جامعة الانبار
كلية العلوم -قسم الجيولوجيا التطبيقية

اسم المادة بالعربي: الجيوفيزياء الجهدية - الطرق الكهربائية

اسم المادة بالإنكليزي: **Potential Geophysics- Electrical Methods**

عنوان المحاضرة: **GPR- Introduction**

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Introduction

Most geophysical methods used in studying archaeology are principally based on the detection of variations of magnetic and electrical properties of underground soil, and identify and separate between artifacts and the natural soil variations. Ground penetrating radar is a near-surface geophysical technique that allows investigators to discover and map (depth and dimensions) buried features by new form of analysis in ways not possible using traditional field methods. It is the only archaeo geophysical method which, allows preparation of 2D slices, and (maps) of underground objects at various depths without their excavation, preparation of 3D reconstructions of the precise shapes and depths of underground objects. It gives the real image of underground objects as radar images in real time during the measurements (Millsom, 1996; Conyers & Goodman, 1997 ; Chamberlain, 1999; Conyers, 2009).

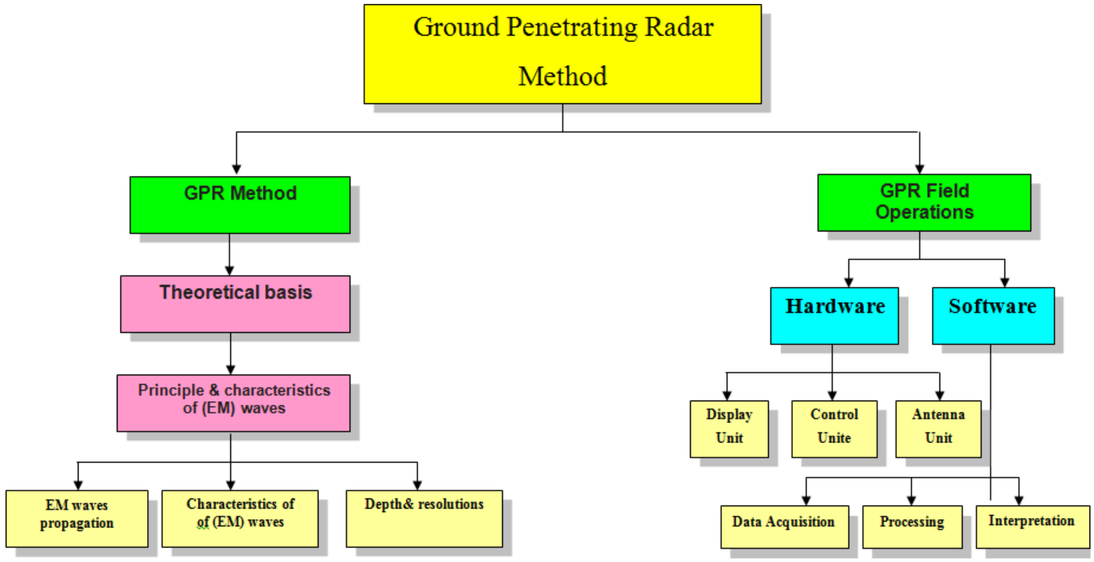


Diagram (2-1) shows the GPR Method

GPR Method

Ground penetrating radar is a technique which use radio waves, typically from the 1 to 1000 MHz frequency range, to map structures and features buried in the ground (or in man-made structures) (Conyers and Goodman, 1997; Gaffney and Gater, 2003; Conyers, 2004).

The GPR data can be used to guide the placement of excavations, define sensitive areas containing cultural remains to avoid and place archaeological sites within a broader environmental context (Kvamme, 2003).

GPR method works by sending a tiny pulse of electromagnetic waves (EM) into an earth (materials) and recording the strength (intensity) and time required for the return of any reflected signal to the surface. Reflection is produce whenever the energy pulse enters into a material with different dielectric permittivity (dielectric constant) from the surrounding materials and dependent on soil and sediment mineralogy changes, clay content, ground moisture, depth of burial, differences in bulk density at stratigraphic, surface topography, and most important water content variations. Some of the GPR energy pulse is reflected back to the antenna, some energy also keeps traveling through the materials until it dissipates or lost (attenuation), and the other waves scattered. If the velocity through the ground known and the travel times of the energy pulses are measured, distance (or depth in the ground) can be accurately measured (Olhoeft, 2000 ; Conyers, 2004), (figure 2-1).

In GPR survey, selection the antenna type with correct operating frequency is one of the most important variables to get the depth of investigation of the features of interest with acceptable resolution in spite of many variables can be influence on the depth of investigation.

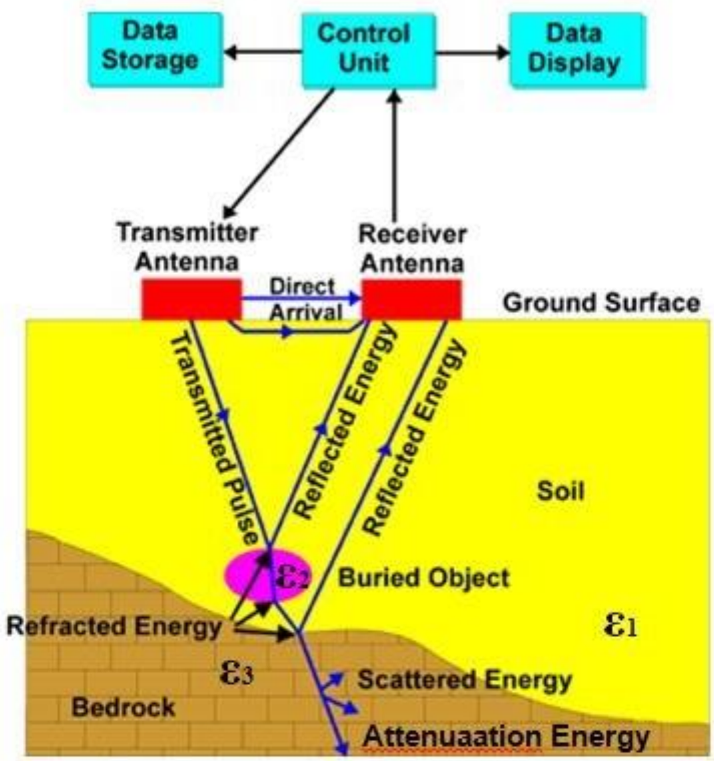


Figure (2-1) shows the GPR method, principle plan (A.S.T.M., 2005).

Electromagnetic Theory:

The electromagnetic (EM) theory including all of the void and geologic anomaly detection methods based upon the propagation of EM wave energy from a transmitting source of EM waves to a receiver. The generation of electromagnetic waves depends on the relationship between the electric and magnetic fields, a changing magnetic field (H) will induce an electric filed (E) (Ampere's Law), and a changing electric field will induce a magnetic field (Faraday's Law) .Electromagnetic waves have energy, momentum, mass, and flow in the direction of propagation through space by means of wave motion. The fields are vector quantities having direction as well as intensity. Maxwell's equations described and proved mathematically the propagation of an electromagnetic field (Maxwell, 1863, 1991). The electric and magnetic fields are propagates in same direction but perpendicular.

Electromagnetic fields when propagating as wave's can be define by wave fronts or by ray paths (Smith, 1997; Stolarczyk, 2003) (figure 2-2).

Any dielectric material will dissipate part of the energy from an electromagnetic wave propagating though it. The source of these losses may investigate by considering Maxwell's equations (Al-Mattarneh, 2008).

The varying of electric fields with time are producing magnetic fields depending on the relative magnitude of losses, the fields may diffuse or propagate as waves. At low frequencies and high losses, the equations reduce to the diffusion equation and are call electromagnetic induction. At the high frequencies of radar, the energy storage in dielectric and magnetic polarization creates wave propagation, (Balanis, 1996; Smith, 1997).

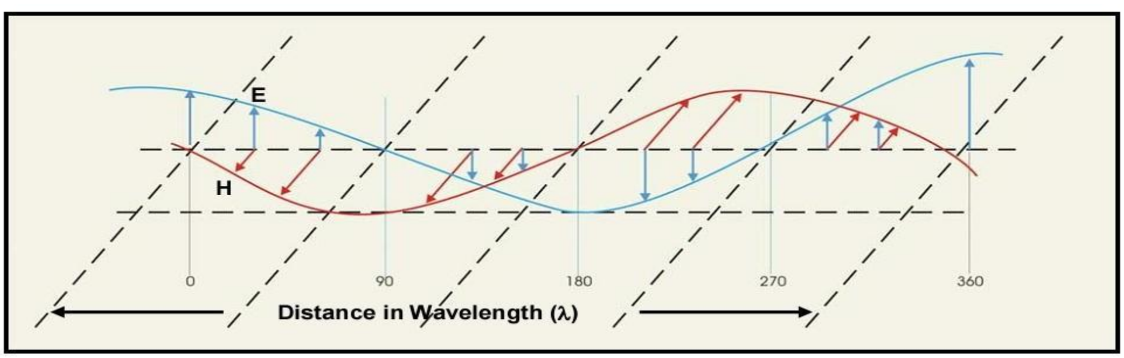


Figure (2-2) Traveling EM waves are composed of electric

(E) and orthogonal magnetic (H) fields (Stolarczyk, 2003)

The equations, which derived from Maxwell equations (Fall, 2007), and control the movement of E.M. waves in any medium can defined by the following:

$$\nabla^2 \mathbf{E} = \mu\sigma \frac{\partial E}{\partial t} + \varepsilon\mu \frac{\partial^2 E}{\partial t^2} \quad (2.1)$$

$$\nabla^2 H = \mu\sigma \frac{\partial H}{\partial t} + \varepsilon\mu \frac{\partial^2 H}{\partial t^2} \quad (2.2)$$

Where:

E = electric field intensity , H = magnetic field intensity, μ = magnetic permittivity, σ = electrical conductivity, ε = dielectric constant, t = time.

Electromagnetic wave Propagation in Subsurface Material:

The electrical and magnetic properties of rocks, soils and fluids (natural materials) control the speed of propagation of radar waves and their amplitudes, and it can determine the nature of media and the water content, (Keller, 1966; Olhoeft, 2000; Annan, 2001; Conyers, 2004).

The EM waves propagate in subsurface materials depending on electrical . characteristics, and these characteristics are determined by electrical conductivity (σ) and the permittivity or dielectric constant (ε). The electrical conductivity is normally controlled by water, and depends on the case of the materials, if the materials conductive, EM field is diffusive and cannot conductive, or dielectric, propagate as EM wave, and if the material is un (EM) field can propagate as EM wave. The materials characteristics vary from diffusive to dielectric, when we change the frequency, while the influence of permittivity is clarified when used the higher frequency, any material behaves . as dielectric (Sato, 2001).

1) such as - . In GPR technique, the electrical properties in (table 2

Material	Dielectric constant (ε)	E.M wave velocity(m/ns)	Attenuation (db)	Conductivity (mS/m)

conductivity (σ), permittivity (ε), and velocity (v) are much more important than the magnetic properties such as magnetic permittivity (μ), and controlling GPR responses because the magnetic properties of most geological materials are the same as those of vacuum, and it is common to assume the relative magnetic permittivity is equal to 1 (Annan, 2001; Conyers, 2004).

Table (2-1) shows the electric properties for some materials (Denial,1996; Annan992)

Air	1	0.30	0	0
Distilled water	80	30	0.002	0.01
Fresh water	80	30	0.1	0.5
Sea water	81-88	10	1	$3*10^3$
Clay	5-40	74-150	1-300	2-1000
Shale	5-15	90	1-100	1 - 100
Silt	5-30	63-100	1-100	1- 100
Dry salt	5-6	130	1-0.01	0.01- 1
Dry sand	3-5	150	0.01	0. 01
limestone	4-8	75-113	1-0.4	0.5 - 2
Saturated sand	20-30	4-30	0.3-0.03	0.1- 1.0

Electrical Conductivity (σ)

Electrical conductivity explains how the material will allow electricity to travel through it such as (copper wires which have great electrical conductivity). On the other hand, it is a measure of the ease at which an electric charge or heat can pass through a material when an electric field is applied in the medium where conductive currents (J) were generated (Olhoeft, 1984; Annan, 2001). In addition, it represents the amount of total dissolved salts (TDS), or the total amount of dissolved ions in the water (Moore, 1989; Michaud, 1991).

A conductor is a material, which gives very little resistance to the
flow of an electric current or thermal energy. Materials classified as metals, semiconductors, and insulators. M etals are the most conductive materials and insulators such as (ceramics, wood, plastics) the least conductive materials (internet/9).

The relation between electric field (E) and conductive currents (J) named the conductivity **(σ)**. Electrical conductivity has unit is the **Siemens per meter**(S/m) or milli-Siemens per meter (m S/m), but conductivity values are often reported as percent.

$$J_c = \sigma E \qquad (2\text{-}3)$$

Jc= density of electric currents, σ = conductivity, E = electrical field

Moreover, according to ohm's low (1827), electric conductivity is the reciprocity of the electric resistivity :

$$\sigma = 1/\rho \qquad (2\text{-}4)$$

Where,

ρ : represent the electrical resistivity.

The electric property of earth materials is described by electric conductivity or electric resistivity (Davis and Annan, 1980; Mukerji and Dvorkin, 1998),and can be classified the materials as (figure2-3):

Conductor when, $\sigma > 10^5$ Siemens per meter (S / m) .

Semi conductor when, $10^{-8} < \sigma < 10^5$ Siemens per meter (S / m).

Insulator when, $\sigma < 10^{-8}$ Siemens per meter (S / m).

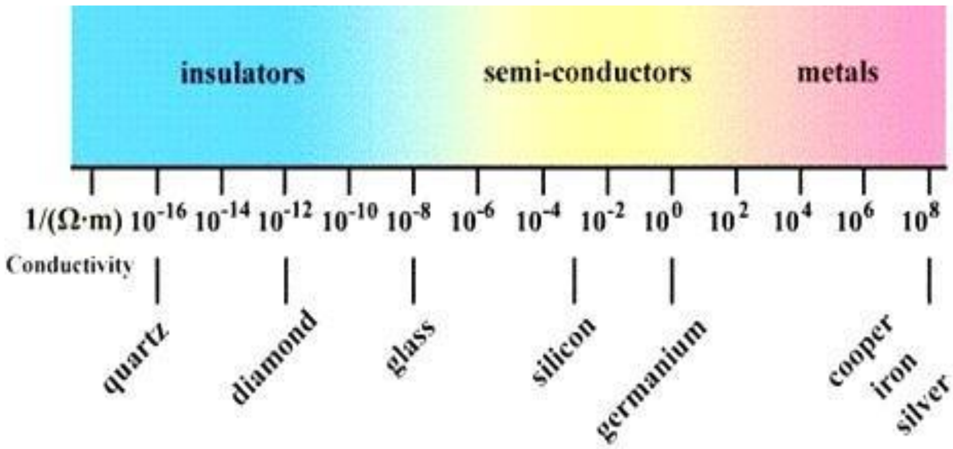


Figure (2-3) shows the electrical Conductivity in Geomaterials internet/14

Dielectric Permittivity (ε):

Dielectric materials can be solids, liquids, or gases. Solid dielectrics are perhaps the most commonly used dielectrics, and many solids are very good insulators. The dielectric properties of soils are functions of volumetric water content, measurement frequency, mineralogy, particle size, bulk density, temperature, salt content, shape and orientation to the imposed EM field surface area, and it is responsible for wave velocity variations (A.S.T.M, 2005; internet/11). A dielectric is an electrical insulator that may be polarized by an applied electric field , displacement of charge occurs in a bulk material gives rise to a dipole moment distribution in the material. This displacement directly proportional to the applied electric field while dielectric loss is a measure of the proportion of the charge transferred in conduction and stored in polarization

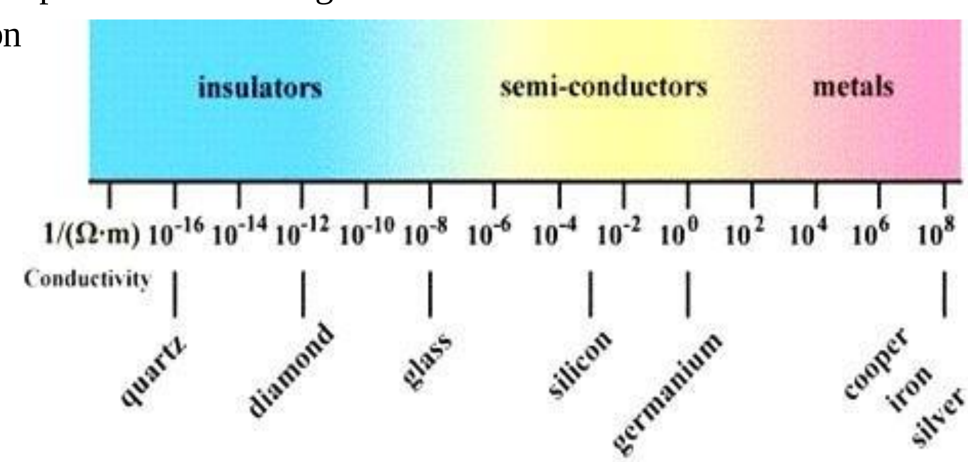


Figure (2-3) shows the electrical Conductivity in Geomaterials internet/14

$$\mathbf{D} = \varepsilon\,\mathbf{E} = \varepsilon r\,\varepsilon 0\,\mathbf{E} = k\,\varepsilon 0\,\mathbf{E} \qquad (2\text{-}5)$$

Where:

D = electrical displacement density, E = electrical field

ε = is the dielectric permittivity or dielectric constant in farad per meter [F/m]

εr or k is the relative electrical permittivity (dielectric constant) : 1 in air and 80 in water of free space, while most of geological materials lies in range 3-30

ε0 = the dielectric permittivity of space free = (8.85×10^{-12} F/m).

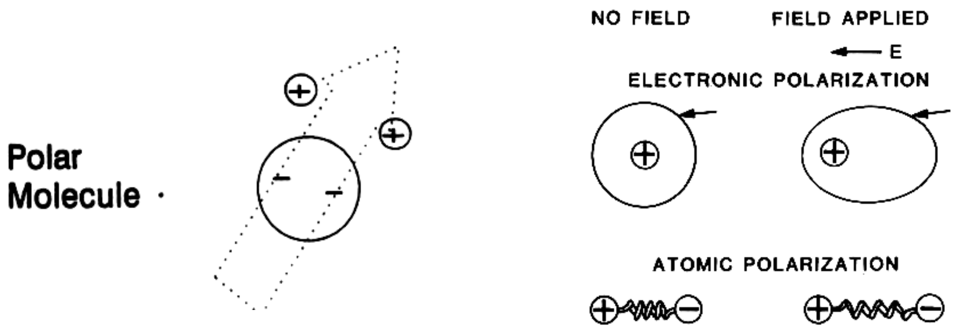


Figure (2-4) shows the Electrical polarization (Annan, 2001)

Relative dielectric constant or relative permittivity (k) or (**εr**) is a important factor for GPR surveys because it controls propagation velocity of (EM) waves through material in earth, and its can be prospectus for mineralogy, porosity, pore fluids, frequency, geometries, and electrochemical interactions between rock components, (Martinez and Bymes, 2001).

Time Domain Reflect meter (TDR) is an apparatus, which measure the water content of the soil by measuring the travel time of an EM pulse reflected by a short parallel rod, which is insert into soil. TDR directly gives the velocity of the EM wave in soil. TDR apparatus is a very compact as shown in (figure 2-5), and it is gives a good estimate of the dielectric constant (sato, 2001).

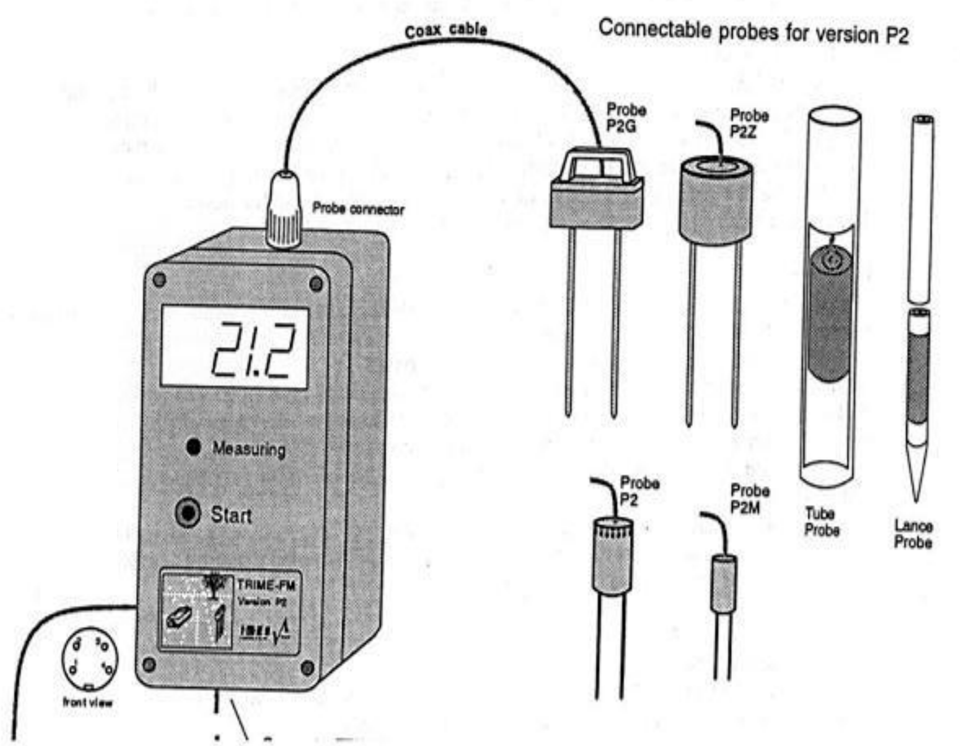


Figure (2-5) TDR apparatus (TRIME-FM), (Sato, 2001).

Magnetic permeability (μ):

Magnetic properties of most geological materials are the same as those of vacuum, and it is common to assume the relative magnetic permeability is equal to one. In electromagnetism, permeability is the measure of the ability of a material to support the formation of a magnetic field within itself. Or, it is the degree of magnetization that a material obtains in response to an applied magnetic field, (Heaviside, 1885, internet /13).

In SI units, permeability is measured in the Henry per meter (H/m), or Newton per ampere squared (N/A2) (Keller, 1966).

In electromagnetism, the auxiliary magnetic field H represents how a magnetic field B influences the organization of magnetic dipoles in a given medium, including dipole migration and magnetic dipole reorientation, the relation to permeability is:

$$\mathbf{B} = \mu\mathbf{H} = \mu_0\mu_r\mathbf{H} = \mu_0(1+\kappa)\mathbf{H} \qquad (2\text{-}6)$$

Where,

B = magnetic flux density, H = Magnetic field, μ = magnetic permeability, μ0 = magnetic permeability in Vacuum, μr = relative magnetic permeability, k = magnetic susceptibility.

Magnetic permeability property does not have greatly influenced on the applications of GPR but Ignoring it can result in significant errors of velocity estimation, which lead to errors in depth estimated. (Olhoeft, 1994).

2.5 Velocity of Electromagnetic Waves:

The velocity of electromagnetic waves propagations is described by the speed of light in a material. The speed of light in a material is always slower than the speed of light in vacuum (or free space). There are many factors that can affect velocity but in electromagnetism the dielectric permittivity and magnetic permittivity polarization properties control the speed of propagation of radar waves. The square of the velocity of propagation is equal to the reciprocal of the product of the complex permittivity times the complex permittivity. In most low loss, nonmagnetic materials, this reduces to the velocity of propagation in the material is equal to the speed of light in vacuum, c, divided by the square root of the relative dielectric permittivity (Olhoeft, 2000). From the propagation constant and the wave number,

$$\gamma^2 = i\omega\mu\sigma - \omega^2\mu\varepsilon = -k^2 = (\alpha + i\beta)^2$$

$$velocity = v = \frac{\omega}{\beta} \approx \frac{c}{\sqrt{\varepsilon_r}} \qquad (2\text{-}7)$$

□ = propagation constant , **k** = wave number,□□ = radian frequency = 2□ f, □ = magnetic permeability,□□ = electrical conductivity, □□ = dielectric permittivity, □**r**= permittivity relative to free space,□□ = attenuation constant,□□□□□□ = phase constant, **c** = speed of light in vacuum.

The range of the ground velocity varying between 0.077 to 0.134 m/ns The minimum velocity is 0.033 m/ns (water), maximum velocity is 0.3 m/ns in (air) , minimum depth with max velocity produces a minimum time of ~ 50 pico-secs and maximum depth with min velocity produces maximum time of ~10- msec (Basson, 2000; Fall, 2007).

The wavelength λ (m), the operating frequency f (Hz), and the velocity of the wave are related in the following equation (Fall, 2007):

Where,

F= Frequency (c/sec.) λ =2□/□=V/f (2-8)

V= velocity (m/sec.)

□ = phase constant

-

2.6 Energy loss of Electromagnetic waves:

Energy loss occurs as a transformation from one type of energy to another. Heat is one of most fundamental forms of loss (intrinsic losses) that result from the movement of EM waves within the media (figure 2-6).

The attenuation describes how energy is lost or dissipated as heat; during the electromagnetic propagation, energy may convert to thermal energy or heat and this will exhibited as temperature rise in the media. The energy is not transform to heat and is still electromagnetic, but it is following a path that is no longer useful or observable (Olhoeft, 2000).

Equation (2-9) for determining the attenuation rate as functions of frequency, and the electrical parameters of the natural media (Heaviside, 1885) in (Stolarczyk, 2003) given as:

$$\alpha = \omega\left[\frac{\mu\varepsilon}{2}\left(\sqrt{1+\frac{\sigma^2}{\varepsilon^2\omega^2}}-1\right)\right]^{1/2} \qquad (2\text{-}9)$$

α = The attenuation factor (in db\m) or Nepers per meter

σ = electric conductivity in siemens / meter (S/m)

$\mu = \mu_r \mu_0$ is the magnetic permeability. $\mu_0 = 4\pi \times 10^{-7}$ in the free space,

and μ_r is the relative permittivity.

$\varepsilon = \varepsilon_r \varepsilon_0$ is the permittivity. $\varepsilon_0 = 1/36\pi \times 10^{-9}$ in the free space , and ε_r is the relative dielectric constant.

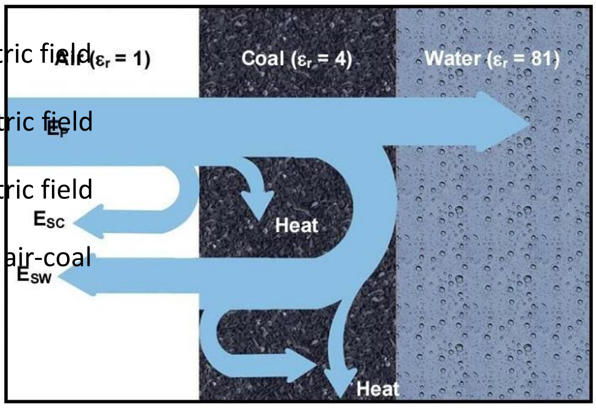


Figure (2-6) shows energy flow in natural media, (Stolarczyk, 2003).

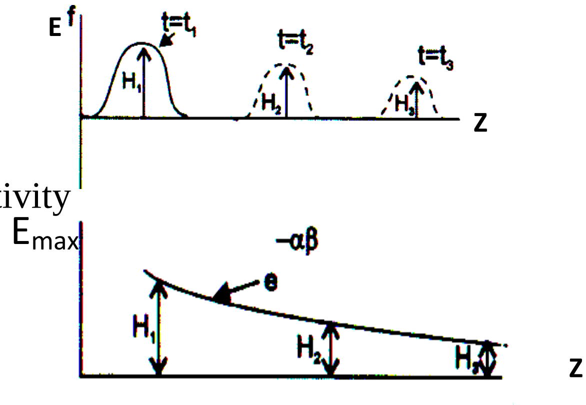
In GPR signals, the attenuation is so important factor, it is the main reason of the energy loss in GPR waves. The depth of penetration is determined by the attenuation of the radar signal due to the conversion of EM energy to thermal energy through electrical conduction, dielectric relaxation, or magnetic relaxation losses (A.S.T.M, 2005). it has inversely proportional with penetration depth (Jol, 2009). In a conductive material (seawater, metallic materials, mineralogical clay soils), attenuation can be great, and the wave may penetrate only a short distance (less than 1 m). In resistive material (fresh water, granite, ice, or quartz sand), the depth of penetration can be tens to hundreds of meters.

During the EM wave propagation in GPR surveying, the difference in amplitudes signals is results to attenuation variations (Olhoeft, 2000; Annan, 2001). Attenuation also occurs due to scattering of the EM energy in unwanted directions by in homogeneities in the subsurface. If the scale of in homogeneity is comparable to the wavelength of EM energy, scattering may be significant (Olhoeft, 1984).Other factors that affect attenuation include soil type, temperature (Morey, 1974), and clay mineralogy (Doolittle , 1987).

In low-loss media velocity is the same as lossless media:

Velocity the same as lossless media:

$$\alpha \approx \sqrt{\frac{\mu}{\varepsilon}}\,\frac{\sigma}{2} \qquad (2\text{-}10)$$



α: attenuation factor, μ**:** The magnetic permittivity

ε **:** permittivity, σ = electric conductivity in siemens / meter (S/m)

Thus exponential decay of wave amplitude with distance.

Figure (2-7) EM field propagate as spatially damped waves when electrical losses are small.

جاهعت االنبار

كليت العلوم- قسن الجيولوجيا التطبيقيت

اسن الوحاضربالغت االنكليزيت: Ali Mishaal Abed

اسن الوحاضر باللغت العربيت: علي هشعل عبد

اسن الوادة باالنكليزي: Electrical Methods

Ground Penetrating Radar

اسن الوادة بالعربي: الطرق الكهربائيت- طريقت الرادار

عنواى الوحاضرة باالنكليزي: Characteristics of Electromagnetic wave

Characteristics of Electromagnetic wave

Reflection of Electromagnetic wave

When radar wave incident on a flat boundary underground separating two different media having dielectric constants of ϵ_1. ϵ_2 part of the energy is reflected by objects such as geological boundary, buried objects and ground water and some of the energy passes through it. The relation between the intensity of the reflected and transmitted fields is described by the Fresnel reflection coefficient which define as the area of a target's surface that contains the portion of the incident wave that arrives at the receive antenna less than 1/2 of a cycle out-of-phase from earliest arriving reflected energy from the target (Sheriff, 1991) .The angle of reflection always equals the angle of incidence inside the ground (Annan, 1992), (figure 2-8).

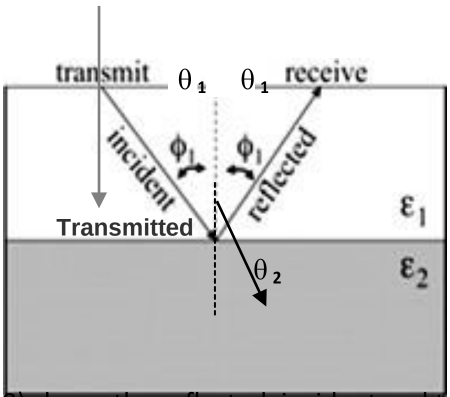


Figure (2-8) shows the reflected, incident and transmitted ray path.

When the electromagnetic wave velocity (v) known, measuring the travel time t (s), the depth (D) of reflecting object can estimate as follows:

$$D = V * t / 2 \qquad (2\text{-}11)$$

Where,

D = Depth (m), **V**= velocity (m/ns), t= Time (ns)

The reflection occurs, when a electromagnetic wave is incident of the boundary between tow media having two different velocities or two different dielectric constants. The wave front of the incident waves will be reflected to the surface. The amplitude of R1, and R2 are defined as a reflection coefficient (Reflection coefficient quantifies how the amplitudes of the electromagnetic fields vary across an interface between two materials

depending on the velocity contrast opposite side of the interface and its values vary between (1) to (-1) of a boundary and is given by:

$$R = \frac{V_2 - V_1}{V_2 + V_1} = \frac{\sqrt{\varepsilon_{r1}} - \sqrt{\varepsilon_{r2}}}{\sqrt{\varepsilon_{r2}} + \sqrt{\varepsilon_{r1}}} \qquad (2\text{-}12)$$

Where,

R = Reflection coefficient, **ε 1**= the relative dielectric constant of first medium, **ε 2** = the relative dielectric constant of second medium (the target) In case material is metal even a thin sheet, the reflection coefficient is R=-1, and it takes the maximum amplitude. Therefore, the reflection from metallic material is always obvious (Sato, 2001).

Scattering

Scattering describes the intensity of the EM waves which reflected from the targets under earth surface, without scattering, there would be nothing for the radar to measure, too much scattering, the radar data becomes uninterruptible noise, unwanted scattering is called "clutter", a type of noise that results from the spatial size and shape distribution of heterogeneity. Desirable scattering comes from the target of interest. The important of the scattering losses are present at high frequencies (Jol, 2009).

The magnitude of the contrast and geometry (size, shape, orientation) are one of the most important factors of wave scattering (Olhoeft, 2000).

Polarization:

Perpendicular electric and magnetic fields (Maxwell equation), and capability of different materials to store energy polarize the electromagnetic waves polarized figure (2-9). Most commercial GPR systems use linearly polarized antennas. The most common antenna arrangement is with the electric fields of the transmitter and receiver antennas are aligned in parallel with each other, parallel with the earth, and towed in a traverse direction perpendicular to the electric field direction. This results in a wave propagating perpendicular to the surface of the earth, into the earth. If such an arrangement is pulled across a buried metallic pipe (or wire or rebar) with the electric fields aligned parallel to the length of the pipe, the pipe appears in the ground penetrating radar data as an excellent reflector, with a hyperbolic shape (the shape is the result of the antenna pattern and geometry of traverse motion). If the antennas are rotated 90 degrees, so they cross the pipe with the electric field direction at right angles to the long axis of the pipe, the pipe disappears in spite of it is still there, but very difficult to see (Olhoeft, 1988).

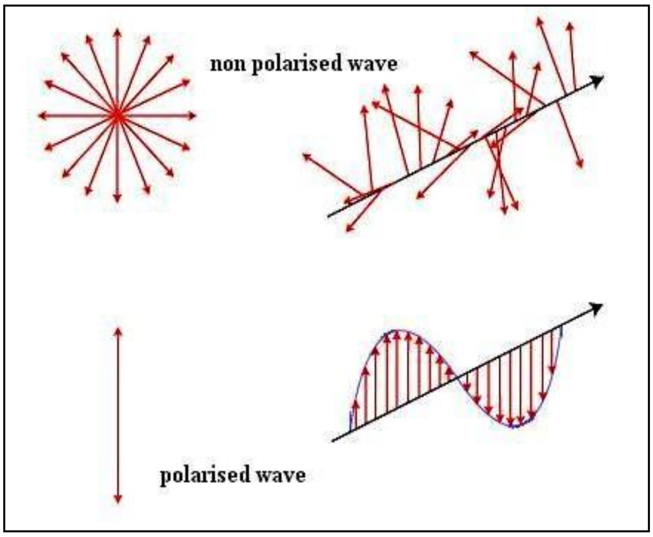


Figure (2-9) shows the Polarization in the waves (Davis and Annan, 1980; Mukerji and Dvorkin, 1998

Penetration Depth:

Penetration depth is the maximum depth range a radar signal can penetrate in a given medium. The maximum depth penetration of GPR signals in the ground is commonly unknown among GPR users because the propagation of the electromagnetic signal depends on the electrical properties of the particular soil and the range of the anteanna frequecy. During the EM propagation in earth materials, the waves will be losses in many forms of loess and this limit the penetration depth in earth materials. The degree of this loss is primarily dependent on the water content and mineralization present, (Reynolds, 1997). The knowledge of the radar energy attenuation is important to identify electrical properties of different materials in the ground (in particular relativity dielectric permittivity and electrical conductivity) and to determine the maximum penetration depth of the GPR signal, when value of both electrical conductivity and Relativity dielectric Permittivity (RDP) were calculated (and confirmed by laboratory tests), it is possible to calculate the Total Propagation Loss (TPL) (Cook, 1975); This last parameter allows the maximum penetration depth of the radar signal to be calculated.

Few studies describe efficient GPR techniques for determining the radar energy attenuation, the relative dielectric permittivity and the electrical conductivity in the field (Cook, 1975; Godio et al., 1998; Leucci, 1999; Reppert et al., 2000). Several studies, instead, describe efficient laboratory techniques for determining these parameters (Topp et al., 1980; Sen et al., 1981; Feng et al., 1985; Olhoeft et al., 1993) in (Leucci and Giannino, 2009).

The real target depth determination is difficult, if not impossible. However, for most cases an estimated depth range can be determined with accuracy wholly dependent upon the subsurface material.

There are several methods to estimate the approximating target depth, one of these methods is using this equation :

$$D = (5.9)\ t / \sqrt{\epsilon_r} \qquad (2\text{-}13)$$

Where,

D = depth of target in inches, t = wave travel time in nanoseconds, scaled from GPR data, (5.9) = a constant incorporating the speed of light and unit conversions, and εr = dielectric constant of subsurface material.

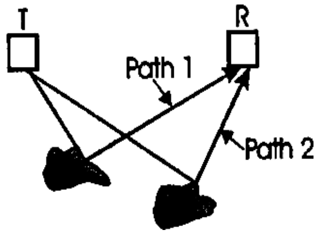
To apply equation (2-13) that required relatively uniform for subsurface material such as (concrete slab, roadway, etc.), reasonably accurate depths can be calculate (internet /7).

The penetration depth proportional inversely with frequency antenna. Signal penetration depth decreases with increasing conductivity. A good rule of thumb is that a target might be detectable if above 0.035/σ m (Fall, 2007).

Resolution:

Resolution is the term used to describe the number of dots, or pixels, used to display an image in digital screen. Higher resolutions mean that more pixels used to create the image, such as 800 x 600. This indicates that there are 800 dots horizontally across the monitor, by 600 lines of dots vertically, equaling 480,000 dots that make up the image you see on the screen (Internet /11).

In GPR techniques, the resolution is define as the radar system capacity to discriminate individual elements in the subsoil, in either on thickness or in size and display the results on screen of GPR. (Daniels, 2004), also defined as the ability of the measurement system to distinguish between



two signals, or the minimum separation that two objects can be separated by and still be uniquely imaged (Annan, 1992 in Fall, 2007), (figure 2-10).

Figure (2-10) shows examining pulse envelopes only,

In GPR techniques, the resolution concept is essentially divided in two parts: vertical (down-range, depth or longitudinal) resolution (▲v), and horizontal (lateral displacement, cross-range, angular, lateral, or plain) resolution (▲h). (Annan, 2001; Daniels, 2004). The radar energy propagates in the ground as an approximately conical spreading; the range of spreading is depending on wave properties such as frequency, wavelengths…etc. . . Resolution has directly proportional with frequency but at the expense of depth of investigation (which generally improves with decreasing frequency, and inversely with wavelengths(Annan and Cosway, 1992; Olhoeft, 1993). . . The vertical and horizontal resolution of GPR can be estimated from the centre frequency (Center frequency (fc) represents the total of number of vibrates in time units) of the antenna, and the relative permittivity (εi) of the ground from which the wavelength (λ) can be derived. The 'footprint' of the (fc) conically spreading energy increases with depth (D) reducing the effective horizontal resolution (Annan and Cosway, 1992; figure 2-11).The longer wavelengths produced by low-centre-frequency antennas will reduce the vertical and lateral resolution of buried targets.

Resolution controller by the wavelength and polarization of the electromagnetic energy. The contrast in electromagnetic properties, the size, the shape, and orientation of the target, may be a function of noise in practice (Annan 1992; Olhoeft, 1993).

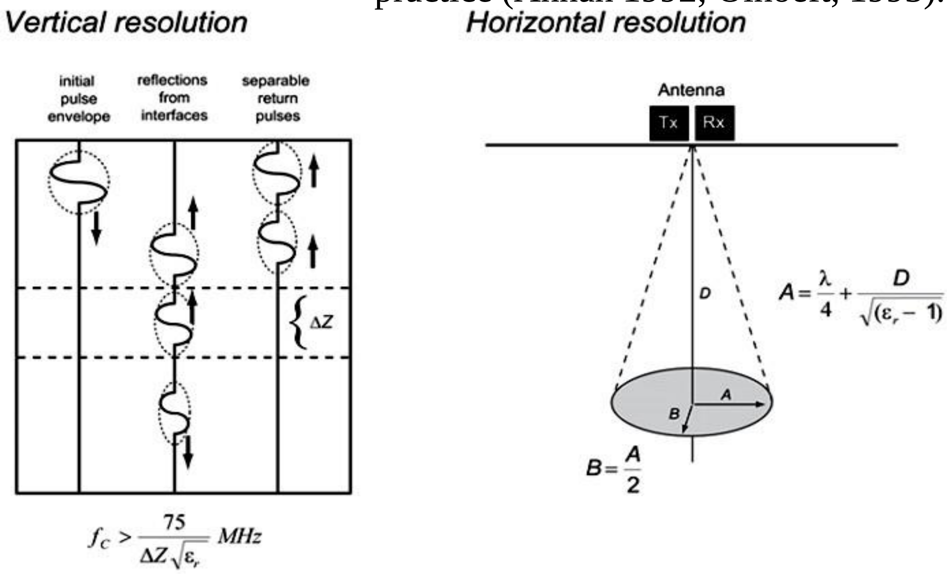


Figure (2-11) shows the vertical and horizontal resolution.(Annan and Cosway, 1992)

Center frequency (MHz)	Depth penetrating for typical soil (m)	Wavelength (λ) in soil E1 = 15 (m)	Horizontal resolution – width of fresnel zone at maximum depth (m)	Vertical resolution λ/4 (m)
1000	1.0	0.08	0.2	0.02
500	2.0	0.16	0.4	0.04
200	3.0	0.39	0.8	0.10

100	5.0	0.77	1.4	0.19
50	7.0	1.55	2.4	0.39

Table (2-2) shows approximate values for the variation of GPR penetration depth and resolution with centre frequency for typical soils (Geophysical Survey in Archaeological Field Evaluation, 2008)

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