Ground Penetrating Radars. Principles, Applications and Design

Principle

Radar techniques, developed originally for the detection of targets in the sky or on the surface of land or sea, are now being adapted as a means of investigating the composition and integrity of non-conducting materials and structures. The radar technique principally detect back-scattered energy from a target; anomalies within a material give rise to reflections and if the radar antenna is scanned over the material an image of the anomalies can be generated.

The principles of radar are well understood and radar for detecting buried objects or Ground Penetrating Radar (GPR) uses the same fundamental physical principles as conventional radar. GPR is the general term applied to techniques which employ radio waves, typically in the 1 to 5000 MHz frequency range, to map structure and features buries in the ground or in man-made structures. Last time GPR has been used in non-destructive testing of non-metallic structures.

A major advantage of the radar technique over the non-destructive testing methods such as ultrasonic is that it is possible to use an antenna (transducer) which is non-conducting. Thus it is technically feasible to scan areas of interest extremely quickly (up to 30 km/h).

The majority of targets sought using sub-surface radar methods are non-metallic so that their scattering cross-section is dependent upon the properties of the surrounding dielectric medium. Most targets and voids in particular have a lower relative permittivity and there is not the phase change at an interface that is observed when the scattering is a metallic boundary. This feature may be used as way of distinguishing between conducting and non-conducting targets.

The most common mode of operation is single-fold common-offset reflection profiling as illustrated in Figure 1. In such a reflection survey, a system with a fixed antenna geometry is transported along survey line to map reflections versus position. This mode of operation gives rise to data such as shown conceptually in Figure 2.

The GPR method measures the travel time of electromagnetic impulses in subsurface materials. Am impulse radar system radiates repetitive electromagnetic impulses into the earth. A broad bandwidth antenna is usually placed in close proximity and electromagnetic coupled to the ground surface. It is able to detect and measure the depth of reflecting discontinuities in subsurface soils and other earth materials to within a few centimeters depending upon the electromagnetic parameters of the earth medium, the depth to and size of the target and the frequency of operation. As the antenna is pulled across the surface a continuous profile record is generated and displayed as a two way travel time versus distance plot on a strip chart recorder and/or color monitor, LCD for immediate evaluation. Depth calculation can be derived from this data once the signal velocity has been determined. The signal from sub-surface radar is transmitted through the ground or a material which attenuates the signal and this causes the range in depth to be limited by the type of material. There is an optimum choice of frequency of operation to achieve best performance in terms of depth and ability to see details in the target structure. This choice is between 1 and 1000 MHz. Generally low frequencies are used for deep probing (>50 m) and high frequencies are used for shallow probing (<50 m).

Applications

GPR techniques potentially powerful approach to non-destructive testing a wide range of possible applications. These vary from the measurement of material parameters, thickness, dielectric constant, hence water content etc., geophysical prospecting, archaeological investigation, detection of buried objects such as pipes, cables, etc. Typical applications are indicated in Tables 1 and 2.

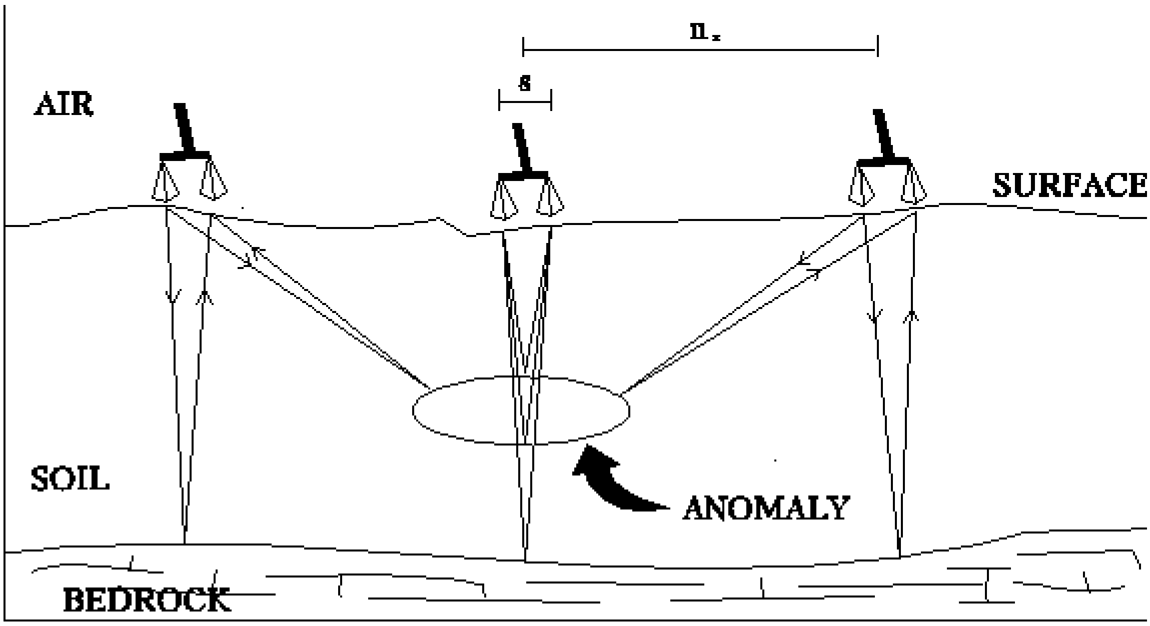

Figure 1. Schematic illustration of single-fold common-offset reflection profiling

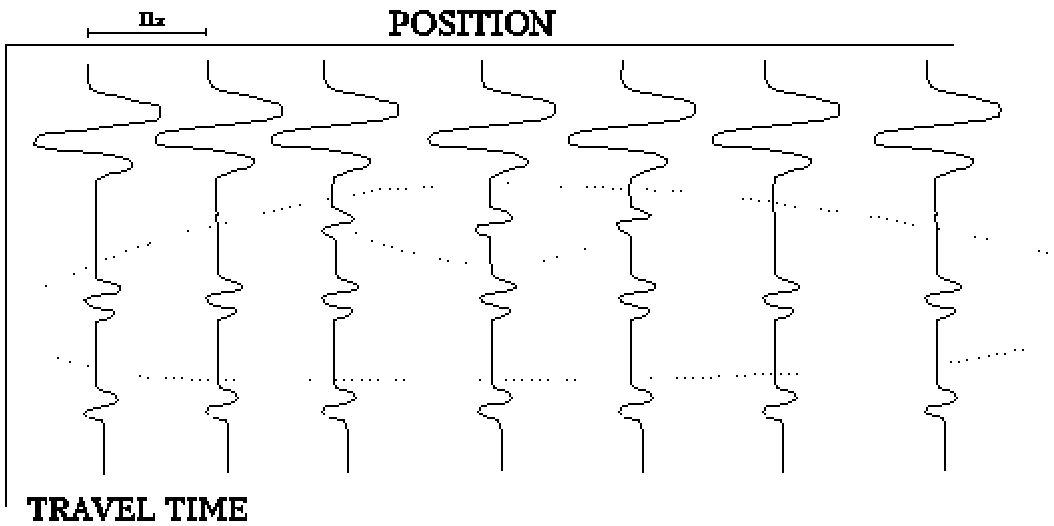

Figure 2. Format of a GPR reflection section with radar events shown for features depicted in Figure 1

Table 1: Typical Applications of Ground Penetrating Radars

CIVIL/STRUCTURAL ENGINEERING	**Miscellaneous**	Void Detection Pavement Thickness Reinforcing Bar Locating / Evaluation Submarine Pipe and Cable Locating
	Utilities	Pipe Leak Detection: Gas Water Oil Filled Electrical Buried Pipe and Cable Mapping
GEOTECHNICAL	**Mining**	Peat Profiling Coal Mining Bauxite
	Hazardous Waste	Hazardous Waste Mapping Landfill Boundaries Trench Boundaries Buried Drums Underground Storage Tank Detection Contamination Instruction Mapping Oil under Ice Detection
	Miscellaneous	Geological Strata Profiling Earthquake Fault Mapping, Highway and other Excavation Projects, Radar Ground Truth Bedrock Mapping: Subway Tunnel Excavations Rock Fracture Mapping: Safety & Other Purposes Crevasse Detection: Safety & Other Purposes Borehole Profiling River & Lake Bottom Profiling Ice Thickness Profiling: Sea Ice, River Ice Permafrost Mapping Sinkhole Prediction Water Table Detection / Mapping
	Ordnance Detection	Mines: Metallic & Non-metallic Unexploded Bombs
	Runway Integrity Movement	Runway Integrity Movement
	Troop/ Equipment Movement	Troop/Equipment Movement
	Save Ice Roads	Save Ice Roads
TRANSPORTATION	**Roads**	Pavement Base / Subgrade Thickness Voids Under Pavement
	Railroads	Railroad Bed Profiling Tie Evaluation
	Airports	Runway Integrity Testing
	Law Enforcement	Buried Body Detection Buried Weapons
	Archaeology	Archaeological Prospecting: Cavity or Chamber Detection, Treasure Prospecting

Table 2: Distance Range Applications of Ground Penetrating Radars

Very Shot Range	Shot Range	Medium Range	Long Range
Road Reinforcement Road Structures Material Integrity Material Production Bridge Structures Building Structures Fiber Optic Cables Buried Objects Borehole Investigat. Security investigation	Tunnel Structures Road Reinstatement Road Structures Material Integrity Material Production Bridge Structure Building Structure Pipes-Cables Buried Objects Concrete Integrity Borehole Investigat. Security Investigation	Tunnel Structures Construct. Surveying Chemical Waste Borehole Investigat. Geological Surveying Resource Assessm. Archaeological Sites	Construct. Surveying Chemical Waste Borehole Investigat. Geological Surveying Resource Assessm. Archaeological Sites

Military applications

Finding and mapping metallic and non-metallic mines and unexploded bombs. Finding secret rooms, cellars, internal boxes. Finding underground warehouses, bomb-shelters, different communications. Wall investigation - finding secret transmitters, receivers and microphones, internal boxes. GPR is the most effective method comparatively to traditional methods, such as magnetic mine finders or acoustic radars (see Figure 3)

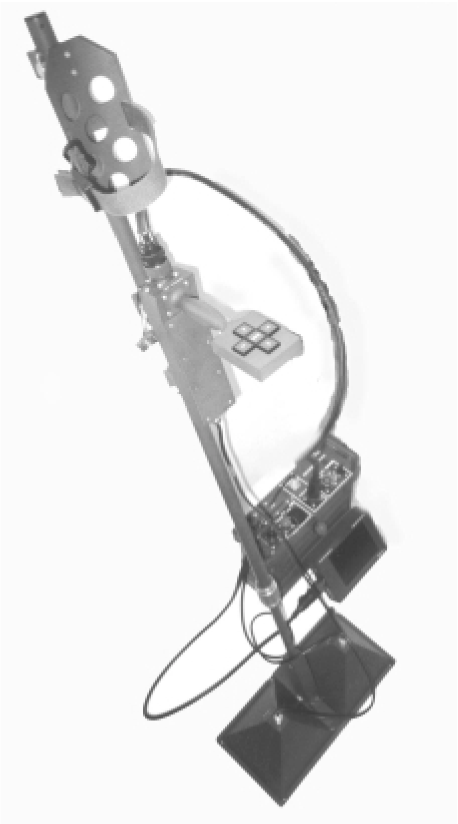

Figure 3: The ITL231A Mine Detector allows to detect metallic mines, non-metallic mines, also plastic mines with small metal pieces

Figure 4: The ER2-02 Ground Penetrating Radar is a field-rugged impulse radar system designed for detection of features or objects buried within horizontal or vertical surface

Locating hazardous waste

Finding and mapping buried hazardous waste can be a time-consuming and dangerous process. Hit and miss techniques can complicate an already serious situation. GPR is a cost-effective method to safety map contamination plumes, buried drums, buried trenches, and boundaries at abandoned landfills. All non-destructively in a fraction of the time it would take by other methods.

Subsurface conditions

Using traditional methods for mapping and detecting subsurface features can be time consuming and costly. Job cost estimating and geological research project require accurate information about subsurface condition. GRP can map and detect bedrock, buried boulders and ledge, water table, soil profiles, faults, voids and sinkholes quickly, easily, accurately and cost effectively (see Figure 4).

Undetected voids

Highways, tunnels, airports, mines and buildings need to be inspected on a regular basis for subsurface voids. GPR is a cost-effective way to find and map voids.

Drilling into rebars

GPR is used to save construction and maintenance money. It accurately locate rebars, high-voltage cables, conduits, and voids in concrete.

Finding buried pipes

GPR is the cost effective tool for locating metallic or non-metallic subsurface features. It can accurately record the depth and location of pipes, cables, ducts, and other man made or natural objects.

Trackbed failure

GPR is a cost-effective method to quickly determine the thickness and conditions of railroad ballast, sub-ballast and sub-grade. Problems such as water intrusion and ballast contamination, as well as finding buried cables, culverts and other features, can be detected with GPR.

Design

There are some parameters to define for single-fold common-offset GPR reflection survey.

Operating frequency

Selection of the operating frequency for 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 specula target) and specify a desire spatial resolution, X. The initial frequency estimate is then defined by the formula:

$$f = \frac{150}{X\sqrt{K}}(MHz)$$

K - relative permittivity (dielectric constant) of most material

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 are indicated in Table 3. There 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.

Table 3: Propagation Depth and Center Frequency used in GPR

Depth, m	Center Frequency, MHz
0.5	1000
1.0	500
2.0	200
5.0	100
10	50
30	25
50	10

Estimating the time window

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

$$W = \frac{2\,x\,Depth}{Velocity}$$

where the maximum depth and minimum velocity likely to be encountered in the survey area are used. The above expression increases the estimate time by 30 % to allow for uncertainties in velocity and depth variations. If no information is available on the electrical properties, Table 4 provides a guide for first estimates of the velocities of common geologic materials.

Table 4: The Parameters of different geologic materials

Material	Typical Relative Permittivity	Electrical Conductivity, mS/m	Velocity, m/ns	Attenuation, dB/m
Air	1	0	0,30	0
Distilled Water	80	0,01	0,033	0,002
Fresh Water	80	0,5	0,033	0,1
Sea Water	80	3000	0,01	1000
Dry Sand	3 – 5	0,01	0,15	0,001
Saturated Sand	20 – 30	0,1 - 1,0	0,06	0,03 - 0,3
Limestone	4 – 8	0,5 – 2	0,112	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

Selecting sampling interval

One of the parameters utilized in designing radar data acquisition is the time interval between points on a record 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 GPR antenna systems, the bandwidth to center frequency ratio is typically about one. What this mean 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. The function relationship is:

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

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

Based on the assumption that the maximum frequency is 1,5 times the nominal antenna center frequency, 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 Table 5 summaries suitable sampling intervals versus operating frequency.

Table 5: 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

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

Selecting Station Spacing

The selection of spacing between discrete radar measurements (see Figure 1) is closely linked to the center operating frequency of antennas and to the dielectric properties of the material involved. In order to assure the ground response is not spatially aliased, the Nyquist sampling intervals should not be exceeded. he Nyquist sampling interval is one of the wavelenght in the host material and expressed as:

$$Nx = \frac{c}{4f\sqrt{K}} = \frac{75}{f\sqrt{K}} (meters)$$

where f is the antenna center frequency (in MHz) and K is the relative permittivity of the host.

If the station spacing is greater than Nyquist sampling interval, the data will not adequately define steeply dipping reflectors.
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.

Selecting Antenna

The plan resolution is defined by the characteristics of the antenna and signal processing employed. In general, to achieve an acceptable plan resolution requires a high gain antenna. This necessitates antenna dimensions greater than the wavelength of the lowest frequency transmitted. To achieve small antenna dimensions and high gain therefore requires the use of a high carrier frequency which generally does not penetrate the ground material sufficient depth. An important consideration when choosing equipment for any particular application is to determined correctly the exact trade-off between plan resolution, size of antenna, scope of signal processing and ability to penetrate the material.

It is important that the antenna is well isolated from the effect of the material, unless this is done, the clutter (unwanted signs whose characteristics are similar to the target) can mask the target return. Thus isolation between the transmit-receive antenna is an important parameter. Once the signal has been received it is necessary to process it from its raw state into a form more suitable for the operator. The form of processing is dependent on the type of radar, the type of target and the form of display required.

Figure 5: The antenna of the ITL231A Mine Detector covers the bandwidth 0.4 to 2.4 GHz and works with both 1 and 2 GHz central frequencies

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 antennas 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.
An estimate of optimum antenna separation is given by the expression:

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

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.

Survey grid and co-ordinate system

An important aspect of survey design is establishment of survey grid and co-ordinate system. The use of a standardized co-ordinate system for position recording is very important; the best data in the world useless if no one knows where they came from. Generally, surveys 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.
The selection of survey line location and orientation should be made such as to maximize 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 lines should be oriented perpendicular to the bedrock relief and line spacing should be selected to adequately sample along-strike variations without aliasing. In situation 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 in meter, a tremendous amount of data has to be collected to fully define a 3-dimensional structure.

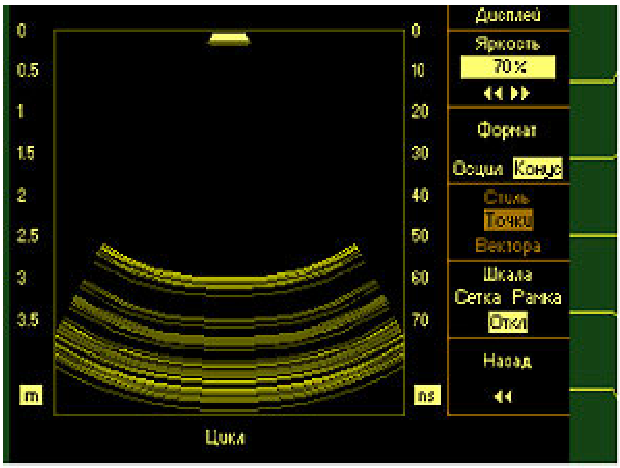

Figure 6: The Profile Format of Display

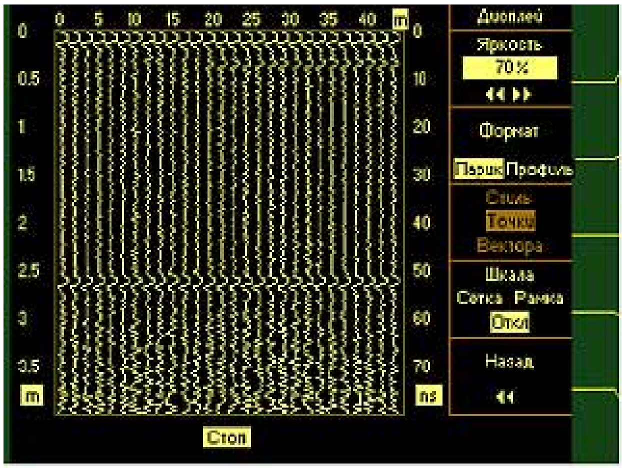

Figure 7: The Conical Format of Display

About Eltesta

ELTESTA is a company which designs and manufacturers an extensive line of high-performance electronic equipment based on Time-Domain Technologies in Pico- and Nanosecond Areas. The key point of these technologies is generating and acquiring electrical signals with very fast rise time. Main coaxial and waveguide units of the instruments built under this technology are: GHz-Samplers, ps-Finite Generators, Wide-Bandwidth Antennas, HF Accessories. All they use very fast semiconductors.

Line of the instruments includes: Wide-Bandwidth PC-Sampling Oscilloscopes also working as Communication Analyzer, Time Domain Reflectometer and Network Analyzer; Pulse, Step and One Sine-wave Generators, Impulse Radars (Ground Penetrating Radar and Mine Detector).

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