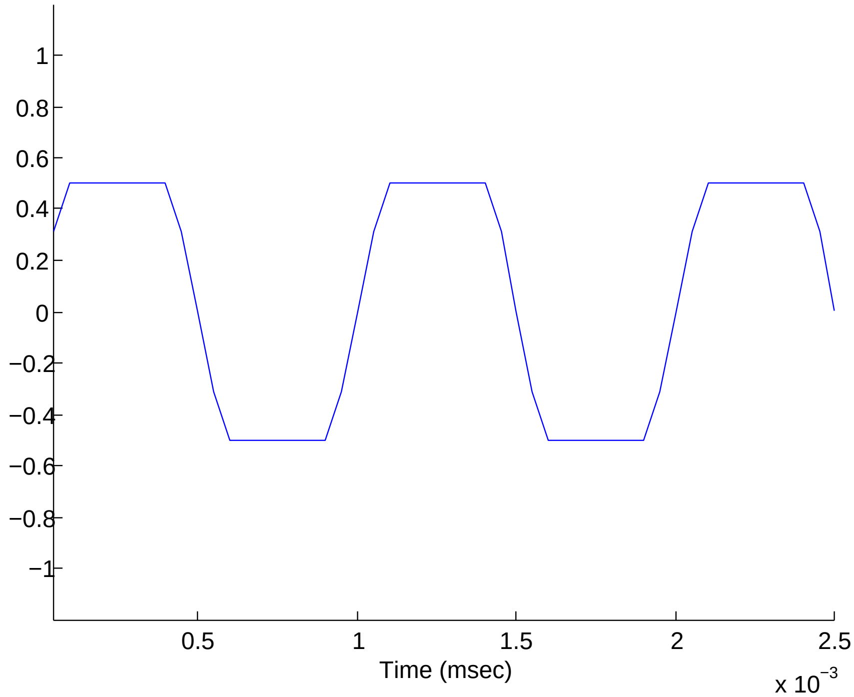

Fig. 2 *Sine wave clipped at half amplitude.*

closer to an operational system. Here, the surface vibration induced by the vibrating buried object is sensed with a scanning LDV.

The possibility of exploiting nonlinear effects in any electronic circuitry used as a detonator is shown to offer the possibility of detection of the reradiation from such devices when excited by a GPR source.

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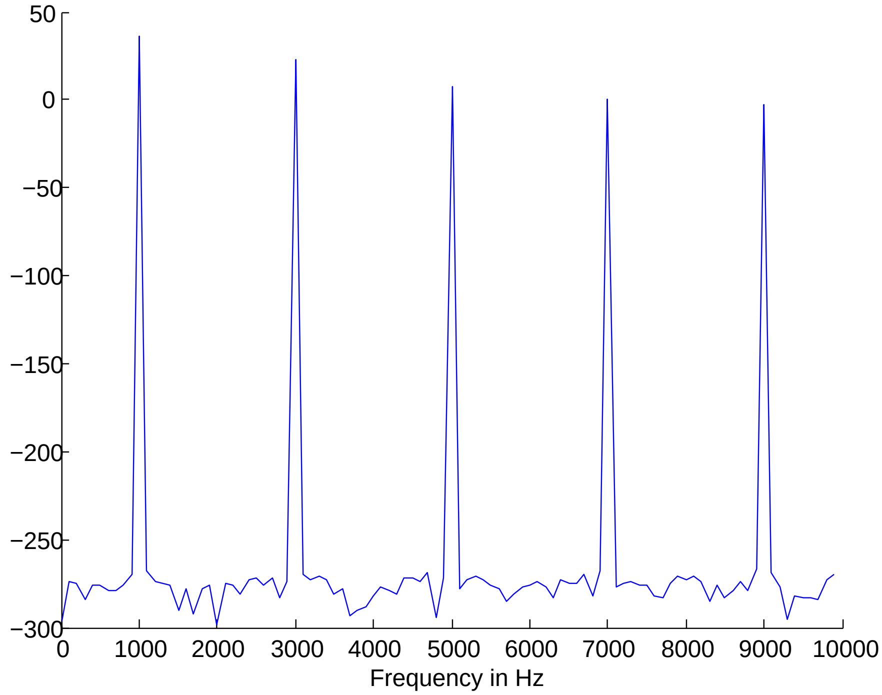

Fig. 3 *Spectrum of clipped sine wave.*

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