APPENDIX

FUNDAMENTALS OF GROUND PENETRATING RADAR (GPR)

The Ground Penetrating Radar (GPR) is a high-resolution geophysical technique used to investigate the subsurface architecture. It is a nondestructive geophysical technique that produces high quality subsurface data. Currently the GPR technique is used in the fields of engineering, geophysical, geological, archeological and other near surface investigations like hydrological and geotechnical inspections. This technique provides a continuous cross-section profile of subsurface along with the three dimensional pseudo image with accurate depth estimation (Fig. A.1). GPR works on the principle of seismic technique due to the resemblance between acoustic and electromagnetic prospecting methods (Davis and Annan, 1989; Cassidy, 2009). The main difference between the two techniques is the vectorial character of electromagnetic waves compared to scalar character of the acoustic waves.

![Diagram](image)

**Figure A.1** Mode of GPR data acquisition and the resulting radar profile in wiggle mode. (a) Diagram showing the manner of signal penetration and internal architecture of the subsurface reflectors. (b) Characteristic of electromagnetic waveform (c) Radar reflection profile in wiggle mode.

A GPR survey is usually carried out with one source and one receiver at a fixed distance and also called as a common-offset measurement while in seismic survey a large number of receivers for every source are required, it is known as a multi-offset measurement. Another difference between the two techniques is depth of penetration and resolution of data. GPR which involves electromagnetic wave is generally used to obtain image of the shallow subsurface upto ~50m. While the seismic techniques which uses sound waves can obtain an image of the subsurface (100 to 10000 m). When a wave is
transmitted in the subsurface ground reflections are generated when a wave hits a layer in the subsurface with different characteristic material properties. GPR reflections are generated (Fig. A.1) when a pulse hits an object or layer with different electromagnetic characteristics (Davis and Annan, 1989; Daniels, 2000).

GROUND PENETRATING RADAR (GPR)

The GPR is non-invasive technique that utilizes differences in electromagnetic properties of subsurface objects to produce an image of the subsurface (Davis and Annan, 1989). The basic principle and working of the GPR involves the transmission of high frequency electromagnetic waves into the ground, which is reflected back from the sediment interfaces showing variable electrical properties in the subsurface and is received on the surface and displayed in form of a profile (Fig. A.1). The GPR profile shows horizontal survey distance versus vertical two-way travel time in nanoseconds (1 ns = 10⁻⁹ second). A ray is defined as a straight line drawn from the transmitter to the edge of the wave front. The interval of time that it takes for the wave to travel from the transmitter antenna to the receiver antenna is simply called the two way travel time. The recording of both pulses over a period of time with receiver antenna system is called a “trace”. The spacing between measurement points is called the trace spacing. The trace is the basic measurement for all time-domain GPR surveys. A scan is a trace where a color scale has been applied to different amplitude values. The two-way travel time depends directly upon the depth of investigation it is greater for deeper objects than for shallow objects. The EM waves sense the changes in physical and composition properties of the subsurface material like grain size, water moisture, dielectric permittivity and electric conductivity (Davis and Annan, 1989). The radar waves travel downward at a specific velocity that is determined primarily by the permittivity of the material (Jol and Bristow, 2003). The relationship between the velocity of the waves and material properties is the fundamental basis for using GPR to investigate subsurface. The frequency-dependent medium properties can be obtained from a CMP measurement (Van der Kruk and Slob, 1998). The propagation speed (velocity) of the transmitted waves is controlled by electromagnetic properties of the examining objects (Davis and Annan, 1989). The presence water content, dissolved minerals, expansive clay, heavy minerals in the subsurface materials may produce significant changes in the radar reflection strength (Topp et al., 1980; Olhoeft, 1984; Beares and Haeni, 1991).
The clayey sediments are normally known to show higher attenuation of radar signal, especially of higher frequencies, thereby affecting penetration as they possess high water retention capacity and low electrical resistivity. Small scale textural variations in the subsurface sediments are consequence of change in permittivity and are sufficient to cause reflections of radar signals (Van Dam and Schlager, 2000). The generalized values of electrical properties of some common earth materials (Table A.1) are present by Neal, (2004). These values of dielectric permittivity control the penetration of radar waves. Higher the dielectric permittivity lowers the penetration of radar signals. Neal (2004) indicated that the changes in the subsurface material will affect the index of refraction, and reflected energy will be produced related to the contrast in the dielectric constant across a boundary between two materials (Table A.2).

Table A.1 Showing typical electric properties of common geological materials (Neal, 2004). Note the relative dielectric permittivity and electromagnetic wave velocity is controlled by water content.

<table>
<thead>
<tr>
<th>Medium</th>
<th>Relative dielectric Permittivity ($\varepsilon_r$)</th>
<th>Conductivity (mS m$^{-1}$)</th>
<th>Attenuation (dB m$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1</td>
<td>0.3</td>
<td>0</td>
</tr>
<tr>
<td>Fresh water</td>
<td>80</td>
<td>0.03</td>
<td>0.5</td>
</tr>
<tr>
<td>Seawater</td>
<td>80</td>
<td>0.01</td>
<td>30,000</td>
</tr>
<tr>
<td>Unsaturated sand</td>
<td>2.55-7.5</td>
<td>0.1-0.2</td>
<td>0.01</td>
</tr>
<tr>
<td>Saturated sand</td>
<td>20-31.6</td>
<td>0.05-0.08</td>
<td>0.1-1</td>
</tr>
<tr>
<td>Unsaturated sand and gravel</td>
<td>3.5-6.5</td>
<td>0.09-0.13</td>
<td>0.007-0.06</td>
</tr>
<tr>
<td>Saturated sand gravel</td>
<td>15.5-17.5</td>
<td>0.06</td>
<td>0.7-9</td>
</tr>
<tr>
<td>Unsaturated silt</td>
<td>2.5-5</td>
<td>0.09-0.12</td>
<td>1-100</td>
</tr>
<tr>
<td>Saturated silt</td>
<td>22-30</td>
<td>0.05-0.07</td>
<td>100</td>
</tr>
<tr>
<td>Unsaturated clay</td>
<td>2.5-5</td>
<td>0.09-0.12</td>
<td>2-20</td>
</tr>
<tr>
<td>Saturated clay</td>
<td>15-40</td>
<td>0.05-0.07</td>
<td>20-1000</td>
</tr>
<tr>
<td>Unsaturated till</td>
<td>7.4-21.1</td>
<td>0.1-0.12</td>
<td>2.5-10</td>
</tr>
<tr>
<td>Saturated till</td>
<td>24-34</td>
<td>0.1-0.12</td>
<td>2-5</td>
</tr>
<tr>
<td>Freshwater peat</td>
<td>57-80</td>
<td>0.03-0.06</td>
<td>&lt;40</td>
</tr>
<tr>
<td>Bedrock</td>
<td>4-6</td>
<td>0.12-0.13</td>
<td>$10^4$-40</td>
</tr>
</tbody>
</table>
Table A.2 Reflection coefficient modeling for typical changes in sediment water content, porosity, lithology and grain shape. The reflection coefficients indicate the proportion of energy theoretically reflected from an interface (Neal, 2004).

<table>
<thead>
<tr>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Porosity (%)</th>
<th>$\varepsilon_r$</th>
<th>Reflection coefficient (+1 to -1)</th>
<th>Geological significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry sand</td>
<td>35</td>
<td>3.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saturated sand</td>
<td>35</td>
<td>20.7</td>
<td>-0.44</td>
<td>Water table</td>
<td></td>
</tr>
<tr>
<td>Dry sand</td>
<td>35</td>
<td>3.1</td>
<td></td>
<td>5% porosity change in dry sand</td>
<td></td>
</tr>
<tr>
<td>Dry sand</td>
<td>30</td>
<td>3.27</td>
<td>-0.013</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saturated sand</td>
<td>35</td>
<td>20.7</td>
<td></td>
<td>5% porosity change in saturated sand</td>
<td></td>
</tr>
<tr>
<td>Saturated sand</td>
<td>30</td>
<td>17.7</td>
<td>+0.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saturated sand</td>
<td>35</td>
<td>20.7</td>
<td></td>
<td>lithology change to high-porosity peat</td>
<td></td>
</tr>
<tr>
<td>Peat</td>
<td>70</td>
<td>46.5</td>
<td>-0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry sand</td>
<td>35</td>
<td>3.1</td>
<td></td>
<td>dry heavy-mineral placer deposit</td>
<td></td>
</tr>
<tr>
<td>Dry heavy-mineral sand</td>
<td>35</td>
<td>19.9</td>
<td>-0.43</td>
<td>saturated heavy-mineral placer deposit</td>
<td></td>
</tr>
<tr>
<td>Saturated sand</td>
<td>35</td>
<td>20.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saturated heavy-mineral sand</td>
<td>35</td>
<td>53</td>
<td>-0.23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Round grains</td>
<td>33</td>
<td>23.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Platey grains</td>
<td>33</td>
<td>16.9</td>
<td>+0.08</td>
<td>grain-shape change</td>
<td></td>
</tr>
<tr>
<td>Isotropic grain packing</td>
<td>33</td>
<td>22.5</td>
<td></td>
<td>orientation change for platey grains</td>
<td></td>
</tr>
<tr>
<td>Anisotropic grain packing</td>
<td>33</td>
<td>16.9</td>
<td>+0.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Criteria for selection of antenna

The present study is carried out using SIR-20 digital radar instrument manufactured by Geophysical Survey Systems Inc. (GSSI), USA with center wave frequencies of 16-200 MHz (Fig. A.2a,b). The GPR system comprises of five main
components; control unit, transmitter, receiver antennas and data storage or display module.

The selection of the antenna is based on the depth of investigation. A high frequency waveform (short wavelength) will provide a more detailed or higher resolution image than a low frequency waveform, but the higher frequencies are attenuated or absorbed at a greater rate (Jol and Bristow, 2003).

GPR operation is digitally controlled by the console (main unit) attached with laptop and another electronic module which connect to the antennas by fiber optic cable. The data is usually recorded in digital format for post-survey processing and display. Distance control along a traverse line are provided by a range of various means which may include, a well calibrated odometers based survey wheel, accurate positioning of profile length, manually marking into the data by an electronic push-button during profiling and differential GPS reading along the transect line.

Depth to which GPR can image below the surface directly dependants on three main factors; the centre frequency of the antenna, the number of interfaces that generate reflections and the dielectric contrast at each interface and the rate at which the signal is attenuated as it travels downward (Jol, 1995). As the GPR pulse arrives at each interface, a portion of it is returned to the surface and the rest continues into the next layer (Daniels, 2000). As the number of interfaces increase, the proportion of energy that propagates down gets reduced. In addition, the greater proportion of energy that is reflected back to the surface at each interface, the less energy that is available to propagate deeper into the ground. This limits the depth of investigation because the reflections of interest get masked by the clutter of the chaotic returns. The conductivity of the investigated material has a major influence on the depth penetration. As the conductivity increases, the material acts more like a conductor than a semi-conductor (Saarenketo, 1998). The frequency used is also important since the resolution of the system and the rate of signal attenuation is proportional to the frequency of the GPR system.

Resolution is controlled by wavelength of the propagating electromagnetic wave in the ground. The vertical resolution depends on the frequency used and the physical properties of the subsurface while the horizontal resolution is a function of the spacing between traces and the footprint of the radar pulse. The wave theory suggests that the greatest vertical resolution that can be expected is 1/4 of the size of a wavelet (Davis and Annan, 1989). The size of the wavelets that are recorded in a GPR profile is a function of the pulse width of the original transmitted pulse. There is strong relationship between
frequency and wavelength (equation B). Lower the frequency greater the wavelength and higher the frequency shorter the wavelength (Davis and Annan, 1989). If we are looking for small targets at shallower depth higher frequency GPR antenna gives adequate resolution but for larger targets like the position of the subsurface water table, lower frequencies should be used. Selection of the operating frequency for a radar survey should be object oriented.

**Data acquisition**

The methodology of GPR technique involves the data acquisition, processing and interpretation. There are different methods for obtaining GPR data acquisition. The data is recorded on a visual readout or in a digital format in a laptop attached with the Main unit (Jol and Bristow, 2003). The measurements from GPR can be made by two different ways. In continuous manner the shielded monostatic antenna is dragged along a transect line to record a high-resolution continuous cross-section of the subsurface (Fig. A.2a, c). The monostatic antenna contains a pre-fixed unmovable configuration of transmitter and receiver inside a shielded cover, that can be attached with an odometer based survey wheel to determine the horizontal survey distance (Fig. A.2a). GPR survey data by monostatic antenna can be carried out in two different ways: time mode and distance mode. In both the manners GPR antenna is moved along the ground or tow behind a vehicle. The time mode survey comprises the data recording in continuous manner without using the survey wheel. The data recorded in this manner measures vertical and horizontal both the axis in time. But in the distance mode a calibrated survey wheel is attached with antenna to calculate the horizontal survey distance.

The second manner comprises a transmitter and receiver as separate entities and the measurements are made by manually shifting the points along the surface. This is known as bistatic antenna configuration (Fig. A.2d). The data collection with unshielded bistatic antennas are quite time consuming and gives low resolution images of subsurface compared to monostatic antenna but the center frequency of the bistatic antenna can be changed to achieve greater depth penetration. The fixed-mode (point mode) arrangement has the advantage of flexibility where as the moving-mode (free run) has the advantage of rapid data acquisition. Different acquisition set-up can be used to obtain information of the subsurface using multi low-frequencies antennas.
**Figure A.2** *(a)* Monostatic antenna of 200 MHz frequency attached with survey wheel; *(b)* Main unit (Console) attached with the laptop to visualize the data during acquisition; *(c)* GPR survey by a 200 MHz monostatic antenna in a continuous mode; *(d)* GPR survey by Multiple Low Frequency (MLF) bistatic antenna in a point mode.

Different type of survey methods are given below:

**Common-offset gather**

This technique involves the collection of repeated measurements in stacked form along a survey line and is known as Common-offset measurement. The Common-offset GPR profiling is commonly used for geological applications to map the continuity of the features at depth. Generally, GPR is used in a common-offset configuration to detect subsurface anomalies and to delineate the lateral and vertical changes in subsurface. The source and receiver antennas are separated by a fixed distance, and measurements are carried out by gradually shifting the antennas over the points with common-offset distance (Fig. A.3a). This method is fast and therefore relatively cheap, but a major drawback can be the lack of wave speed information of the subsurface. However, when an object having contrasting electrical properties is present in the subsurface, a hyperbolic reflection occurs in the GPR data. From this hyperbola, the wave speed in the subsurface can be estimated as described in Van der Kruk and Slob (1998).
Common-mid point (CMP)

Common midpoint survey (CMP) is a GPR technique to estimate the subsurface velocity structure of the study area. It is generally used to analyze the variable velocity and density layers of the shallow subsurface (Huisman et al., 2003; Jol and Bristow 2003). The CMP profiles are obtained in a point mode with the help of bistatic antennas, where the orientation of the antennas is perpendicular to the electric field polarization. The measurements are taken by manually shifting to transmitter and receiver from a midpoint to opposite directions up to a maximum distance. In this technique the high pulses of EM energy are radiated downward at every shooting point and the receiver records the signals in stacked form. The stacking of the signals facilitates to reduce the signal to noise ratio. In the CMP mode the transmitted EM waves repeatedly travel through same material but the offset distance between the antennas are changed (Fig. A.3b). It provides a plot between antennas separation (offset distance between antennas) and two way travel time. The strongest reflections at the top of the data are the direct air waves and the direct ground waves. The CMP data can identified from the alignment of these two reflections which represent to direct propagation of radar waves from transmitter to receiver through air and top skin of the ground (Neal, 2004). The calculated velocity obtained by this method is used to convert the time window into the depth scale and in advanced GPR data processing (Yilmaz, 2001; Huisman et al., 2003).

Figure A.3 (a) the configuration for Common Offset (CO) survey; (b) the configuration for the Common Mid Point (CMP) survey.
**Wide-angle-reflection-refraction (WARR)**

This is the Common source method in which the transmitter is fixed and the receiver is gradually shifted opposite to source with common step size. The common receiver method allows shifting of the position of transmitter away from stable receiver antenna (Fig. A.4). The Common source and Common receiver methods of GPR data collection are also known as wide-angle-reflection-refraction (WARR) technique and is generally used to make out the penetration speed (velocity) of the radar waves. This technique is generally used in the areas having rugged topography where it is not easy to place an antenna at fixed position and shifting to other along a line at discrete points. The acquisition fundamentals of this technique are similar to the previously described CMP method.

![Figure A.4 Antenna configuration used in the Wide-angle-reflection-refraction (WARR). Here the transmitter (S) is kept fixed and the receiver is gradually shifted opposite to source with common step size.](image)

**3-D GPR surveying**

Three-dimensional GPR surveying is complex but an interesting method to recognize the shallow subsurface geological setup. It provides the vertical and lateral dimensions of buried object or structure present in the subsurface. Three-dimensional displays have an advantage of looking at the entire survey site at once. It allows the creation of plan views at different depths as well as perspective views by cutting the 3D solid cube in slices (Patidar et al., 2006). To obtain a three-dimensional image of the subsurface, numerous measurements are carried out along parallel survey lines to record reflected and diffracted electromagnetic waves (Fig. A.5).

The software used for 3D GPR data processing interpolates the 2D parallel profiles into the systematic format to create the 3D solid cube. In practice, several parallel survey lines are measured with common offset present between the source and receiver antenna. This offset should be same for inline (parallel to the survey line) and crossline directions (perpendicular to the survey line). The quality and resolution of 3D GPR data
depends upon the grid layout, sampling and scanning speed of the antenna and the electromagnetic properties of the surveying medium (Daniels, 2000). Surface normalization operations should be performed prior to data interpretation when the 3D grid lines are situated over the undulated terrain. The sampling intervals should not be too sparse which may result in loss of subsurface information. Accurate positioning of sets of profiles, selection of viewing angle for presentation, combination of frequency cutoff filters, thickness of time slice and suitable colour range are some important criterions to be followed during data analysis (Young and Sun, 1998).

![Figure A.5](image)

**Figure A.5** A typical GPR survey pattern for carrying out the 3D GPR data acquisition.

**Data processing**

Appropriate processing is required to remove the unwanted signals from the data generated either by subsurface or surface anomalies, while some GPR data can be left unprocessed (Neal, 2004). The processing and analysis of GPR data needs understanding of fundamentals of geophysics (Yilmaz, 2001). There is lot of similarity in data acquisition procedures of GPR surveys and seismic reflection surveys, so many techniques of seismic data processing can directly be applied to process the GPR data (Young et al., 1995; Fisher et al., 1996). In many cases very little processing is required to locate the target of interest. The GPR technique involves the propagation of electromagnetic waves (EM) of specific central frequency in the subsurface where it may interact with subsurface materials in a variety of ways like, attenuation, reflection,
refraction and diffraction. The raw GPR data may not show the true subsurface image because of external noises produced by electronic bodies, geometrical inhomogeneity of the subsurface materials, concrete structures, metallic bodies and many other things. All the radar data do not require all kinds of processing algorithms. It is based on the accuracy of data sets and subsurface conditions. Processing of GPR data involves modification in raw data; so that it is more easily visualized and interpreted but the selection of processing parameters should be based on the physical modeling and theoretical background of the geophysics and not on the users whims (Jol and Bristow, 2003; Olhoeft, 2000).

The step may include the header file parameters editing using field notes, which contain the information about the data collection parameters, range of time window, scanning and sampling speed and some background information. The next step is to apply the time-zero correction for shifting the traces along the time axis (ns) to correct the misalignment of the first break in radar profile (Neal, 2004). It is important for accurate depth estimation for subsurface reflections. Similarly, the distance normalization operation is applied to reduce the difference of antenna towing speed and to get accuracy of horizontal scale for GPR profile (RADAN for Windows, 2000). This operation calculates the number of scans between every horizontal meter and then equally divides them throughout the distance to get actual scanning speed of the receiver. Some GPR profiles collected in adverse conditions require special processing.

**Amplitude and Gain adjustments to the data**

The presence of the clay rich horizon in the subsurface may results in the attenuation of the radar signals (Jol, 1995). This will results in lowering of the amplitude of the reflected reflections at the receiving end. Attenuation of the GPR signals depends on the dielectric conductivity of the examining substances and may be on account of malfunctioning of the equipment (Davis and Annan, 1989). The data quality can be enhanced by applying gain adjustments of each trace. To correct the spherical dispersion and enhance the quality of radar signals, automatic gain control (AGC) function is applied. AGC function computes the signal amplitude of individual trace over a time window and amplified to signal with average point (Annan, 1999). Linear gain and Exponential gain can also be used to enhance the quality of the lower reflection amplitudes.
Static adjustments to the data

Many time the GPR survey is carried out over an inclined surface which may leads to significant distortion of the subsurface images if uncorrected (Fisher et al., 1996). This problem is made worse because the radiated energy from a transmitter always propagates outwards from the antenna at right angles to the surface (Neal, 2004). The topographic corrections require the repositioning of traces at their original place which can be carried out by the Surface normalization operation shifted to traces along the time axis using GPS track profiles or field elevation data, which is very necessary to calculate the accurate depth of subsurface feature for a better interpretation of the sedimentary facies and structural discontinuities.

Filtering of radar data

The main purpose of filtering is to remove unwanted background noise caused by the subsurface anomalies or due to surface distractions (Kruk and Slob, 2004). Filtering strategies can include band pass (removing frequencies in a certain range), low pass (removing low-frequency signals), and high pass filtering (removing high-frequency signals). But, the over filtering of the data may leads to the generation of the artifacts.

Migration

Migration is one of the important procedures to convert diffracted GPR signals to their correct position (Olhoeft, 2000). According to Young and Sun (1998) the migration function is applied to rearrange the true position of steeply dipping subsurface reflections and hyperbolic diffractions. Generally the buried metallic objects, boulders, strata of higher electric conductivity or overhead objects like; hi-tension electric lines, tress, mobiles phones and concrete structures scattered to radar signals and appear as a strong hyperbolic return in the GPR profiles. The shape of the hyperbola depends on the velocity of the reflected waves (Young and Sun, 1998).

Generally the migration can be carried out in two ways, time migration and depth migration (Yılmaz, 2001). Time migration is suitable for the areas having small to moderate lateral velocity variations where as depth migration suits for the area having large variations in lateral velocity.

Deconvolution

This function is applied to eliminate the effect of ringing from GPR data (Todeschuck et al., 1992). Ringing generally occurs on account of multiple reflections “ringing” which mask original radar reflections. The ringing multiples associated with water layers and weathered subsurface horizon can be wipeout by passing the data
through Deconvolution (Neal, 2004). This process is quite difficult procedure and may not produce the good results. Although, it may be very useful where reverberation is a major problem. Proper care should be taken while performing the Deconvolution during processing and perhaps it should not be used as an essential processing step (Neal, 2004).

**Velocity analysis**

The velocity analysis generally involves determining the propagation speed of the radar waves in the subsurface materials, then converting the reflection travel times into the depths. The electromagnetic energy generally travels at the speed of light (0.3mns⁻¹) in a free space media. And its velocity in the subsurface usually ranges from 0.01-0.16mns⁻¹ (Table A.1). Velocity determination can be carried out by three different methods: Common-Mid Point (CMP) velocity survey, Point-Source reflection analysis and direct water depth measurements or core depth logging. The first two methods are generally more effective for determining velocities of the upper surface geological layers. The data acquired by Common-Mid Point (CMP) method gives more direct image of the subsurface velocity structure and is very common for determining the subsurface velocity of wavy. This method provides accurate results determining the precise depths of subsurface reflectors. The velocity of the electromagnetic waves can be determined from equation A, where as the signal wavelength can be calculated from equation B: described by Benson (1995).

\[ v = \frac{c}{\sqrt{E_r}} \quad \ldots \ldots \ldots \quad (A) \]

where:

- \( v \) = The velocity of the wave through the subsurface material.
- \( c \) = The speed of light (30 cm/nanosecond).
- \( E_r \) = The relative dielectric constant.

\[ \lambda = \frac{\nu}{f} \quad \ldots \ldots \ldots \quad (B) \]

where:

- \( \lambda \) = Wavelength.
- \( \nu \) = The velocity of the wave through the subsurface material.
- \( f \) = Frequency.

Existence of moisture in subsurface sediments limits the penetration of radar waves. As shown in Table A.1, water has highest dielectric permeability as compare to
other geological material. The velocity increases at frequencies greater than 1000 Mhz because of the relaxation of the water molecules (Davis and Annan, 1989). The attenuation of radar signals are also occurs when the heterogeneous subsurface medium are scanned by higher frequencies.

**Time-depth conversion**

Velocity of the subsurface plays an important role in order to determine the depth of the anomaly precisely. The radar reflections in the GPR survey directly depends on the dielectric and conductivity of the subsurface material (Davis and Annan, 1989). Common-Midpoint Survey (CMP) with bistatic antennas helps in determining the velocity of the radar wave in the subsurface media which indeed can be used for determining the dielectric constant of the beneath material. In general during the acquisition a tentative dielectric constant is used depending on the field understanding which can be changed in the later stage by the value obtained by velocity analysis. According to Benson (1995) the depth of subsurface reflector can be determined by the equation given below.

\[ d_r = \frac{v \cdot t_r}{2} \]

where:

- \( d_r \) = The depth to the reflector.
- \( v \) = The velocity of the wave through the subsurface material.
- \( t_r \) = The two-way travel time to the reflector (taken from the GPR trace).

**Data interpretation**

The interpretation of GPR data is the most ambiguous part of this modern geophysical technique (Yilmaz, 2001). It is based on the characterization of specific signal patterns received from the subsurface anomalies obtained from the propagating media. Important aspect of the interpretation of the GPR data is to distinguish the true reflections or clutters from external objects (Jol and Bristow, 2003). A record of the field conditions and survey strategies helps a great deal during the interpretation. At times the raw GPR data does not represent the real picture of the subsurface due to occurrence of diffraction of radar wave from complex buried structures, which may appear as a random or multiple reflections and may require some special processing steps (Annan, 1999; Daniels, 2000). The concept of radar stratigraphic interpretation is derived from the
principles of seismic stratigraphy and can be directly applied to GPR interpretation (Jol and Smith, 1991; Neal, 2004).

The presence of water in sediments strongly affects the radar reflections because the water content shows higher dielectric constant than air filled sediments (Ekes and Hickin, 2001; Sridhar and Patidar, 2005).

Interpretation of fault plane zone in GPR profile is a tough task and in some cases requires some special processing steps like, Migration and Deconvolution along with some a good field understanding (Gross et al. 2004). The arrival time of direct ground waves is a function of ground surface propagation velocity (Kruk and Slob, 2004). The interpretation of GPR data should be object-oriented because sometimes much interference are incorporated with the data, which cannot be removed by processing. Over filtering in order to clean the data may result in generation of artifacts.

The reflection patterns of the processed profile is to be critically evaluated in terms of parameters like: thickness and intensity variations of the reflected signals, changes in the dip of the reflections, termination or displacement of the reflections along a plane, reductions in amplitude strength, presence of diffraction hyperbolas, frequency variation along the vertical trace and many other complementary reflection patterns. GPR data can be analyzed in many different ways depending on the aims and objective of the interpretation.

**Utility and Limitations of GPR**

GPR is one of the important tools, ideally suited for obtaining realistic high resolution subsurface image up to the 50 m.

- The instrument is compact and easy to handle compared to the logistic requirement of other geophysical survey instruments, hence can be easily transported and operated in far off places.
- There is no need for digging electrodes for measuring subsurface reflections by GPR.
- The GPR can detect small structures, palaeo-liquefaction features from the contrast between dielectric permittivity of sand and clay which is not possible by any other geophysical technique (Maurya et al., 2005).
- The GPR study provides a great help in delineating the shallow subsurface nature of the seismically active faults.
• GPR has provided a new dimension in the field of Archeology and civil engineering.

The main disadvantages of the GPR technology are as follows:

• In the areas having significant structural relief, data may get contaminated by echoes and multiple reflections and can create confusion during processing and interpretation.

• Presence of conducting material like saline water, clays and heavy minerals can strongly influence the GPR depth penetration.

• The method is time consuming which requires a lot of time in setting the acquisition parameters.