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Principles of Mine Detection by Ground-penetrating Radar

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Abstract. Ground-penetrating radar (GPR) is a sensor which has a good potential for use in buried land mine detection. Compared to metal detectors (EMI sensors), GPR can detect both metallic and non-metallic objects, and has the capability of imaging the target shape. However, application of GPR to mine detection has suffered from many technical problems. In this chapter, the principles of GPR, especially the relation of GPR signal to physical parameters, is described. The dielectric properties of objects are essential in GPR surveying, and in practical situations, soil moisture and soil inhomogeneity are the most important parameters to consider in mine detection by GPR.

Keywords: GPR, Dielectric constant, Clutter, Signal processing

2.1 Introduction

Ground-penetrating radar (GPR) has been extensively applied to investigate subsurface structures or buried objects in geology, civil engineering, environmental and soil science. This non-destructive method of subsurface analysis is becoming increasingly important for many environmental and shallow geophysical applications. GPR can quickly and accurately determine the subsurface structure. The GPR equipment can easily move on the ground surface but does not have to touch it, and it can detect both metallic and non-metallic objects in the soil. Due to these features, many attempts have been made to employ GPR in buried land mine detection. However, unfortunately, the detection of mines by GPR has many technical difficulties, and it is not easy to achieve. In this chapter, we describe the principles of GPR and then discuss how it can be utilized for land mine detection.

2.2 GPR Principles

2.2.1 Electromagnetic Wave Propagation in Soil

Electric properties of materials are determined by electrical conductivity, permittivity and permeability. The permittivity is the most important parameter for

GPR, because at a high frequency any material behaves as dielectric. The electromagnetic wave behavior in subsurface material is strongly dependent on its electrical conductivity, and the electrical conductivity is normally controlled by water. When a material is conductive, the electromagnetic field is diffusive and cannot propagate as an electromagnetic wave. When it is resistive, or dielectric, an electromagnetic field can propagate as an electromagnetic wave. Electromagnetic induction (EMI) sensors, which are normally referred to metal detectors use this frequency range, because penetration into the soil is easy.However, GPR uses electromagnetic waves and its interpretation is easier because the diffusion effect is less. When we use higher frequencies, any material behaves as dielectric because the displacement current dominates the conducting current, and the electromagnetic field propagates as a wave, although the attenuation gets higher.

GPR measures the reflected electromagnetic wave from the subsurface structure. The velocity and reflectivity of the electromagnetic wave in soil is characterized by the dielectric constant (permittivity) of the soil. When the dielectric constant of the soil is ε_r, the velocity in this material is given by

$$v = \frac{c}{\sqrt{\varepsilon_r}} = \frac{3\times10^8}{\sqrt{\varepsilon_r}}\,(\text{m/s}). \tag{2.1}$$

2.2.2 Reflection of Electromagnetic Waves from Land Mines

GPR transmits a pulsed electromagnetic wave from a transmitting antenna located on the ground surface and signals are received by a receiving antenna, on the ground surface. When the electromagnetic wave velocity v is known, measuring the travel time τ (s), we can estimate the depth of the reflecting object d (m) as follows:

$$d = \frac{v\tau}{2}\,(\text{m}). \tag{2.2}$$

The travel time is defined as the time from the being transmitted to signal and the time signal is received, which corresponds to the propagation time from the reflecting object.

The reflection occurs, when the electromagnetic wave encounters any electrically inhomogeneous material. The most significant electrically inhomogeneous material is metal. Any buried metallic material such as pipes and cables are quite easily detected by GPR. However, it is very important to note that even an insulating material can be an electrically inhomogeneous material. Insulating material is referred to as dielectric material, and its characteristics are defined by the dielectric constant. The dielectric constant is also called permittivity.

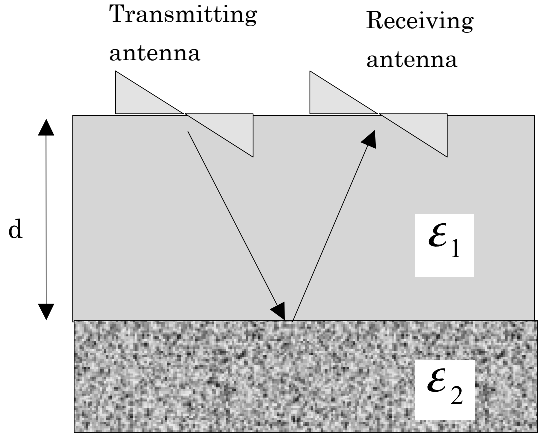


Figure 2.1. Electromagnetic wave reflection at a geological boundary

When electromagnetic wave is incident to a flat boundary of two different materials having the dielectric constant of ε_1 and ε_2 (Figure 2.1), the Electromagnetic wave having an amplitude of 1 is reflected by the boundary and its amplitude is Γ. Γ is defined as the reflection coefficient of a boundary and is given by

$$\Gamma = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}}\,. \tag{2.3}$$

Equation 2.3 shows that the amplitude of the reflected wave is defined by the ratio of the dielectric constant of the two materials. The reflection coefficient Γ takes a value between $-1 \le \Gamma \le 1$. If the lower material is metal, the reflection coefficient is

$$\Gamma = -1\,, \tag{2.4}$$

and it takes the maximum amplitude. Therefore, the reflection from metallic material is always very obvious. This condition stands even when the metallic material is a thin sheet, because all the electromagnetic energy is reflected by the metal.

In actual GPR measurement, the radar target is not infinitively large, but it has a finite size. Generally, a larger target reflects stronger signals, when the size of the target is smaller than that the wavelength. The reflectivity of an isolated target is measured by radar cross section (RCS). The size of typical anti-personnel landmine is less than 10 cm in diameter, and the thickness is less than 5 cm. When the scattering object is small, RCS is proportional to the size of the objects. Therefore, the RCS of landmines is very small as a target of GPR.

The dielectric constant of subsurface material is based on rocks, and soils, which varies in its constituent material itself. However, the dielectric constant of these materials is similar, and the water contained in the material is the most significant for the value of the dielectric constant. The dielectric constant, the attenuation of typical subsurface materials are summarized in Table 2.1. Figure 2.2 shows the typical relationship between the dielectric constant of soil and its water content. From Equation 2.3, we can understand any change of water conditions in the soil and geological formations can cause the electromagnetic reflection. The dielectric constant of the rock and soil material in dry conditions have a value between 3 and 5, and their contrasts are not so large. We can see that the contrast

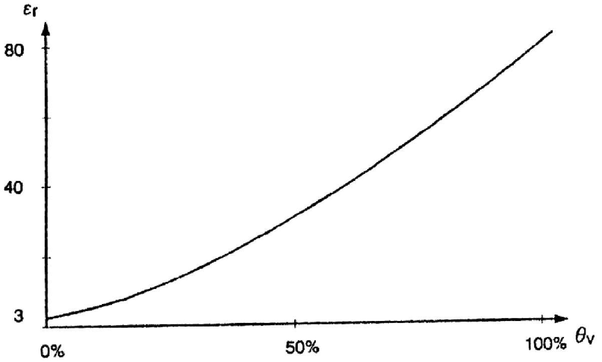


Figure 2.2. The typical relative permittivity and water content of soil

Table 2.1. Attenuation and relative permittivity of subsurface materials measured at 100 MHz [1]

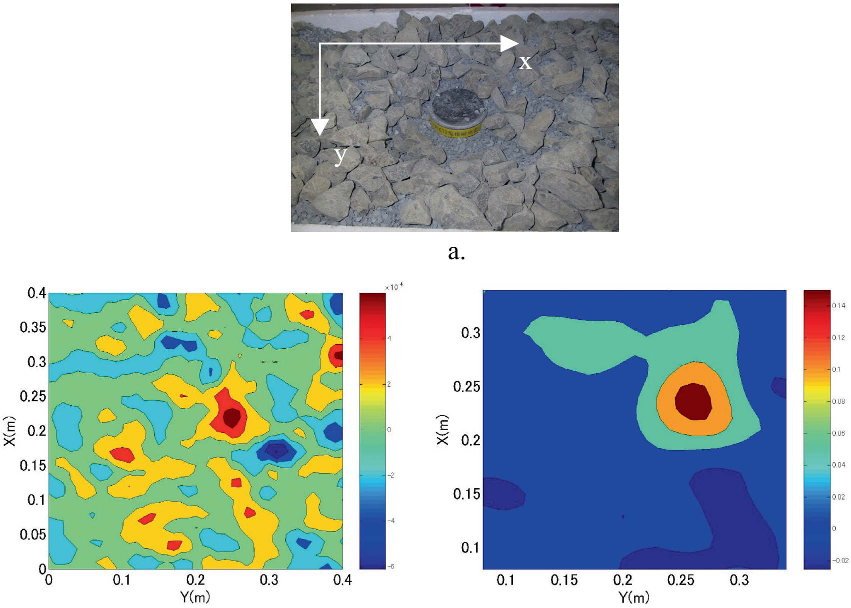
Material	Attenuation (dB/m)	Relative permittivity ε_r
Air	0	1
Clay	10-100	2-40
Concrete: dry	2-12	4-10
Concrete: wet	10-25	10-20
Fresh water	0.1	80
Sand: dry	0.01-1	4-6
Sand: saturated	0.03-0.3	10-30
Sandstone: dry	2-10	2-3
Sandstone: wet	10-20	5-10
Seawater	1000	81
Soil: firm	0.1-2	8-12
Soil: sandy dry	0.1-2	4-6
Soil: sandy wet	1-5	15-30
Soil: loamy dry	0.5-3	4-6
Soil: loamy wet	1-6	10-20
Soil: clayey dry	0.3-3	4-6
Soil: clayey wet	5-30	10-15
TNT	-	3
Plastic	-	2-4

of the dielectric constant between soil and land mines is very small. That is the second reason why the detection of plastic mines by GPR is very difficult.

2.2.3 Clutter

The dielectric constant changes with soil moisture. Therefore, even if the material of the soil is homogeneous, when moisture is not homogeneous, the electromagnetic wave can be reflected by the soil. This condition is often found in minefields, and it causes strong “clutter”. Figure 2.3 shows one example of clutter in a GPR image due to a strongly inhomogeneous medium. Figure 2.3a shows the soil, which contains gravel and stones and a landmine model (Type-72). Figure 2.3b shows the horizontal slice of the GPR raw data. We see a lot of scattering due to the soil, and the reflection from the land mine is not very clear. Figure 2.3c shows the migrated GPR image obtained from Figure 2.3b. Migration is a very powerful signal processing methods, which we will discuss in the following section.

Clutter in radar technology is defined as reflections from targets, which we are not interested in. Therefore, inhomogeneous moisture in the soil, small stones and gravel included in the soil are causes of the clutter. Another source of clutter in GPR is the reflection from the ground surface. Most of the GPR systems used for landmine detection are scanned very close to the ground surface and we receive very strong reflection from the ground surface, because the contrast of the dielectric constant between the air and the soil is very large, and the ground surface of minefields is not flat, it causes more complicated EM scattering.



a.

b.

c.

Figure 2.3. Inhomogeneous soil effect on GPR images. a. A land mine buried in a inhomogeneous soil; b. Horizontal slice of GPR raw data; and c. Migrated GPR image

We should note that the clutter is not random noise. If we have time-varying random noise, we can measure it over time and can remove the random signal by time averaging. However, the clutter in the radar is a deterministic signal, and stable in time. Therefore it cannot be removed by the time-averaging method. When the reflection from the target is weak, and the noise level is high, we can achieve a better signal to noise (S/N) ratio by increasing the transmission power. It is possible, when the transmission signal is propagated through a very homogeneous medium such as air. For example, air traffic control radar transmits high power electromagnetic waves to detect airplanes at great distances. However, GPR is a completely different situation. Even if we transmit a higher power signal, the signal strength ratio of the reflection from landmines and clutter does not change. The S/N ratio can be improved by increasing transmission power, only for the system noise. However, the system noise is a time-varying random noise, and the noise level can be decreased by averaging the received signal over a long time. Buried land mines are static targets, and do not move like airplanes. Therefore, the GPR system can stay at one location and acquire the received data for a longer time to increase the S/N ratio. This situation is valid for most GPR surveys, therefore the transmission power of GPR can be very weak.

2.3 GPR Survey

2.3.1 Operation Frequency

The performance of a radar system can be evaluated by two important factors, namely maximum detectable range and radar resolution. The maximum detectable range is defined by the maximum distance, at which the radar can detect the object, the radar resolution is defined as the minimum distance between two different objects which are located close to each other that can be differentiated. If we have a short pulse, we can differentiate two targets located in the same direction. This is a range resolution, and it is determined by the pulse width. In the case of landmine detection, range resolution is the same as the depth resolution. A shorter pulse contains wider frequency bandwidth. Therefore the range resolution is determined by the operation frequency bandwidth of the system. Azimuth resolution is determined by the horizontal separation of the target. If GPR antennas have a sharper radiation pattern, the azimuth resolution can be increased, but compared to the wavelength for GPR for landmine detection, the antenna size must be very small to achieve a sharp beam. In order to solve this problem, a “migration algorithm” can be used.

The maximum detectable range, which is the maximum detectable depth in GPR, is determined by the ratio of the transmitted power and the minimum detectable signal level, which is normally the noise level of the receiver. The detectable range in a free space is determined by the radar equation, but for GPR, the detectable depth is strongly dependent on the subsurface material. Therefore, this ratio is called the system performance of a GPR system and is used as an

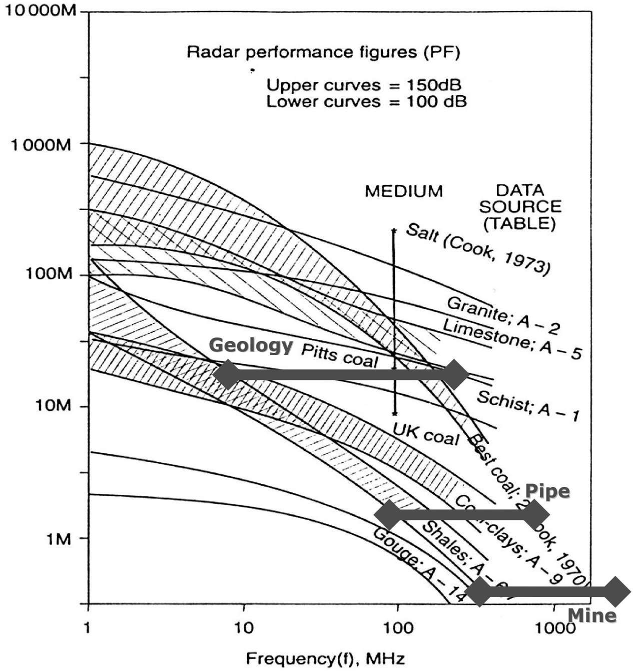


Figure 2.4. GPR system performance and the maximum detectable range

indicator of the maximum detectable depth. Typical GPR systems have a performance factor between 100–150 dB. Figure 2.4 shows the corresponding maximum detectable range in some subsurface materials.

The electromagnetic wave propagating through subsurface material suffers from strong attenuation. The attenuation is dependent on the frequency, and higher frequencies normally have higher attenuation. However, most of the landmines to be detected are buried very shallowly, and clutter dominates the limitation of the range (depth) resolution rather than attenuation. Summarizing the parameters governing the radar characteristics:

Frequency	Low	—	High
Wavelength	Long	—	Short
Attenuation	Small	—	High
Radar Resolution	High	—	Poor
Maximum Detectable Depth	Deep	—	Shallow

Since the radar resolution and the maximum detectable depth are completely opposing factors, as for frequency, the selection of the operating frequency is the most important design factor in GPR. Most GPR systems work at 50 MHz to 1 GHz, but GPR for landmine detection uses the frequency range 1–4 GHz.

2.3.2 GPR System

A diagram of a typical GPR system is shown in Figure 2.5. The radar system is composed of a transmitter, a receiver, antennas connected to them, a controlling unit and a signal display with a recording system.

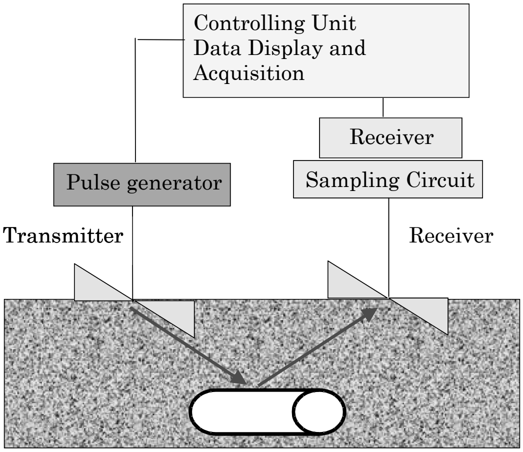


Figure 2.5. GPR System Diagram

2.3.3 Signal Processing

One of the advantages of GPR is real time measurement. Raw GPR profiles give us much information, but some signal processing improves the data quality significantly. Migration is a signal processing technique for image reconstruction. GPR data is acquired by moving antenna position, and the data is processed afterwards. This processing is equivalent to the synthetic aperture radar processing, which is commonly used for radar remote sensing. Figure 2.3 shows an example of migration processing applied to GPR signal.

References

[1] D. J. Daniels Ed., (2004) Ground Penetrating Radar 2nd Edition, IEE Radar, Sonar and Navigation series 15, Institution of Electrical Engineers, London, UK.

[2] C. S. Bristow and H. M. Jol, Ed., (2003) Ground Penetrating Radar in Sediments, Geological Society, Special Publication 211, Geological Society.

[3] L. Conyers, D. Goodman, (1997) Ground-Penetrating Radar – An Introduction for Archaeology, Altamira Press, Walnut Creek, CA, USA.

[4] L. C. Shen, J. A. Kong, Applied Electromagnetism, 3rd Edition, PWS Publishing Co., 1995.