Limits of Detection of Buried Landmines Based on Local Echo Contrasts

B. Sai, I. Morrow, P. van Genderen

Delft University of Technology, Faculty of Information Technology and Systems
International Research Centre for Telecommunications-transmission and Radar (IRCTR)
Mekelweg 4, 2628 CD Delft, The Netherlands
E-mail: b.sai@its.tudelft.nl, i.morrow@its.tudelft.nl, p.vangenderen@its.tudelft.nl

Abstract

This paper describes some works, being carried out in the IRCTR, focused on landmine detection by using an ultra-wideband (UWB) impulse Ground Penetrating Radar (GPR). In landmine detection, a ground penetrating radar has to deal with multiple, lossy, probably inhomogeneous medium problems, and its performance is associated with the properties of local soil and buried targets, implementation of its hardware and software. It is more significant for a carrierless video pulse radar to use the term, peak power, in a sense of detection of buried targets. Concerning reflected signal levels, the contrast of electromagnetic characteristics between a buried landmine and its surrounding soil is of utmost importance. The analysis shows that a minimum discernable signal (MDS) being approximately as low as -100 dB below the transmitted peak power of a GPR system is demanded so that signals scattered from various non-metallic landmines buried in a variety of typical grounds can be detected by radar. This is of great difficulty for conventional time-domain impulse radar system to achieve such a goal. Improvements and modifications are necessarily needed specially for GPR landmine detection. We discuss the various key factors within this problem which can yield results worthy of being used in system design/configuration by means of a far-field, two-medium approach.

Keywords: UWB impulse radar, landmine detection, ground penetrating radar

1. INTRODUCTION

There are about 100 million landmines still buried in 64 countries. The humanitarian aim to achieve the global clearance of landmines has become an issue of predominance. To make a reliable, easily-interpreted and less time-consuming operational system for landmine detection is a real challenge. Ground Penetrating Radar (GPR) is one of the most prospective sensors for detecting various buried and non-metallic anti-personnel (AP) landmines. As a starting stage of the process of landmine detection, it is basically desirable that all buried landmines be detected within a scanned area. As radar targets to be detected are a wide variety of hidden dielectric landmines, any failure of detection leads to very dangerous consequence for deminers. This, in a technical sense, demands a GPR should have a capability of detecting the signals reflected from any types of dielectric landmines buried in various types of ground, which undoubtedly makes the work of producing such a radar extremely formidable. In order to make a purpose-designed/optimized GPR system, special attention has been paid to the limits of detection of buried landmines based on local echo contrast. Based on our extensive review of landmine category and minefield scenarios[1,2], some commonly-encountered dielectric AP mines and soils were chosen, as extreme cases, to determine the optimum technical specifications of an impulse GPR system. In terms of buried target detection, the strength of radar echoes is usually associated with contrasts of electromagnetic characteristics between targets and their surrounding soils. A simplified far-field two-medium problem is used to treat the propagation processes of waves emitted by a transmitting antenna. A radar that is quoted in this context is a common bistatic UWB video-pulse GPR. Our intention is to make this kind of systems optimized and adapted to mine detection purpose. It should be apparent that a purpose-designed radar system has to have its performance predicted in the presence of the above environments before it will be constructed. The following discussion is of relevance to the technical issues mentioned above.

2. BISTATIC ANTENNA AND PROPAGATIONS IN TWO MEDIA

We assume that soil is homogeneous and has a permittivity of $\varepsilon_2(f)$ and a conductivity of $\sigma_2(f)$. Further supposing that a dielectric solid sphere with a permittivity of $\varepsilon_3(f)$ is buried in the soil and its lateral boundary effects are neglected due to an assumption of a virtual layer, Δd, which has a very large horizontal dimension, and the same thickness as the sphere's shown in Figure 1. The dielectric solid sphere has an intrinsic impedance of η_3.

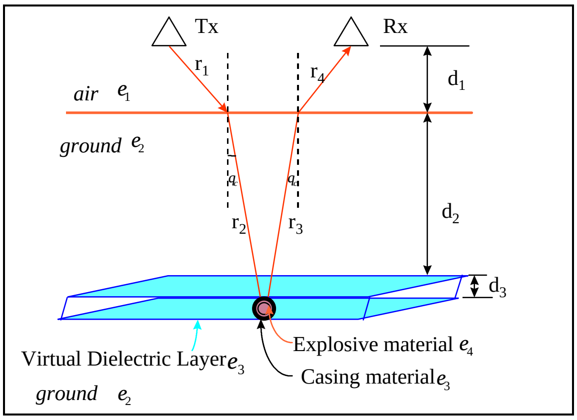


Figure 1 Estimate of the incident and reflected power under the two-medium scenario

For two half dielectric spaces (η_1, η_2), i.e. air and ground, when a radiated signal, from a transmitting antenna, reaches the air-ground interface, the magnitude of the ratio between the average transmitted and incident power flow, κ, is

$$\kappa_{as} = \frac{\eta_1}{\eta_2}\left(\frac{E_t^s}{E_i^a}\right)^2 = \frac{4\eta_2\eta_1}{\left(\eta_2+\eta_1\right)^2} \qquad (1)$$

where, η_1 is the intrinsic impedance of air. η_2 is an intrinsic impedance of soil.

When the incident field impinges against the surface of a buried target given in Figure 1, the magnitude of the reflected electric field strength from a target of finite thickness is

$$E_r^s = E_i^s \Gamma\left\{1-\Gamma(1-\Gamma)(1+\Gamma)-\Gamma^3(1-\Gamma)(1+\Gamma)-\cdots\right\} \qquad (2)$$

where, Γ is the ratio of reflected to incident electric field strength at two dielectric half spaces, η_2, η_3, i.e. soil and dielectric targets as given below according to Fresnel's law.

$$\frac{E_r^s}{E_i^s} = \Gamma = \frac{\eta_3-\eta_2}{\eta_3+\eta_2} \qquad (3)$$

Therefore, the magnitude of the ratio between the average reflected and incident power flow, γ, is

$$\gamma = \left(\frac{E_r^s}{E_i^s}\right)^2 = \qquad (4)$$

$$\left|\Gamma\left\{1-\Gamma(1-\Gamma)(1+\Gamma)-\Gamma^3(1-\Gamma)(1+\Gamma)-\cdots\right\}\right|^2$$

Actually, γ denotes a reflection coefficient based on average power of unity area.

3. ESTABLISHMENT OF RADAR RANGE EQUATION FOR GPR SYSTEM

A UWB signal essentially has instantaneous frequency spectral energy. The highest and lowest frequencies of its matched bandwidth in certain soil are two key parameters. At least, half of the minimum wavelength in the soil should be comparable with or less than the maximum physical dimension of a buried landmine. Otherwise, the energy of those wavelengths that are far larger than the maximum dimension of a buried landmine will hardly be reflected but keep on "going forward". If a short pulse has an equivalent duration of τ, the down range resolution in certain soil is

$$\Delta R_z = \max\left\{\frac{c\tau}{2\sqrt{\varepsilon_2}}, \frac{\lambda_{\min}}{2\sqrt{\varepsilon_2}}\right\} \qquad (5)$$

where, c is the light speed in free space.

The cross range resolution is

$$\Delta R_x = \max\left\{\frac{\lambda_{\min}}{2\sqrt{\varepsilon_2}\tan\left(\frac{\theta}{2}\right)}, \frac{\lambda_{\min}}{2\sqrt{\varepsilon_2}}\right\} \qquad (6)$$

where, θ denotes the beamwidth of the receiving antenna. Assuming that the highest frequency component received is the same as that transmitted, the physical dimensions of the buried landmine are greater than the resolutions defined above.

In a far-field approach, a UWB radar illuminating area (footprint) on the virtual layer shown in Figure 1 is usually larger than the geometrical cross section of a small buried landmine. Therefore, we use a reflection coefficient of average power of unity area to handle the process of the reflection from a dielectric landmine. The received power of unity area by a receiving antenna can be expressed as

$$P_r(f) = \frac{P_t(f)G(f)}{4\pi R_1^2}\kappa_{as}\cdot\gamma\cdot\kappa_{as}\frac{A_{eff}(f)}{4\pi R_2^2}\cdot e^{-2\alpha(r_2+r_3)} \qquad (7)$$

where, $R_1 = r_1 + r_2$, $R_2 = r_3 + r_4$; $\gamma(f)$ denotes a magnitude of the ratio between the average reflected and incident power flow between the boundary interface of the target and soil at a frequency, f. κ_{as} denotes a magnitude of the ratio between the average transmitted and incident power flow at air-ground interface. G is the power gain function of the transmitting antenna; A_{eff} is the effective aperture function of the receiving antenna. $P_t(f)$ and $P_r(f)$ are the transmitting and receiving power spectral densities on unity area, respectively. $\alpha(f)$ is an attenuation factor of the soil, being equal to

$$\alpha = \frac{2\pi f}{c}\sqrt{\frac{\mu_2 \varepsilon_2}{2}\left(\sqrt{1+\tan^2\delta}-1\right)} \qquad (8)$$

4. PROPERTIES OF NON-METALLIC MINES AND SOIL

4.1 OVERVIEW OF LANDMINES

It is necessary to understand the features of mines, in terms of their shapes, case material, explosives, geometry and locations. Table 1and Table 2 give the results of our review of landmines by categorization.

- Case material:

Many types of mines were designed and constructed with very little metallic content. Their packages can be made of plastic, wood, fiberglass, bakelite, ceramic, cardboard, concrete, neoprene, and resin. On a basis of rough statistics, it is noted that among various AP mines those constructed from plastic material account for approximately 50%.

- Explosives and sensitivity:

Mine main charge, in addition to TNT, may be RDX, PETN, Comp B, Nitro-Penta and melinite. Sophisticated mines may incorporate demining countermeasures. They may be blast-proof, or incorporate anti-disturbance devices that detonate when mines are moved or detected, injuring or killing the deminer.

Shape	Case Mat.	Geometry Height: (H) mm Diameter: (D) mm Length: (L) mm Width: (W) mm	Burial Depth (DP) cm
Cylindrical/Round	plastic	H: 30 ~ 260; D: 30 ~ 180	DP: 0 ~ 25; Max.: 50
Rectangular/Square	plastic	L: 70 ~ 400; Max.: 620 W: 25 ~160; H: 31 ~ 260	DP: 0 ~ 15 To bottom of mine
Irregular	plastic	N/A	DP: 0 ~ 12
Cylindrical/Round	wood	N/A	N/A
Rectangular/Square	wood	L: 20 ~ 480; W: 12 ~120 H: 10 ~ 230	DP: 0 ~ 10; Max.: 25
Cylindrical/Round	metal	H: 30 ~ 350; D: 35 ~ 220 Max.: 120, 230	DP: 0 ~ 30
Rectangular/Square	metal	L: 65 ~ 380; Max.: 480 W: 25 ~180; Max.: 380 H: 50 ~ 220	DP: 0 ~ 8
Spherical	metal	D: ~ 60	N/A
Cylindrical	*others*	*H: 40 ~ 90; D: 70 ~ 135*	DP: 0 ~ 10

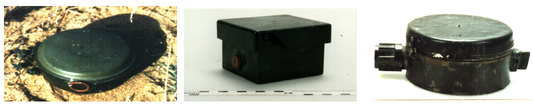
Table 1 Some characteristics of AP mines

SHAPE	CASE MAT.	GEOMETRY Height: (H) mm Diameter: (D) mm Length: (L) mm; Width: (W) mm	BURIAL DEPTH (DP) cm
Cylindrical/Round	plastic	H: 90 ~ 290; Max: 1100 D: 110~ 340	DP: 0 ~ 30 Max.: 100
Rectangular/Square	plastic	L: 160 ~ 330; Max.: 1210 W: 65 ~ 330; H: 55 ~ 195	DP: 0 ~ 20 Max: 200
Irregular	plastic /metal	N/A	DP: 0 ~ 30
Cylindrical/Round	wood	H: ~ 70; D: ~ 350	DP: 0 ~ 15
Rectangular/Square	wood	L: 210 ~ 620; W: 12 0 ~ 340 H: 70 ~ 230	DP: 0 ~ 25
Cylindrical/Round	metal	H: 65 ~ 260; Max: 1100 (L) D: 90 ~ 500	DP: 0 ~ 50 Max: 150
Rectangular/Square	metal	L: 175 ~ 300; Max.: 850 W: 95 ~280; H: 10 ~ 140	DP: 0 ~ 20 Max: 95
Cylindrical	others	H: 70 ~ 120; D: 70 ~ 350	DP: 8 ~ 15; Max: 35

Table 2 Some characteristics of AT mines

- Location and burial depth:

Mines can be emplaced by various methods and in various terrains. They may be found in the places such as riverbanks, paths, roads, fields or even under rocks in forested or overgrown areas, etc. AP mines are usually installed at depths of 0 to 25 cm with dimensions from 3 cm to 15 cm. Figure 2 shows some examples of AP mines. AT mines could be buried deeper than 25 cm, sometimes up to 50 cm or more. But these mines usually have larger dimensions than shallowly buried mines. In the case of non-metallic landmines, their burial depths are typically from 0 to 25 cm in a clayey soil due to their effects of explosion whereas they could be larger than 25 cm, even up to 50 cm in a sandy soil. Therefore, the maximum detection depth can be 25 cm in clayey soil and in sandy soil, the maximum depth is 50 cm.



Type 72B
plastic/rubber
3.9 cm x 7.9 cm

NR 15
plastic/chemical fuse
9.5 cm x 8.8 cm x 6.5 cm

PMN
plastic/rubber
5.6 cm x 11.2 cm

Figure 2 Examples of non-metallic AP mines

4.2 DIELECTRIC CHARACTERISTICS OF LANDMINES AND SOIL

Dielectric properties of typical casing and explosive materials of landmines are given in Table 3. One of the most common AP mines is a plastic mine charged with TNT. At 1 GHz, TNT has a dielectric constant of approximately 2.9, and plastic casing has a dielectric constant of 2.91[3]. Since there is little difference of the dielectric constants between plastic and TNT, we can regard the plastic mine as a target having an average dielectric constant of ε_3^a.

$$e_3^a = (e_3 + e_4)/2 \cong 2.9 \qquad (9)$$

Regarding soil types in minefields, Table 4 and Table 5 show properties of typical soil. Obviously, sandy soil and clay are two extreme cases that should be taken into account with respect to a GPR landmine detection.

Material	Frequency					
	0.3 GHz		1 GHz		3 GHz	
	e_r	tan$d$	e_r	tan$d$	e_r	tan$d$
E Resin	-	-	-	-	2.43	0.0006
Plastic	2.67	0.0285	2.91	0.0784	-	-
Neoprene	4.24	0.0636	-	-	4.0	0.0339
Nylon	3.08	0.0138	3.06	0.014	3.02	0.012
Comp B	3.20	0.0035	-	-	3.20	0.002
Bee Wax	-	-	-	-	2.35	0.005
TNT	2.89	0.0039	-	-	2.86	0.0018

Table 3 Properties of typical explosive and case material

Material	Frequency					
	0.3 GHz		1 GHz		3 GHz	
	e_r	tan$d$	e_r	tan$d$	e_r	tan$d$
Sandy soil (dry)	2.55	0.01	-	-	2.55	0.0062
Sandy soil (4% moist.)	4.5	0.03	-	-	4.4	0.046
Sandy soil (2-18% moist.)	2.5	0.026	-	-	2.5	0.03
Sandy soil (16.8% moist.)	20	0.03	-	-	20	0.13
Loamy soil (dry)	2.47	0.0065	-	-	2.44	0.0011
Loamy soil (14% moist.)	20	0.16	-	-	20	0.12
Clayey soil (20% moist.)	20	0.52	-	-	11.3	0.25

Table 4 Properties of typical soil

Material	Loss a' at 100 MHz (dB/m)	Loss a' at 1 GHz
Wet clay	5-300	50-3000
Loamy soil	1-60	10-600
sandy soil	0.01-2	0.1-20
Brick	0.3-2.0	3-20
Concrete	0.5-2.5 dB/m	5-25 dB/m
Ice	0.1-5 dB/m	1-50 dB/m

Table 5 Attenuation loss of typical materials

For a given transmitted power and a buried dielectric object, two major factors, i.e. soil attenuation and dielectric contrast between an object and its surrounding soil will affect radar echoes. The most important is which factor will play a dominant role in landmine detection.

As an example, we consider the two extreme ground conditions for estimating signal levels. Assuming that 1 GHz is a median frequency of a transmitted UWB signal at which sandy soil has a dielectric constant of 4 and maximum attenuation of 20 dB/m, and wet clay has a relative permittivity of 25 and maximum attenuation of 100 dB/m. The inside attenuation of a buried plastic landmine can be neglected because it usually has a small height. According to (4) the ratio between the average reflected to incident power flow for sandy soil is

$g \cong 0.$

And for wet clay

$g \cong 0\ 07$

clay and sandy soil is approximately 13. This implies that when a signal is radiated into ground, two

One is that a travelling distance of the radiated energy depends on soil attenuation which is a function of

propagate farther which determines maximum detection depth (two-trip). The other is the effect of

surrounding soil. Poor contrast value means the power will pass through a buried object and very little would

contrast is independent of depth of a buried object. For instance, a plastic landmine mentioned as a previous

poor contrast and hence low signal level. Lower reflected signal level infers a higher front-end receiver

5. COMPUTATION OF THE CONTRASTS FOR SOME AP MINES

Based on the previous discussion, we use two types of antennas to give examples for estimation of the entire signal levels with regard to landmine detection. Resistively loaded dipole antenna and TEM horn antenna are chosen in the following examples. According to Eq. (7), we obtained resultant combination of antenna and ground types. The final results are given in Table 6.

Antenna types[4,5]	Ground types	Depth (m)	Plastic mines (e_3)	Signal loss (dB)
resistive dipole G=1.5, r =10%	sandy soil	0.5	2.9	107
	wet clay	0.25	2.9	117
TEM horn G=15	sandy soil	0.5	2.9	67

These results of estimation obtained from our first-order model compare well with those obtained by theoretical FDTD computation using finite-difference, time-domain technique[6].

6. CONCLUSIONS

For GPR landmine detection, the major challenge is the signal level from a buried dielectric mine that can generate an electromagnetic contrast to its surrounding medium(soil). Very small MDS of a GPR system is required so that signal reflected from a landmine having a poor contrast can be detected by a radar system. Moreover, very high dynamic range is required as well due to surface or metal-debris reflections on various ground. Surface reflections can be removed by means of signal processing in order to detect shallowly buried landmines. In the above examples, it can be seen that at least 100 dB dynamic range is required to be able to detect commonly-encountered nonmetallic AP landmines buried in various soil. Most UWB impulse GPRs usually operate in the Time Domain. Therefore, it is difficult for commercial time-domain equipment to achieve a high dynamic range. High gain antenna and radar front-end conditioner are one way to alleviate such system requirements and achieve a desired dynamic range, and thus improve the performance of an impulse GPR to be used for detection of landmines.

REFERENCES

[1] "Mine Facts", US Department of Defense, 1995

[2] "Hidden Killers, The Global Landmine Crisis", Office of International Security and Peacekeeping Operations, US Department of State, 1994

[3] A.R. Von Hippel, editor, "Dielectric materials and applications," John Wiley & Sons, Inc., NY, 1954

[4] C.A. Balanis, "Antenna Theory, Analysis and Design", 2nd edition, John Wiley & Sons, Inc., 1997

[5] J.D. Taylor "Introduction to Ultra-Wideband Radar Systems", CRC Press, Inc. 1995

[6] I.L. Morrow, "Initial FDTD Computations of Signals Received and Transmitted through an Air-ground Interface", IRCTR Report, No. NTP_009, March, 1998