CHAPTER 2

GPR BASIC PRINCIPLES

Ground-penetrating radar (GPR) is a high resolution geophysical technique of imaging and mapping shallow subsurface soil and ground structures using high frequency electromagnetic (EM) waves. GPR method is neither destructive nor invasive making it suitable for use also in urban settings and archaeological environments. Basic principles of GRR including EM wave propagation and GPR field surveys are described in this Chapter.

2.1 EM Wave Propagation

GPR waves are a form of EM energy with two oscillating fields, electrical and magnetic fields (Figure 2.1). The radar energy used in most applications has a frequency range between 10 to 1,500 MHz (Annan and Cosway, 1994) which is the same range as television, FM radio, cellular phone and etc. (Figure 2.2).

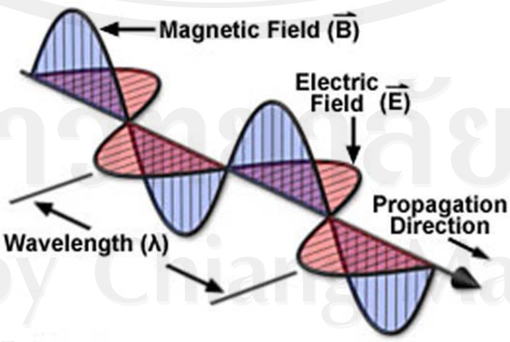

Figure 2.1. Electromagnetic wave propagation which electrical and magnetic fields are perpendicular to each other. (From Microscopy Resource Center, 2012).

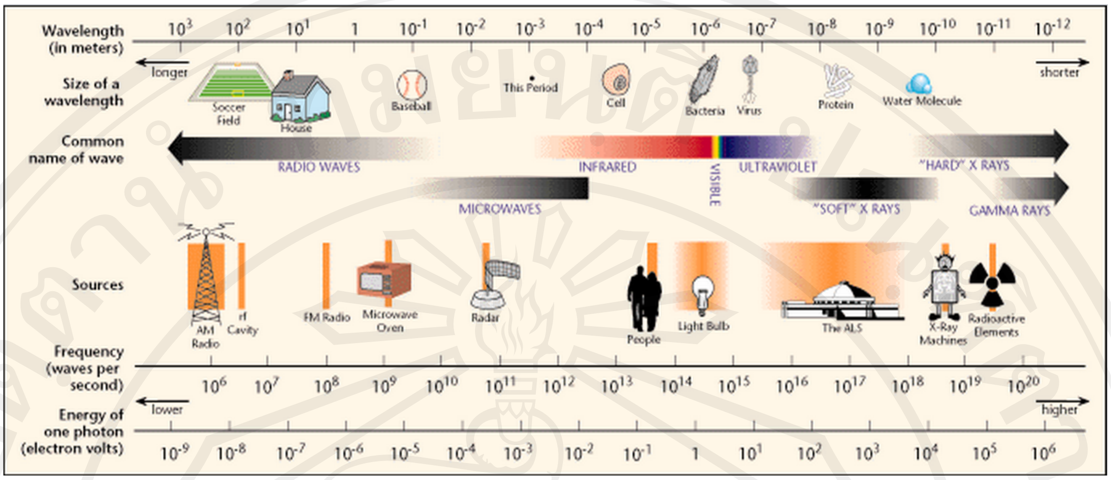

Figure 2.2. Electromagnetic wave spectrums. Wavelength, frequency and energy per photon are represented in top, middle and bottom scales, respectively. (From MicroWorlds, 2012).

The EM field is mathematically described the physics by the four Maxwell's equations (Sharma, 1997), as follows;

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{2.1}$$

$$\nabla \times H = j + \frac{\partial D}{\partial t} \tag{2.2}$$

$$\nabla \cdot B = 0 \tag{2.3}$$

$$\nabla \cdot D = \rho_C \tag{2.4}$$

where E is electric field intensity (V/m), H is magnetizing field intensity (A/m), B is magnetic induction or flux density (T), D is electric displacement (C/m), ρ_c is electric charge density (C/m^3), and j is current density (A/m^2). The other three constitutive relationships describe a material's response to EM fields,

$$D = \varepsilon E \tag{2.5}$$

$$B = \mu H \tag{2.6}$$

$$j = \sigma E \tag{2.7}$$

where ε, μ, and σ are dielectric permittivity (F/m), magnetic permeability (H/m), and electrical conductivity (S/m) of medium, respectively. By using these relationships Maxwell's equation is reduced in terms of only two vectors, *E* and *H* (Grant and West, 1965). Further, by assuming for *E* and *H* a time-dependence of the form $E(t)=E_0e^{i\omega t}$, where ω ($=2\pi f$) is the angular frequency of the field, the vectorial for *E* and *H* take the following form:

$$\nabla^2 E = i\omega\mu\sigma E - \varepsilon\mu\omega^2 E \tag{2.8}$$

$$\nabla^2 H = i\omega\mu\sigma H - \varepsilon\mu\omega^2 H \tag{2.9}$$

where $i = \sqrt{-1}$ and f is EM wave frequency (Hz).

These are the basic equations for the propagation of electric and magnetic field vectors in an isotropic homogeneous medium with physical properties, ε, μ, and σ. The rock properties (ε, μ, and σ) and angular frequency ω can be grouped into one term, k^2, given by

$$k^2 = -i\omega\mu(\sigma + i\omega\varepsilon) = \mu\varepsilon\omega^2 - i\omega\mu\sigma \tag{2.10}$$

The field Equations (2.8) and (2.9) can then be written as

$$\nabla^2 E + k^2 E = 0 \tag{2.11}$$

$$\nabla^2 H + k^2 H = 0 \tag{2.12}$$

The quantity $k = \sqrt{(\mu\varepsilon\omega^2 - i\omega\mu\sigma)}$ is called the complex wave number or the propagation parameter. The behavior of the propagation parameter with change in frequency is important to an understanding of EM wave propagation and attenuation. Two important extreme cases can be distinguished.

1. At low frequencies ($f < 10^5$ Hz), the displacement currents are much smaller than conduction currents $(\mu\varepsilon\omega^2 << i\omega\mu\sigma)$, because ε for most rocks is small (~ $10\varepsilon_0$, where $\varepsilon_0 = 9\times10^{-12}$ F/m) and σ for favorable targets in EM survey is usually ~>0.01 S/m. In this regime, known as the 'inductive' regime, the propagation parameter is approximately given by

$$k^2 = -i\omega\mu\sigma \tag{2.13}$$

   The propagation of this EM fields depends mainly on σ, and are used in EM induction surveys.

2. At high frequency (f > 10 MHz or higher), displacement current dominate over conduction current $(\mu\varepsilon\omega^2 >> i\omega\mu\sigma)$ in earth materials of low conductivity (σ < 1 mS/m). For this case , the propagation parameter is given by

$$k^2 = \mu\varepsilon\omega^2 \tag{2.14}$$

   The propagation of the EM field depends mainly on ε of the rock. Propagation fields of this type are used in GPR.

Rocks with low electrical conductivity (σ < 0.01 S/m), the propagation of EM waves at GPR frequencies is mainly controlled by dielectric permittivity (ε) of rock materials. Relative permeability or dielectric constant is a measure of the ability of a material to store a charge from an applied EM field and then transmit that energy (von Hippel, 1954; Wensink, 1993). The terms dielectric constant (K) defined as Equation (2.15).

$$K = \frac{\varepsilon}{\varepsilon_0} \tag{2.15}$$

where ε_0 (= 8.85×10^{-12} F/m) is dielectric permittivity of free space. Table 2.1 represents dielectric constant of some materials.

Table 2.1 Typical dielectric constant of common material (Modified from Davis and Annan, 1989).

Material	Dielectric constant
Air	1
Dry sand	3-5
Dry silt	3-30
Ice	3-4
Asphalt	3-5
Volcanic ash/pumice	4-7
Limestone	4-8
Granite	4-6
Permafrost	4-5
Coal	4-5
Shale	5-15
Clay	5-40
Concrete	6
Saturated silt	10-40
Dry sand coastal land	10
Average organic-rich surface soil	12
Marsh or forested land	12
Organic-rich agricultural land	15
Saturated sand	20-30
Fresh water	80
Sea water	81-88

EM wave can reflect at the boundary between two mediums which have different dielectric constant. The significant reflection occurs when changing of dielectric constant between boundaries cover over a short distance. The amplitude of reflections at the interface between two mediums can be calculated using Equation (2.16) (Sellman et al., 1983; Walden and Hosken, 1985; Van et al., 2002).

$$R = \frac{\sqrt{K_1} - \sqrt{K_2}}{\sqrt{K_1} + \sqrt{K_2}} \tag{2.16}$$

where R is the coefficient of reflectivity at the boundary between two mediums, K_1 represents dielectric constant of overlying medium and K_2 represents dielectric constant of underlying medium. The highest reflection amplitude usually occurs at the boundary of two thick mediums which have great properties different. The transmission can be defined as;

$$T = 1 - R \tag{2.17}$$

The GPR velocity of propagation remains essentially constant and the GPR signal is independent of frequency (Figure 2.3a) (Harry, 2009). GPR velocities are related to the relative permittivity (K) as given by;

$$v = \frac{c}{\sqrt{K}} \tag{2.18}$$

where c is a velocity of EM wave in vacuum, ~0.3 m/ns (3x10^8 m/s) and v is a velocity of EM wave in the medium (m/ns).

All wave properties present similar behavior. Wave properties depend on $\sqrt{\omega}$ at low frequencies indicate diffusion behavior, while it becomes frequencies independent at high frequencies (Figure 2.3b). The transition from diffusion to propagation behaviors is present when electric current change from conduction-dominant to displacement current-dominant behavior. For simple material, the transition frequency is;

$$f_t = \frac{\sigma}{2\pi\varepsilon} \tag{2.19}$$

The attenuation of a GPR wave and it depth of penetration depend on the electrical conductivity and dielectric constant of medium through which the wave propagates. In case of low-loss media ($\sigma/\varepsilon\omega \ll 1$), attenuation factor ($\alpha$) can be calculated by Equation (2.20);

$$\alpha = \frac{\sigma}{2}\sqrt{\frac{\mu}{\varepsilon}} = \frac{\sigma}{2}\sqrt{\frac{\mu_0}{K\varepsilon_0}} \tag{2.20}$$

where $\mu=\mu_0=4\pi\times10^{-7}$ H/m, $\varepsilon_0 = 8.85\times10^{-12}$ F/m.

Skin depth (δ) is the referred depth that amplitude of the field is reduced to $1/e$ (i.e. 37%) of its surface value. Skin depth (δ) can be written as;

$$\delta = \frac{1}{\alpha} = \frac{2}{\sigma}\sqrt{\frac{\varepsilon}{\mu}} = \frac{2}{\sigma}\sqrt{\frac{K\varepsilon_0}{\mu_0}} = (5.31\times10^{-3})\frac{\sqrt{K}}{\sigma} \tag{2.21}$$

GPR operates at frequencies where the capacitive properties dominate the conductive properties and thus the attenuation remains essentially constant at different conductivities (Figure 2.3b).

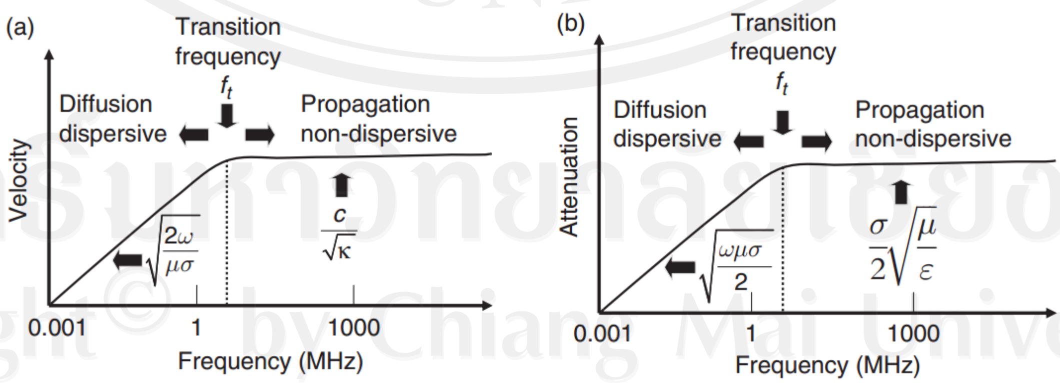

Figure 2.3. Variation in (a) velocity and (b) attenuation in a simple medium with non-dispersive physical properties. (From Harry, 2009).

2.2 GPR Field Survey

A typical GPR system has three main components: antennas, control unit and display unit (Conyers, 2004). The transmitting antenna radiates a short high-frequency EM pulse into the ground, where it encounters changes in dielectric constant, the EM pulse scattered back toward the receiving antenna. Both transmitter and receiver perform with the timing unit which controls the generation and detection of signals.

Most of GPR applications were employed with the source on the ground. Signal paths between a transmitter and a receiver on the surface can be treated as rays following the paths depicted in Figure 2.4 (Harry, 2009). GPR signal can travel directly from a transmitter to a receiver (A), can travel into the ground and reflect back to the surface (R), and travel with critical angle (G).

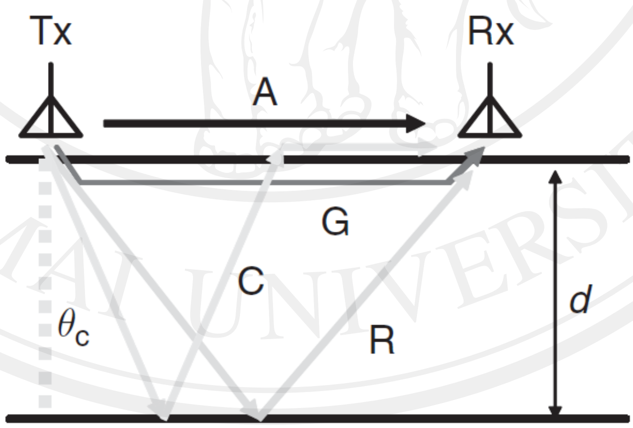

Figure 2.4. Signal paths between a transmitter and a receiver treated as rays following the paths. A is the direct airwave, G is the direct ground wave, R is the reflected wave, and C is the critically refracted wave. (From Harry, 2009).

In GPR field survey, receiver antenna encounters electromagnetic signal from the surrounding (Figure 2.5). Major signals are from communication and transmitter disturbing the recorded GPR data. Shielding transmitter and receiver give advantages that;

a. maximize the energy on the path AA' to and from the subsurface target (i.e., focus or direct signal downward);

b. minimize the direct transmitter to receiver energy on path B;

c. minimize the energy that escapes into the air as on path CC'; and

d. minimize external EM noise as indicated by signals D.

In contrast, shielding also yields various drawbacks in field practical. Shielding-generated signals can be large and reverberate for a long period of time, greatly increasing the system ring-down (Harry, 2009). An effective shield leads to larger transducer size, greater weight, and increased manufacturing cost. The cost, size and weight of shielded antenna are the critical consideration for low frequencies performing. Then shielded antenna is common used for high frequency GPR systems.

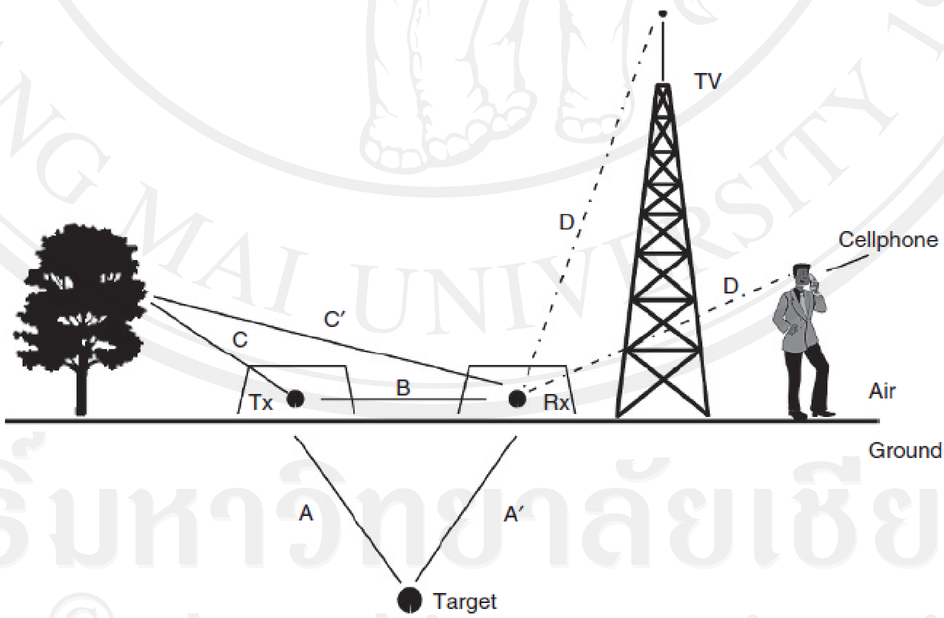

Figure 2.5. A ground penetrating radar (GPR) system emits and detects radio wave signals. There are many possible signals and paths and the objective is to maximize the target response and minimize others. (From Harry, 2009).

The ideal frequency distribution of EM pulse is a bell shape distribution around the center frequency. Figure 2.6 represents an ideal and real EM pulse of 200 MHz transmitter. In the real situation, depending on GPR system and design of the individual transmitter, the frequency distribution is rarely bell shape but usually an asymmetrical spiky distribution around the center frequency. The frequency distribution of the recorded GPR data presents as bell shape as an emitted EM pulse but its frequency band is broader and the center frequency is shifted to lower frequency. Because high frequencies of EM pulse were absorbed easier than lower frequencies. The maximum effective depth of penetration of GPR signal is a function of frequency and the physical characteristics of the material (Batey, 1987).

There are three general survey techniques.

1. Common-offset reflection surveys

   Using a single transmitting and receiving antenna with fixed offset at each measurement location.

2. Multi-offset reflection and refraction surveys

   Using the same technique as seismic survey which can be estimated for velocity, improve signal to noise ratio, but time consuming and expensive.

3. Transillumination surveys

   Performing GPR survey in the borehole for engineering and environmental studies.

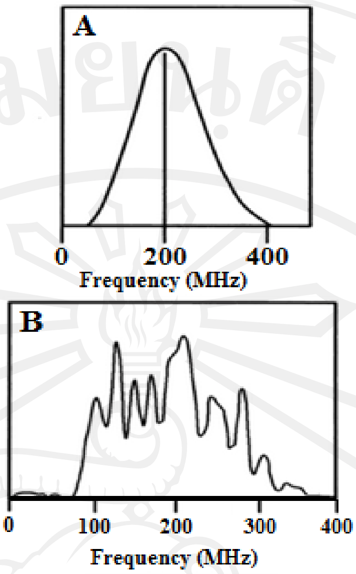

Figure 2.6. Frequency distribution of the electromagnetic pulse with central frequency of 200 MHz emitted from GPR transmitter. (a) The ideal emitted EM pulse and (b) real emitted EM pulse. (Modified from Conyers, 2004).

In this study, a fixed offset shielded antenna was employed. GPR data were collected continuously together with moving of antenna along the line survey but antenna moving velocity may vary by uncertainly of tower or mover. So, distance interval marker was used to fix the position along the line survey (normally every 1 m) and then number of obtained GPR data traces in every marked interval were adjusted to the same number.