Ground Penetrating Radar

Survey Design

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1. What is Ground Penetrating Radar?

Ground penetrating radar (or GPR for short) is the general term applied to techniques which employ radio waves, typically in the 1 to 1000 MHz frequency range, to map structure and features buried in the ground (or in man-made structures). Historically, GPR was primarily focused on mapping structures in the ground; more recently GPR has been used in non-destructive testing of non-metallic structures. The applications are limited only by the imagination and availability of suitable instrumentation.

The concept of applying radio waves to probe the internal structure of the ground is not new. 'The successful application of these techniques, however, is still in its infancy. Without doubt the most successful early work in this area was the use of radio echo sounders to map the thickness of ice sheets in the Arctic and Antarctic and sound the thickness of glaciers.

Work with GPR in non-ice environments started in the early 1970's. Early work focused on permafrost soil applications, Annan and Davis (1976). As an understanding of strengths and weaknesses of the method became apparent, its application areas broadened as described by Davis and Annan (1989) and Scaife and Annan (1991). Applications in other areas are described by Morey (1974), Benson et al (1984) and Ulriksen (1982).

Radar systems can be deployed in three basic modes which are referred to as reflection, velocity sounding and transillumination. These modes are depicted in Figure 1. The most common mode of operation is single-fold, fixed-offset reflection profiling as illustrated in Figure 2. This mode of operation gives rise to data such as shown conceptually in Figure 3. An example section from good radar terrain is presented in Figure 4.

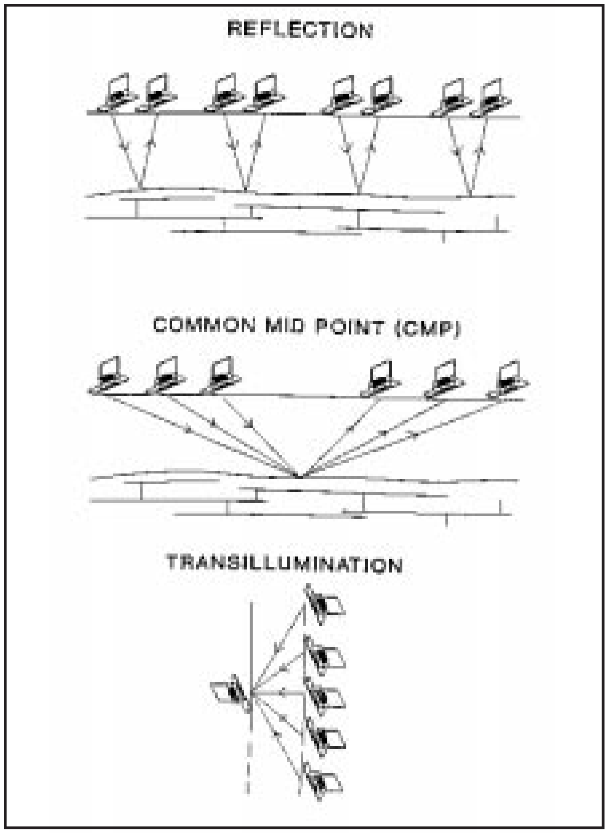


Figure 1: Illustration of the three basic modes of GPR operation.

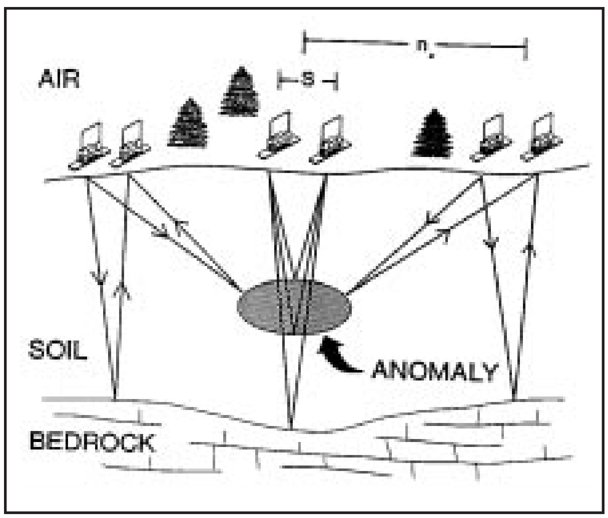


Figure 2: Schematic illustration of common-offset single-fold profiling.

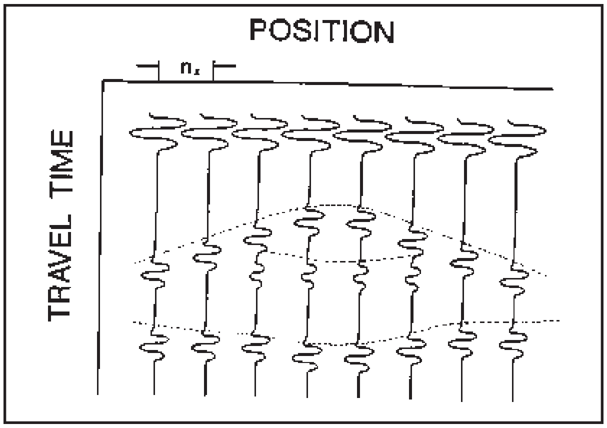


Figure 3: *Format of a GPR reflection section with radar events shown for features as depicted in Figure 2.*

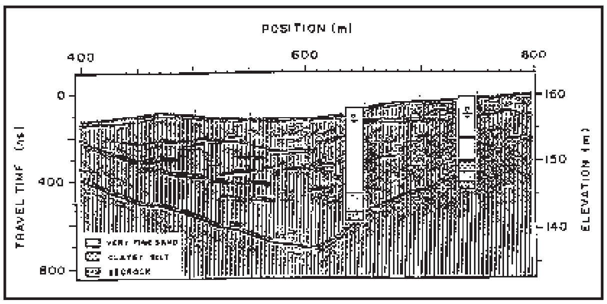


Figure 4: *100 MHz GPR section mapping bedrock depth beneath sand and gravel overburden.*

Estimation of velocity versus depth is conducted frequently with GPR systems; one of the simplest and most common methods is common-midpoint (CMP) sounding such as depicted in Figure 5. By varying antenna spacing and identifying the time move out versus antenna separation for the various EM wavefronts (Figure 6), radar wave velocity in the ground can be estimated.

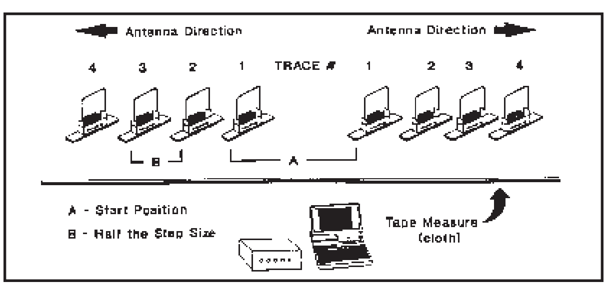


Figure 5: *Procedure for conducting a CMP velocity sounding.*

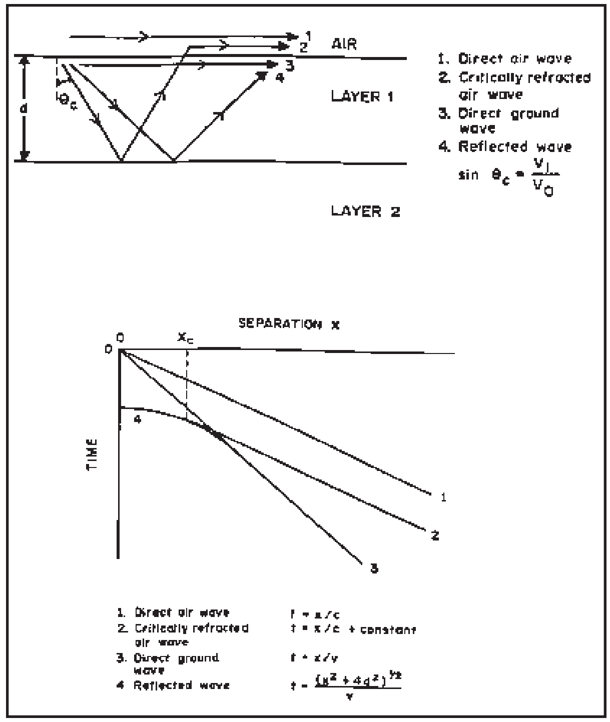


Figure 6: *Illustration of CMP sounding ray paths and idealized event arrival time versus antenna separation and display.*

These two most common forms of GPR surveying are the subject of this paper on survey design. Multifold reflection surveys (Fisher et al, 1992), which are in essence a merger of the basic CMP sounding and reflection mode, as well as transillumination gathers which form the basis of GPR tomography (Olsson et al, 1987) depend on the same principles discussed here.

In the following, a number of simple guidelines are given to aid with design of a GPR survey. The reader should note that common sense must prevail. The rules provided are based on simplifying more complicated relationships. Rules-of-thumb simplify a problem for expediency! The user desiring to become knowledgeable with GPR is encouraged to question the underlying assumptions; this will lead to true understanding of GPR.

2. Problem Definition

The most important step in a ground penetrating radar (GPR) survey is to clearly define the problem. This step is not unique to radar but common to all geophysical techniques although often overlooked in the urge "to rush off and collect data". There are five fundamental questions to be answered before deciding if a radar survey if going to be effective.

Question 1: What is the target depth?

The answer to this question is usually the most important. If the target is beyond the range of GPR in ideal conditions then GPR can be ruled out as a viable method very quickly.

Question 2: What is the target geometry?

The target to be detected should be qualified as accurately as possible. The most important target factor is target size (i.e., height, length, width). If the target is non- spherical, the target orientation (i.e., strike, dip, plunge) must be qualified.

Question 3: What are the target electrical properties?

The relative permittivity (dielectric constant) and electrical conductivity must be quantified. In order for the GPR method to work, the target must present a contrast in electrical properties to the host environment in order that the electromagnetic signal be modified, reflected, or scattered.

Question 4: What is the host material?

The host material must be qualified in two ways. First the electrical properties of the host must be defined. The relative permittivity and electrical conductivity have to be evaluated. Second, the degree and spatial scale of heterogeneity in the electrical properties of the host must be estimated. If the host material exhibits variations in properties which are similar to the contrast and scale of the target, the target may not be recognizable in the myriad of responses (commonly referred to as volume scattering and clutter) generated by the host environment.

Question 5: What is the survey environment like?

The GPR method is sensitive to the surroundings in which measurements are made. Two important factors are the presence of extensive metal structures and of radio frequency electromagnetic sources or transmitters. Another aspect of the survey environment is accessibility. Can the equipment and the operator get to the area of interest safely and economically? Are there any unusual conditions or hazards (heat, cold, wet, toxic contamination, explosive atmosphere)?

In general, there are few environments where radar cannot be used but available instrumentation may not be suited to the specific situation.

3. Evaluating GPR Suitability

Prediction of whether GPR will "work" for the problem at hand is not clear cut. In general it is easier to rule out situations where radar is totally unsuitable than to state with confidence that radar will be successful. Again, this is not a unique feature of the GPR method but is a fact of life with all geophysical methods. GPR tends to have more mystery because people have not normally had as much experience with it as with some other methods.

There are some basic tools which assist the GPR user in the decision making process. The two most important are the radar range equation, and numerical simulation techniques. Some examples are described by Annan and Chua (1988). The radar range equation (RRE for short) does a basic allocation of available power against all the loss mechanisms to yield a "yes/no" answer on whether a target will return sufficient power to be detectable. The RRE has to simplify the problem at hand; therefore, the results are good guides, not absolute predictors of success or failure. The basic steps of the radar range equation are depicted in Figure 7. Example results of an automated program to carry out these calculations are shown in Figure 8. Nomograms for specific systems and targets can also be generated such as shown in Figure 9.

Numerical simulation techniques (NST for short) are not well developed for GPR. Simple programs for flat layered earth structures are commercially available and are instructive to use. More complex 2 and 3-dimensional modeling programs are not available. The basic concepts for plane (flat) layered earth modeling are shown in Figure 10 accompanied by an example synthetic generated by the commercial Sensors & Software Inc. Synthetic Radargram program.

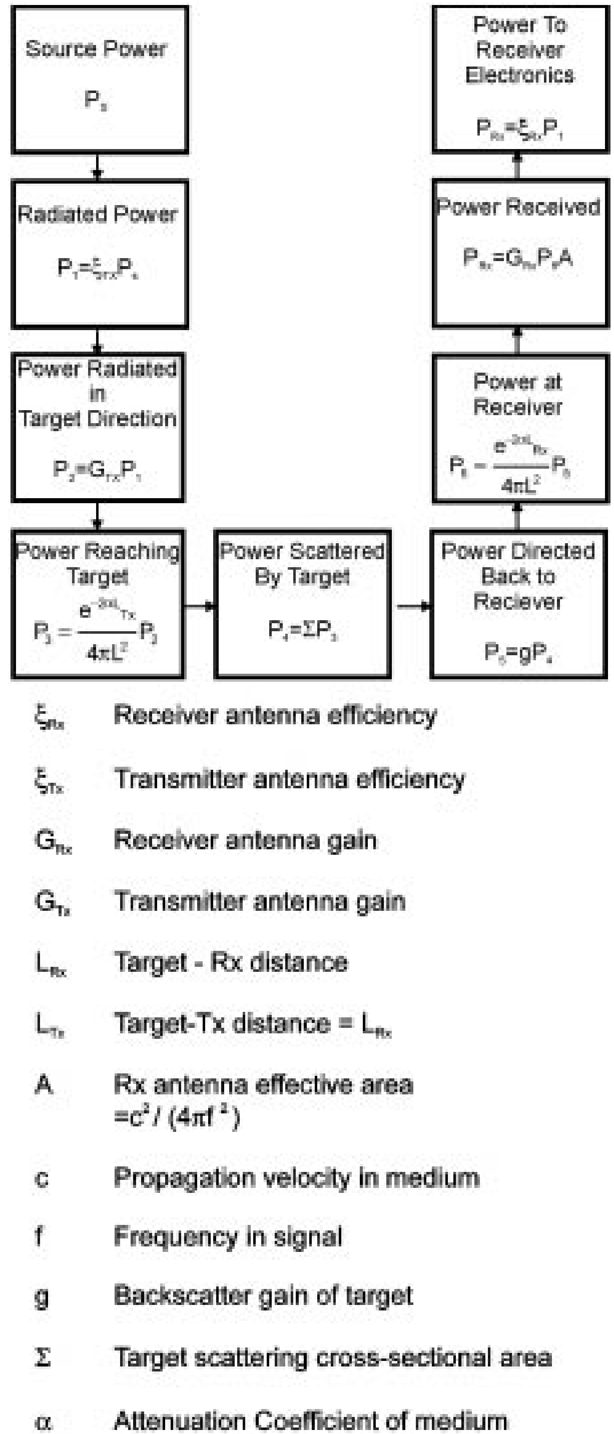


Figure 7: Block diagram of radar range equation.

Answering the question "Will GPR work?" is neither easy nor exact. Addressing the following three questions will certainly help in anticipating the answer.

```
                 Sensors & Software Inc.
           RADAR RANGE PERFORMANCE PARAMETERS

SYSTEM FACTORS
--------------
System Q (dB)                       133.88      Tx Voltage (V)      1000.00
Tx to Antenna Efficiency (dB)       -20.00      Rx Noise (uV)        199.99
Transmitter Antenna Gain (dB)         3.00      Frequency (MHz)       25.00
Antenna to Rx Efficiency (dB)       -20.00
Rx to Antenna Gain (dB)               3.00
Receiver Effective area (dB)         -1.48
                                  ----------
Net System Q  (dB)                   98.53

PROPAGATION FACTORS
-------------------
Spreading Losses (dB)               -74.02
Attenuation Loss (dB)               -36.00

ELECTRICAL & GEOMETRICAL PARAMETERS
-----------------------------------
Target Distance (m)                  20.00    Attenuation (dB/m)        0.90
Target Diameter (m)                   0.50    Conductivity(mS/m)        7.33
Layer Thickness (m)                   0.01    Tan Delta                 0.30
Target K                              8.00    Host K                   16.00

TARGET PARAMETERS
-----------------
Target Reflectivity (dB)            -12.38
Thin Layer Reflectivity (dB)        -44.24
Thin Layer Beta (dB)                -31.86
Diameter/Wavelength (dB)            -13.56

                                     Point      Rough    Specular   Thin Spec.
B1                                   -6.25       0.83     -0.76      -3.93
B2                                    0.00       1.00      2.00       2.00
B3                                    4.00      -1.00      0.00       0.00
Target Backscatter (dB)              -6.61       7.34     10.61     -13.25

RESULTS
-------
Performance (dB)                    -18.10      -4.13      7.12     -24.74
Target Amplitude (uV)                24.89     124.28    453.98      11.59
Stacks                               64.55       2.59      1.00     297.81

Window Required (ns)     533.33
```

Figure 8: Example listing of a radar range equation analysis of a problem.

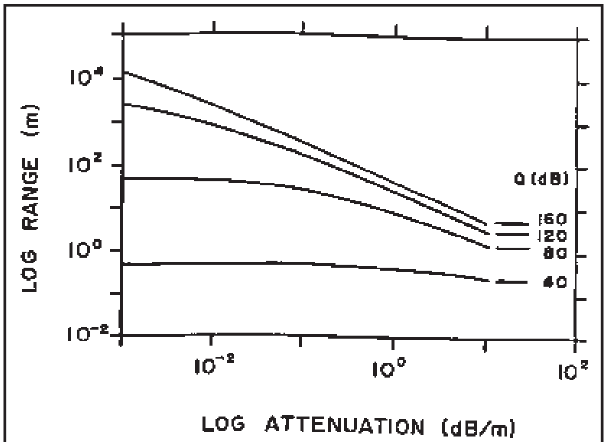


Figure 9: Radar range equation nomogram example.

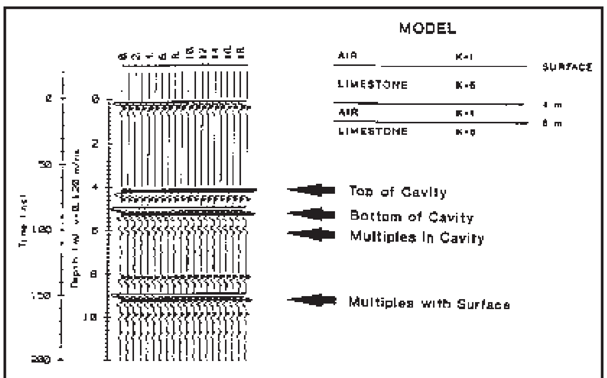


Figure 10: Illustration of a synthetic radargram program to predict a GPR response.

Question 1: Is the target within the detection range of the radar irrespective of any unusual target characteristics?

The way to answer this question is to calculate or measure the host attenuation coefficient. Using the radar range equation and the system performance factor (example in Figure 8), compute the maximum range that a reflector of the anticipated target type can be detected. If the target is at a depth greater than this range, radar win not be effective. A conservative rule-of-thumb is to state that radar will be ineffective if the actual target depth is greater than 50% of the maximum range.

Commercial radar systems can typically afford to have a maximum of 60 dB attenuation associated with conduction losses. A rough guide to penetration depth is

$$d_{max} < \frac{30}{\alpha} \quad \text{or} \quad d_{max} < \frac{35}{\sigma}$$

where a is attenuation in dB/m and a is conductivity in mS/m. These equations are not universal but are applicable when attenuation is moderate to high (< 0. 1 dB/m) which is typical of most geologic settings.

Question 2: Will the target generate a response detectable above the background clutter? In other words, does the target have sufficient contrast in electrical properties and is it physically enough to reflect or scatter a detectable amount of energy?

Power reflectivity is estimated using the expression

$$Pr = \left| \frac{\sqrt{K_{Host}} - \sqrt{K_{Target}}}{\sqrt{K_{Host}} - \sqrt{K_{Target}}} \right|^2$$

Two conservative rules-of-thumb for predicting success are as follows. First, the electrical properties of the target should be such that the power reflectivity be at least 0.01. (Note that a metal target is equivalent to $K_{Target} \rightarrow \infty$.) Second the ratio of target depth to smallest lateral target dimension should not exceed 10:1.

Question 3: Is there anything that precludes use of radar?

One example would be a radio transmitter located at the site. Another example would be a tunnel lined with metal mesh to prevent loose rock from falling. In the first case external signals may saturate the sensitive receiver electronics. In the later, all the radar signal would be reflected at the tunnel wail and none would penetrate into the tunnel wall.

If the above questions can be answered in a positive manner then there is a reasonable chance GPR will work. The above conditions are posed in a conservative manner and intended to err on the pessimistic side. More detailed analyses can employ RRE and NST techniques. In general it is almost impossible to obtain reliable estimates of all of the parameters involved in RRE and NST; these procedures are most effectively used as part of a sensitivity analysis. The conclusions drawn win be fuzzy but informed.

As with all predictions nothing beats a real field trial and if practical should be an integral component in survey design optimization. Unfortunately, financial constraints usually are a real and limiting factor.

4. Reflection Survey Design

The most common mode of GPR surveying is common-offset, single-fold reflection profiling. In such a reflection survey, a system with a fixed antenna geometry is transported along a survey line to map reflections versus position.

There are seven parameters to define for a common-offset, single-fold GPR reflection survey. These are the frequency, the time window, the time sampling interval, the station spacing, the antenna spacing, the line location and spacing, and the antenna orientation.

4.1 Selecting Operating Frequency

Selection of the operating frequency for a radar survey is not simple. There is a trade off between spatial resolution, depth of penetration and system portability. As a rule, it is better to trade off resolution for penetration. There is no use in having great resolution if the target cannot be detected!

The best way to approach the problem is define a generic target type (i.e., point target, rough planar target, or specular target) and specify a desired spatial resolution, x. The initial frequency estimate is then defined by the formula.

$$f = \frac{150}{x * \sqrt{K}} \text{MHz}$$

K is the relative permittivity (or dielectric constant) of the host material.

Using this frequency and the radar range equation (see Figure 7 and 8), the ability to penetrate to sufficient depth to detect the target can then be evaluated. If penetration is insufficient, reduce the frequency until adequate penetration is achieved. Note that there is a practical limit placed on this process by available instrumentation and the electrical properties of the host.

A simple guide is to use the following table which is based on the assumption that the spatial resolution required is about 25% of the target depth.

Depth (m)	Center Frequency (MHz)
0.5	1000
1.0	500
2.0	200
5.0	100
10.0	50
30.0	25
50.0	10

The above are values based on practical experience. Since every problem requires careful thought, the above values should only be used as a quick guide and not a replacement for thoughtful survey planning.

4.2 Estimating the Time Window

The way to estimate the time window required is to use the expression

$$W = 1.3 \frac{2 \times \text{Depth}}{\text{Velocity}}$$

where the maximum depth and minimum velocity likely to be encountered in the survey area are used. The above expression increases the estimated time by 30% to allow for uncertainties in velocity and depth variations.

If no information is available on the electrical properties, Table 1 provides a guide for first estimates of the velocities of common geologic materials.

4.3 Selecting The Sampling Interval

One of the parameters utilized in designing radar data acquisition is the time interval between points on a recorded waveform. The sampling interval is controlled by the Nyquist sampling concept and should be at most half the period of the highest frequency signal in the record. For most ground penetrating radar antenna systems, the bandwidth to center frequency ratio is typically about one. What this means is that the pulse radiated contains energy from 0.5 times the center frequency to 1.5 times the center frequency. As a result the maximum frequency is around 1.5 times the nominal center frequency of the antenna being utilized.

Based on the assumption that the maximum frequency is 1.5 times the nominal antenna center frequency, the data should be sampled at a rate twice this frequency. For good survey design it is better that one uses a safety margin of two. As a result the sampling rate should be approximately six times the center frequency of the antenna being utilized. Based on this analysis the following table summarizes suitable sampling intervals versus operating frequency.

Antenna Center Frequency (MHz)	**Maximum Sampling Interval (ns)**
10	16.7
20	8.3
50	3.3
100	1.67
200	0.83
500	0.33
1000	0.17

The function relationship is

$$t = \frac{1000}{6f}$$

where f is the center frequency in NM and t is time in ns.

In some instances it may be possible to increase the sampling interval slightly beyond what is quoted but this should only be done when data volume and speed of acquisition are at a premium over integrity of the data. In any event the sampling interval should never be more than 2 times that quoted here.

4.4 Selecting Station Spacing

The selection of spacing between discrete radar measurements (see Figure 2) is closely linked to the center operating frequency of the antennas and to the dielectric properties of the subsurface materials involved. In order to assure the ground response is not spatially aliased, the Nyquist sampling intervals should not be exceeded. The Nyquist sampling interval is one quarter of the wavelength in the host material and expressed as

$$n_x = \frac{c}{4f\sqrt{K}} = \frac{75}{f\sqrt{K}} \text{ (in m)}$$

where f is the antenna center frequency (in NM) and K is the relative permittivity of the host. If the station spacing is greater than the Nyquist sampling interval, the data will not adequately define steeply dipping reflectors. In areas of flat lying reflectors, this criterion can be compromised.

The spatial interval of measurement is clearly illustrated by the example sections shown in Figure 11 and 12. The 50 MHz data in Figure 11 were collected with a station spacing of 3m which is considerably larger than the computed Nyquist interval of 0.5 to 0.75. The data in Figure 11 clearly define the strong relatively flat lying reflectors. The steeply dipping events are aliased and appear as 'hash' on the section. The shown section sampled at a 0.5m station interval shown in Figure 12 clearly defines the steeply dipping features.

There are practical trade-offs to be made in selection of station interval. From a practical viewpoint, data volume and survey time are reduced by increasing the station interval. From a data interpretation standpoint, adhering to the Nyquist sampling interval is very important. There is also nothing to be gained by spatial oversampling. The sampling interval is extremely important as this example indicates and should be carefully weighed in the survey design process.

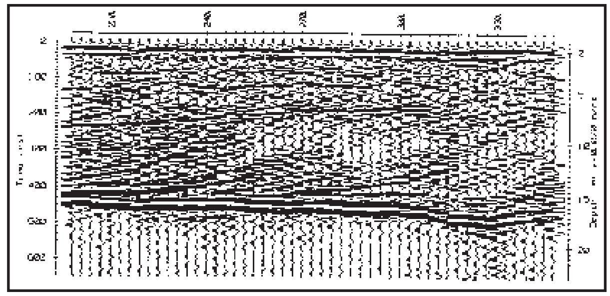


Figure 11: GPR reflection section from a deltatic environment obtained using 50 MHz antennas at a 3m station spacing.

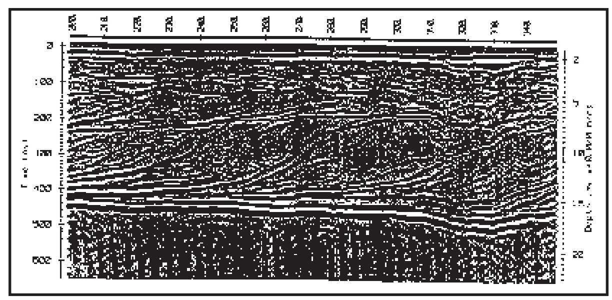


Figure 12: Same section as Figure 11 but station interval reduced to Nyquist sampling interval of 0.5 m.

4.5 Selecting Antenna Separation

Most GPR systems employ separate antennas for transmitting and receiving (commonly referred to as bistatic operation) although the antennas may be housed in a single module with no means of varying the antenna separation. The ability to vary the antenna spacing can be a powerful aid in optimizing the system for specific types of target detection. To maximize target coupling, antennas should be spaced such that the refraction focusing peak in the transmitter and receiver antenna patterns point to the common depth to be investigated. Since the antenna pattern peaks at the critical angle of the air-earth interface as illustrated in Figure 13, (Annan et al, 1975 and Smith 1984). An estimate of optimum antenna separation is given by the expression

$$S = \frac{2\ \text{Depth}}{\sqrt{(K-1)}}$$

Increasing the antenna separation also increases the reflectivity of flat lying planar targets which can sometimes be advantageous.

If little is known about the survey area, a safe rule-of-thumb is set S equal to 20% of the target depth. In practice, a small antenna spacing is often used because operational logistics usually demand simplicity of operation. Depth resolution of targets decreases as antenna separation increases although this factor is small until S approaches half the target depth.

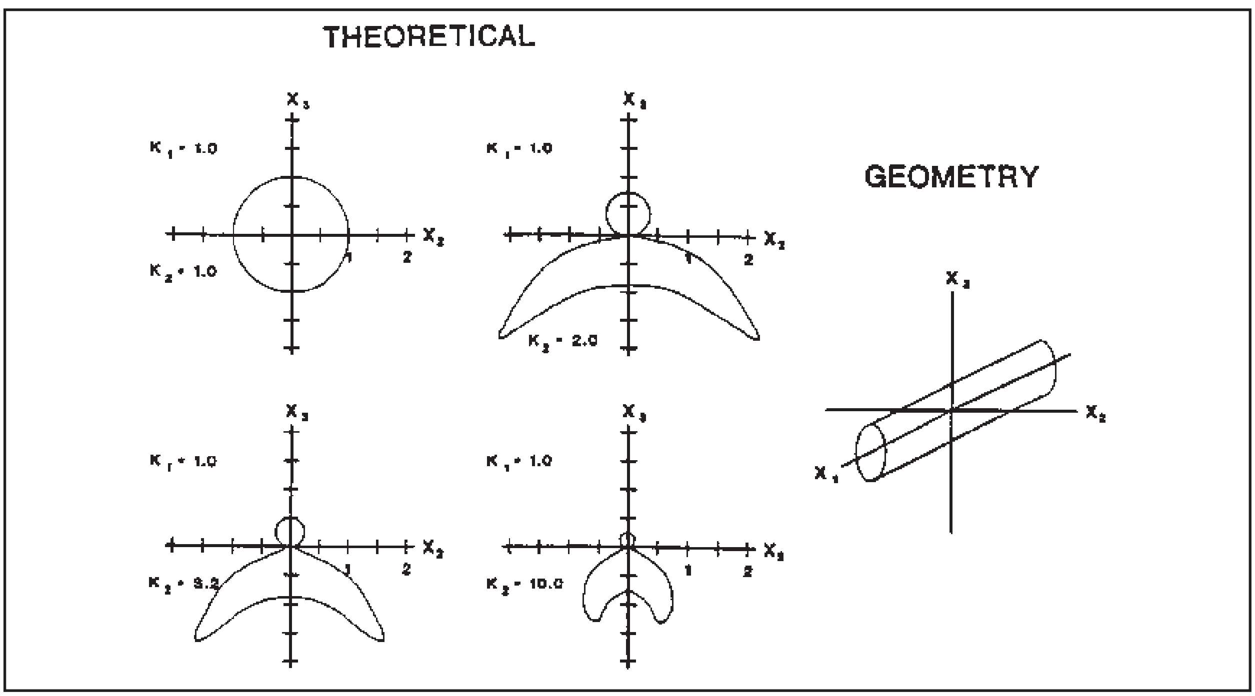


Figure 13: Variation in antenna patterns as relative permittivity of the ground (K_2) changes. (Upper medium is K_1=1.)

4.6 Survey Grid and Coordinate System

An important aspect of survey design is establishment of a survey grid and coordinate system. The use of a standardized coordinate system for position recording is very important; the best data in the world are useless if no one knows where they came from.

Generally, survey lines are established which run perpendicular to the trend of the features under investigation in order to reduce the number of survey lines. Line spacing is dictated by the degree of target variation in the trend direction. If isolated small targets are sought, the line spacing should be less than the radar footprint illustrated in Figure 14.

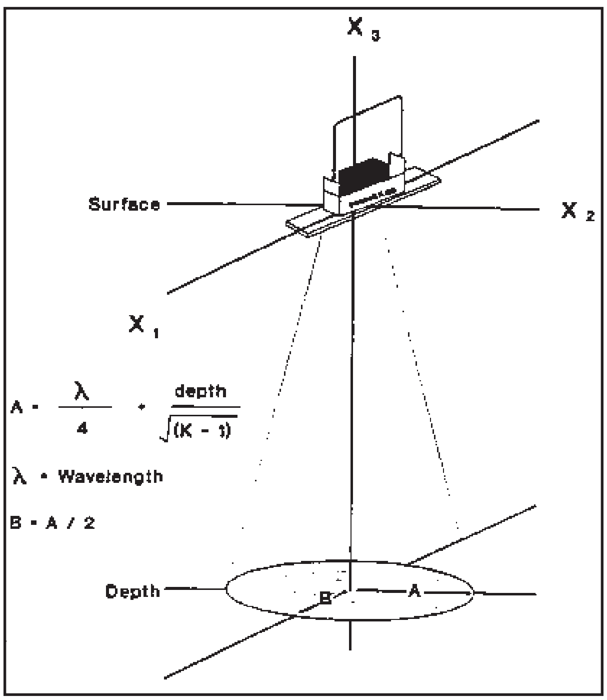


Figure 14: Simplified GPR footprint concept where shaded zone depicts area illuminated at depth.

The selection of survey line location and orientation should be made such as to analyze target detection. All survey lines should be oriented perpendicular to the strike of the target if the target has a preferred strike direction. In attempting to cover an area to map a feature such as bedrock depth, the survey fines should be oriented perpendicular to the bedrock relief and line spacing should be selected to adequately sample along-strike variations without aliasing. In situations where strike is known and the structure 2-dimensional, a very large spacing between lines can be employed. If there is no two dimensionality to the structure, then line spacing must be the same as the station spacing to assure that the ground response is not aliased. Needless to say, when nx is a fraction of a meter, a tremendous amount of data has to be collected to fully define a 3-dimensional structure.

4.7 Selecting Antenna Orientation

The last factor and seldom discussed factor to be considered is the antenna orientation. In general, the antennas used for GPR are dipolar and radiate with a preferred polarity. The antennas are normally oriented so that the electric field is polarized parallel to the long axis or strike direction of the target. There is no optimal orientation for an equi-dimensional target. In some instances, it may be advisable to collect two data sets with orthogonal antenna orientations in order to extract target information based on coupling angle. If the antenna system is one which attempts to use a circularly polarized signal the antenna orientation becomes irrelevant. Since most commercial systems employ polarized antennas, orientation can be important. The various arrangements of antenna deployment are illustrated in Figure 15. The most commonly used is the one designated ‘PR-BD’.

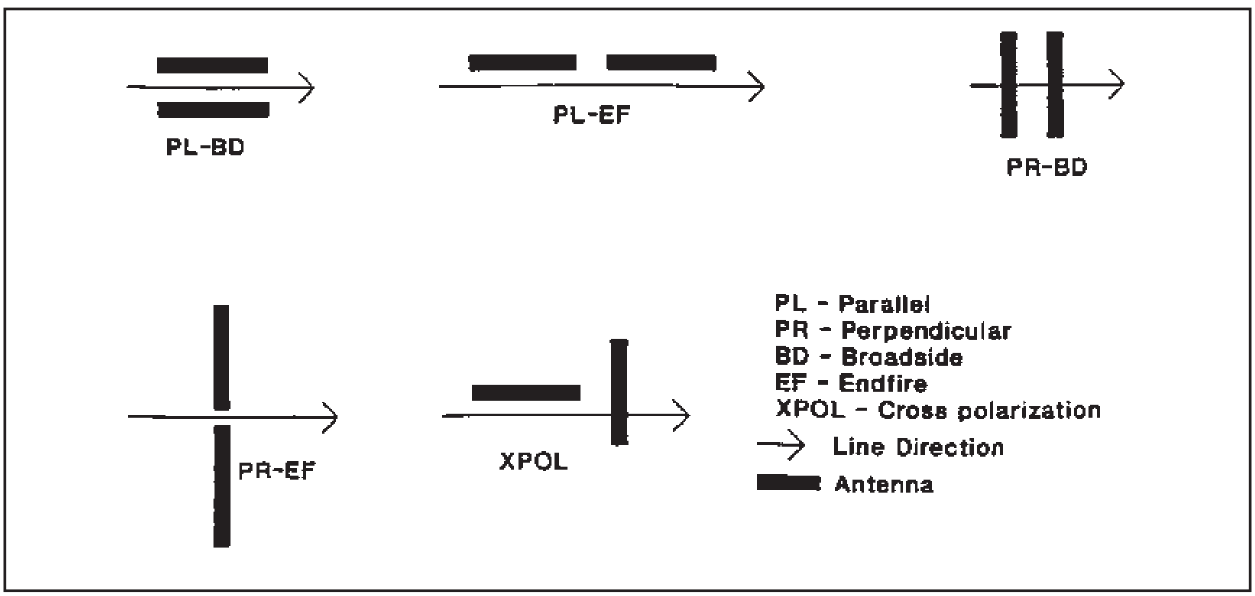


Figure 15: Illustration of trhe various modes for antenna deployment. (E field assumed aligned along the antenna axis.)

5. CMP/WARR Velocity Sounding Design

The CMP (common mid-point) and WARR (wide angle reflection and refraction) sounding modes of operation are the electromagnetic equivalent to seismic refraction and wide angle reflection. CMP/WARR soundings are used to obtain an estimate of the radar signal velocity versus depth in the ground by varying the antenna spacing at a fixed location and measuring the change of the two-way travel time to the reflections as illustrated in Figures 5 and 6.

In the CMP sounding, both the antennas are moved apart about a fixed location. In a WARR sounding, one antenna is held fixed while the other is moved away. In early GPR systems utilizing metallic cables, the WARR approach of sounding was preferred because cable handling was a major concern in obtaining data free of system artifacts. With modem systems such as those employing fiber optics cables, the CMP approach is the standard mode of operation since the reflected signal is more likely to come from a fixed spatial location rather than moving about on the surface of a reflector as occurs with a WARR sounding.

Optimal CMP/WARR soundings are obtained when the electric fields of the antennas are parallel and the antennas are moved apart along a line which is perpendicular to the electric field polarization (the 'PR-BD' configuration in Fig 15). This configuration gives the widest angular coverage of a subsurface reflector. In addition, close coupling of the antennas to the ground should be maintained in order to maximize reflection energy detectable at angles beyond the critical angle of the air-earth interface.

The procedure for a CMP/WARR sounding is simple. A reflector is normally identified from a reflection section. A point on the ground surface is selected which is over the reflector. Antennas are then positioned over the target point with minimal separation. The initial spacing is usually n_x, the Nyquist station interval selected for reflection profiling. Data are then acquired at antenna separations which increase as integer multiples of n_x. If the CMP mode is used, both antennas are moved out from the center point in steps of n_x /2. If WARR mode is used, one antenna is moved out in step intervals of n_x. The maximum separation in a CMP/WARR sounding is usually 1 to 2 times the reflector depth. If the ground attenuation is high, the signals may die out before the maximum separation is reached.

The reflection arrival times should have a hyperbolic dependence (to first order) on antenna separation. Example data sets are shown in Figure 16 for both the PR-BD and PLEF antenna configurations.

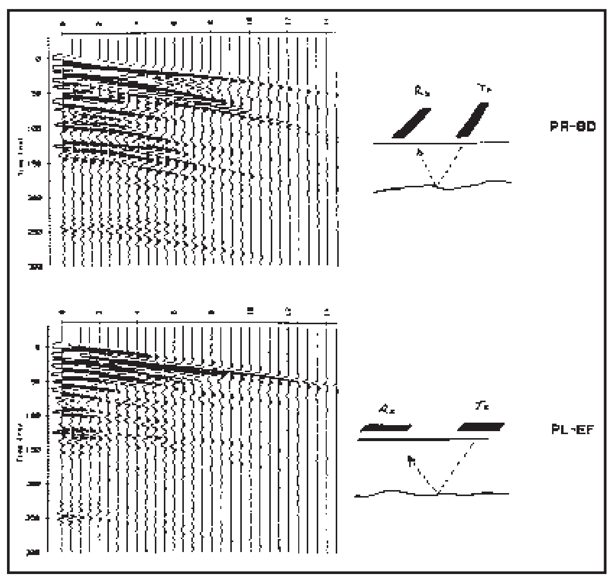
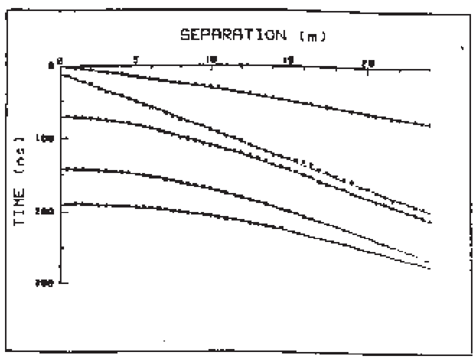


Figure 16: CMP sounding data with 2 modes of antenna polarization. (Data acquired at 500 m position on reflection section shown in Figure 4.

Analysis of the move out hyperbola of time versus separation permits estimation of propagation velocity and target depth. The basic interpretation procedure is "T¹-X²", analysis commonly used in early seismic reflection interpretations. In simple terms, a plot of travel time squared versus antenna separation squared yields a straight line relationship whose slope gives a velocity estimate and whose time intercept yields a depth estimate (see Figure 17). Computerized schemes of varying degrees of complexity are now commonly used to do this type of analysis such as the velocity stack shown in Figure 18.



EVENT	INTERCEPT (ns)	VELOCITY (m/ns)	K	DEPTH (m)
AIRWAVE	+0.00	.305	1.000	
GROUNDWAVE	+12.46	-.130	5.357	
REFLECTOR 1	+72.23	-.122	6.067	4.399
REFLECTOR 2	+141.41	.107	7.914	7.540
REFLECTOR 3	+189.49	-.120	6.239	11.380

EVENT	LAYER VELOCITY (m/ns)	K	THICKNESS (m)
LAYER 1	.122	6.07	4.4
LAYER 2	.0906	11	3.14
LAYER 3	.10	5.52	3.84

Figure 17: T^2 - X^2 analysis of CMP/WARR sounding.

CMP/WARR soundings provide a measure of signal attenuation in the ground although to date the estimation is more qualitative than quantitative. In addition, at sites with a large amount of surface clutter, CMP/WARR soundings can aid in separating above and below ground reflections.

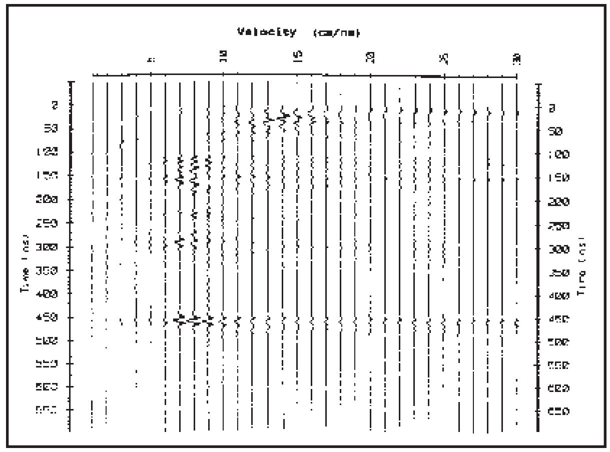


Figure 18: Example of moveout velocity stacking of a PR-BD data set (partially presented in Figure 16.)

6. Summary

The preceding survey design guidelines provide a basis for survey planning. As mentioned earlier, the use of common sense and a logical thought process are needed to conduct high quality GPR surveys. The more planning that goes into a survey, the higher the likelihood of success and the easier the interpretation of the results.

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TABLE 1

Properties of Common Geologic Materials

Typical Relative Permittivity, Electrical Conductivity, Velocity and Attenuation Observed in Common Geologic Materials

MATERIAL	K	σ (mS/M)	v (m/ns)	α (dB/m)
Air	1	0	0.30	0
Distilled Water	80	0.01	0.033	$2x10^{-3}$
Fresh Water	80	0.5	0.033	0.1
Sea Water	80	$3x10^{3}$	.01	10^{3}
Dry Sand	3-5	0.01	0.15	0.01
Saturated Sand	20-30	0.1-1.0	0.06	0.03-0.3
Limestone	4-8	0.5-2	0.12	0.4-1
Shales	5-15	1-100	0.09	1-100
Silts	5-30	1-100	0.07	1-100
Clays	5-40	2-1000	0.06	1-300
Granite	4-6	0.01-1	0.13	0.01-1
Dry Salt	5-6	0.01-1	0.13	0.01-1
Ice	3-4	0.01	0.16	0.01