Standard Guide for
Using the Surface Ground Penetrating Radar Method for Subsurface Investigation[1]

This standard is issued under the fixed designation D 6432; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 *Purpose and Application*:

1.1.1 This guide summarizes the equipment, field procedures, and interpretation methods for the assessment of subsurface materials using the impulse Ground Penetrating Radar (GPR) Method. GPR is most often employed as a technique that uses high-frequency electromagnetic (EM) waves (from 10 to 3000 MHz) to acquire subsurface information. GPR detects changes in EM properties (dielectric permittivity, conductivity, and magnetic permeability), that in a geologic setting, are a function of soil and rock material, water content, and bulk density. Data are normally acquired using antennas placed on the ground surface or in boreholes. The transmitting antenna radiates EM waves that propagate in the subsurface and reflect from boundaries at which there are EM property contrasts. The receiving GPR antenna records the reflected waves over a selectable time range. The depths to the reflecting interfaces are calculated from the arrival times in the GPR data if the EM propagation velocity in the subsurface can be estimated or measured.

1.1.2 GPR measurements as described in this guide are used in geologic, engineering, hydrologic, and environmental applications. The GPR method is used to map geologic conditions that include depth to bedrock, depth to the water table (Wright et al **(1)**[2]), depth and thickness of soil strata on land and under fresh water bodies (Beres and Haeni **(2)**), and the location of subsurface cavities and fractures in bedrock (Ulriksen **(3)** and Imse and Levine **(4)**). Other applications include the location of objects such as pipes, drums, tanks, cables, and boulders , mapping landfill and trench boundaries (Benson et al **(6)**), mapping contaminants (Cosgrave et al **(7)**; Brewster and Annan **(8)**; Daniels et al **(9)**), conducting archaeological (Vaughan **(10)**) and forensic investigations (Davenport et al **(11)**), inspection of brick, masonry, and concrete structures, roads and railroad trackbed studies (Ulriksen **(3)**), and highway bridge scour studies (Placzek and Haeni **(12)**). Additional applications and case studies can be found in the various *Proceedings of the International Conferences on Ground Penetrating Radar* (Lucius et al **(13)**; Hannien and Autio, **(14)**, Redman, **(15)**; Sato, **(16)**; Plumb **(17)**), various *Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems* (Environmental and Engineering Geophysical Society, 1988–1998), and The Ground Penetrating Radar Workshop (Pilon **(18)**), EPA (**19**), and Daniels **(20)** provide overviews of the GPR method.

1.2 *Limitations*:

1.2.1 This guide provides an overview of the impulse GPR method. It does not address details of the theory, field procedures, or interpretation of the data. References are included for that purpose and are considered an essential part of this guide. It is recommended that the user of the GPR method be familiar with the relevant material within this guide and the references cited in the text and with Guides D 420, D 5730, D 5753, D 6429, and D 6235.

1.2.2 This guide is limited to the commonly used approach to GPR measurements from the ground surface. The method can be adapted for a number of special uses on ice (Haeni et al **(21)**; Wright et al **(22)**), within or between boreholes (Lane et al **(23)**; Lane et al **(24)**), on water (Haeni **(25)**), and airborne (Arcone et al **(25)**) applications. A discussion of these other adaptations of GPR measurements is not included in this guide.

1.2.3 The approaches suggested in this guide for using GPR are the most commonly used, widely accepted, and proven; however, other approaches or modifications to using GPR that are technically sound may be substituted if technically justified and documented.

1.2.4 *This guide offers an organized collection of information or a series of options and does not recommend a specific course of action. This document cannot replace education or experience and should be used in conjunction with professional judgements. Not all aspects of this guide may be applicable in all circumstances. This ASTM standard is not intended to represent or replace the standard of care by which the adequacy of a given professional service must be judged, nor should this document be applied without consideration of a project's many unique aspects. The word "Standard" in the title of this document means only that the document has been approved through the ASTM consensus process.*

1.3 *Precautions*:

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[1] This guide is under the jurisdiction of ASTM Committee D-18 on Soil and Rock and is the direct responsibility of Subcommittee D18.01 on Surface and Subsurface Characterization.

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[2] The boldface numbers in parentheses refer to the list of references at the end of this standard.

1.3.1 *It is the responsibility of the user of this guide to follow any precautions in the equipment manufacturer's recommendations and to establish appropriate health and safety practices.*

1.3.2 *If this guide method is used at sites with hazardous materials, operations, or equipment, it is the responsibility of the user of this guide to establish appropriate safety and health practices and to determine the applicability of any regulations prior to use.*

1.3.3 *This guide does not purport to address all of the safety concerns that may be associated with the use of the GPR method. It is the responsibility of the user of this guide to establish appropriate safety and health practices and to determine the applicability of regulations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

D 420 Guide to Site Characterization for Engineering, Design, and Construction Purposes[3]

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[3]

D 5088 Practice for Decontamination of Field Equipment Used at Nonradioactive Waste Sites[3]

D 5608 Practice for Decontamination of Field Equipment Used at Low Level Radioactive Waste Sites[3]

D 5730 Guide for Site Characterization for Environmental Purposes With Emphasis on Soil, Rock, the Vadose Zone and Ground Water[4]

D 5753 Guide for Planning and Conducting Borehole Geophysical Logging[4]

D 6235 Guide for Expedited Site Characterization of Hazardous Waste Contaminated Sites[4]

D 6429 Guide for Selecting Surface Geophysical Methods[4]

3. Terminology

3.1 *Definitions*:

3.1.1 Definitions shall be in accordance with the terms and symbols given in Terminology D 653.

3.1.2 The majority of the technical terms used in this guide are defined in Sheriff **(27)**.

3.1.3 *Additional Definitions*:

3.1.3.1 *antenna*—a transmitting GPR antenna converts an excitation in the form of a voltage pulse or wave train into EM waves. A receiving GPR antenna converts energy contained in EM waves into voltages, which are regarded as GPR data.

3.1.3.2 *attenuation*—(*1*) the loss of EM wave energy due to conduction currents associated with finite conductivity (σ) and the dielectric relaxation (also referred to as polarization loss) associated with the imaginary component of the permittivity (ϵ''), and magnetic relaxation associated with the imaginary component of magnetic permeability.

(*2*) The term "attenuation" is also sometimes used to refer to the loss in EM wave energy from all possible sources, including conduction currents, dielectric relaxation, scattering, and geometrical spreading.

3.1.3.3 *bandwidth*—The operating frequency range of an antenna that conforms to a specified standard (Balanis **(28)**). For GPR antennas, typically the bandwidth is defined by the upper and lower frequencies radiated from a transmitting GPR antenna that possess power that is 3 dB below the peak power radiated from the antenna at its resonant frequency. Sometimes the ratio of the upper and lower 3-dB frequencies is used to describe an antenna's bandwidth. For example, if the upper and lower 3-dB frequencies of an antenna are 600 and 200 MHz, respectively, the bandwidth of the antenna is said to be 3:1. In GPR system design, the ratio of the difference between the upper frequency minus the lower frequency to the center frequency is commonly used. In the preceding case, one would have a ratio of 400:400 or 1:1.

3.1.3.4 *bistatic*—the survey method that utilizes antennas. One antenna radiates the EM waves and the other antenna receives the reflected waves.

3.1.3.5 *conductivity*—the ability of a material to support an electrical current (material property that describes the movement of electrons or ions) due to an applied electrical field. The units of conductivity are Siemens/metre (S/m).

3.1.3.6 *control unit* (C/U)—An electronic instrument that controls GPR data collection. The control unit may also process, display, and store the GPR data.

3.1.3.7 *coupling*—the coupling of a ground penetrating radar antenna to the ground describes the ability of the antenna to get electromagnetic energy into the ground. A poorly coupled antenna is described as being mismatched. A well-coupled antenna has an impedance equal to the impedance of the ground.

3.1.3.8 *depth of penetration*—the maximum depth range a radar signal can penetrate in a given medium, be scattered by an electrical inhomogeneity, propagate back to the surface, be recorded by a receiver GPR antenna, and yield a voltage greater than the noise levels of the GPR unit.

(*1*) In a conductive material (seawater, metallic materials, or mineralogic clay soils), attenuation can be great, and the wave may penetrate only a short distance (less than 1 m). In a resistive material (fresh water, granite, ice, or quartz sand), the depth of penetration can be tens to thousands of metres.

3.1.3.9 *dielectric permittivity*—dielectric permittivity is the property that describes the ability of a material to store electric energy by separating opposite polarity charges in space. It relates ability of a material to be polarized in the electric displacement, D, in response to the application of an electric field, E, through $D=\epsilon E$. The units of dielectric permittivity, ϵ, are farads/metre (F/m). Relative dielectric permittivity (previously called the dielectric constant) is the ratio of the permittivity of a material to that of free space, 8.854×10^{-12} F/m. Whenever the dielectric permittivity is greater than that of free space, it must be complex and lossy, with frequency dependence typically described by the Cole-Cole (Cole and Cole **(28)**) relaxation distribution model. Nearly all dielectric relaxation processes are the result of the presence of water or clay minerals (Olhoeft **(29)**).

3.1.3.10 *dielectric relaxation*—generally used to describe EM wave attenuation due to ϵ'' (the imaginary part of the complex permittivity). The term is derived from the empirical

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[3] *Annual Book of ASTM Standards*, Vol 04.08.

[4] *Annual Book of ASTM Standards*, Vol 04.09.

relationship developed by describing the frequency-dependent behavior of dielectrics. The classical Debye formulation contains a term referred to as the relaxation time.

3.1.3.11 *diffusion*—the process by which the application of an external force (stimulus) results in a flux or movement of something (response). In electromagnetics, diffusion describes the movement of charges in response to an applied electric field or in response to an applied time-varying magnetic field. Diffusion is the low-frequency, high-loss, limiting behavior of electromagnetic wave propagation and is descriptive of behavior that decays rapidly (exponentially) with distance and time, generally to 1/*e* of the initial amplitude in ½π of a wavelength.

3.1.3.12 *dipole antenna*—a linear polarization antenna consisting of two wires fed at the middle by a balanced source (Balanis **(27)**).

3.1.3.13 *Fresnel zone*—the area of a target's surface that contains the portion of the incident wave that arrives at the receive antenna less than ½ of a cycle out-of-phase from earliest arriving reflected energy from the target. There are multiple Fresnel zones that form annular rings around the first Fresnel zone (Sheriff **(26)**).

3.1.3.14 *loss tangent*—There are three loss tangents: electric, magnetic, and electromagnetic. Each loss tangent is the ratio of the imaginary to the real parts or the lossy to the storage parts of the response to the stimulus in the force-flux stimulus-response equations. The electrical loss tangent is the ratio of the imaginary to the real part of the dielectric permittivity plus the electrical conductivity divided by radian frequency times the real part of the permittivity. It represents the cotangent of the phase between E and J (electric and current density). The magnetic loss tangent is the ratio of the imaginary to the real part of the complex magnetic permeability. It represents the cotangent of the phase angle between H and B (magnetic field and magnetic induction). The electromagnetic loss tangent is the ratio of the real to the imaginary parts of the complex propagation constant, and it represents the cotangent of the phase angle between E and H.

3.1.3.15 *magnetic permeability (µ)*—the property that describes the ability of a material to store magnetic energy by realignment of electron spin and motion. It relates ability of a material to be magnetized (magnetic polarization) in the magnetic induction, B, in response to the application of a magnetic field H, through $B=\mu H$. The units of magnetic permeability, µ, are Henry/metre. Relative magnetic permeability is the ratio of the permeability of a material to that of free space, $4\pi \times 10^{-7}$ H/m. It is commonly assumed that magnetic properties are those of free space. Whenever the magnetic permeability is greater than that of free space, it must be complex and lossy, with frequency dependence typically described by the Cole-Cole (Cole and Cole **(28)**) relaxation model. Nearly all magnetic properties are the result of the presence of iron in a variety of mineralogical forms (Olhoeft **(29)**). In some of the literature, magnetic susceptibility is used with a variety of units and normalizations (Hunt et al **(30)**).

3.1.3.16 *megahertz* (MHz)—a unit of frequency. One megahertz equals 10^6 Hz.

3.1.3.17 *monostatic*—(*1*) a survey method that utilizes a single antenna acting as both the transmitter and receiver of EM waves. (*2*) Two antennas, one transmitting and one receiving, that are separated by a small distance relative to the depth of interest are sometimes referred to as operating in "monostatic mode."

3.1.3.18 *nanosecond* (Ns) —a unit of time. One nanosecond equals 10^{-9} s; one billionth of a second.

3.1.3.19 *polarization*—(*1*) the storage of electrical or magnetic energy by the application of electric or magnetic fields to matter. (*2*) The orientation of the direction of the vector electromagnetic field is described by the polarization vector. Most GPR antennas are linearly polarized, though some are circularly polarized (Balanis **(27)**).

3.1.3.20 *propagation*—when sufficient energy storage is available compared to energy dissipation (loss) processes in a material, electromagnetic waves may propagate instead of exponential rapid decay (diffusion). Propagation is characterized by a decay in amplitude from the source to 1/*e* in several wavelengths, a distance called the skin depth or attenuation length.

3.1.3.21 *receiver*—the electronics that are connected to antenna that is excited by EM waves and converts the EM energy into voltages.

3.1.3.22 *relative permittivity (relative dielectric permittivity; sometimes called Dielectric constant)*—property of an electrical insulating material equal to the ratio of the capacitance of a capacitor filled with a given material to the capacitance of the identical capacitor filled with air. Earth materials are classified generally as conductors, semiconductors, and insulators (dielectrics). The relative permittivity is the ratio of the dielectric permittivity of a material to the permittivity of free space (or vacuum). The permittivity of free space is 8.85×10^{-12} F/m but the relative permittivity of free space is 1 (dimensionless ratio).

3.1.3.23 *scan*—the recording of EM energy over a selected time range for a fixed antenna position. Also referred to as a "trace."

3.1.3.24 *scattering*—the general term that describes the change in direction of electromagnetic wave propagation that occurs at a change in material properties over a short distance compared to a wavelength for an interval comparable to or greater than a wavelength. Scattering includes reflection (reverse change in direction), refraction (forward change in direction), and diffraction (caused by rapid changes that are small compared to a wavelength in both occurrence and interval).

3.1.3.25 *time gain*—also known as range gain control or time varying gain. It is the amplification applied to a trace as a function of time.

3.1.3.26 *transmit pulse*—the voltage impulse that excites the transmitting antenna.

3.1.3.27 *transmitter electronics*—the electronics that, after receiving a trigger pulse from the control unit, send the transmit signal to the transmitting antenna.

3.1.3.28 *travel time*—the time required for the radar signal to travel from the transmitting antenna to a target or receiving antenna.

3.1.3.29 *two-way travel time*—the time required for the radar signal to travel from the transmitting antenna to a scatterer and return to the receiving antenna.

4. Summary of Guide

4.1 *Summary of the Method*—The GPR equipment utilized for the measurement of subsurface conditions normally consists of a transmitter and receiver antenna, a radar control unit, and suitable data storage and display devices (Fig. 1).

4.1.1 A circuit within the radar control unit generates a train of trigger pulses that are sent to the transmitter and receiver electronics. The transmitter electronics produce output pulses that are radiated into the ground from the transmitting antenna.

4.1.2 The receiving antenna detects the EM waves that are reflected from interfaces at which the EM properties of the material(s) change. These signals are sent to the control unit for amplification. As the antenna(s) are moved along a survey line, a series of scans is collected and positioned side by side to form a profile of the subsurface (Fig. 2).

4.1.3 Because the in situ properties of soil, rock, and water vary greatly, and the radar penetration depth is dependent upon these properties, the depth of penetration can range from less than one metre to greater than 30 metres. In certain conditions such as in thick polar ice or salt deposits, penetration depth can be as great as 500 m.

4.2 *Complementary Data*—Geologic data obtained from other complementary surface geophysical methods (Guide D 6429), borehole geophysical methods (Guide D 5753), and non-geophysical methods may be necessary to help interpret and assess subsurface conditions. The most important complementary data are the location of the antenna and its orientation. The single largest error in any kind of geophysical interpretation, especially radar, is not knowing where the antenna was when the data were taken (for example, location surveying data).

5. Significance and Use

5.1 *Concepts*—This guide summarizes the equipment, field procedures, and data processing methods used to interpret geologic conditions, and to identify and provide locations of geologic anomalies and man-made objects with the GPR method. The GPR uses high-frequency-pulsed EM waves (from 10 to 3000 MHz) to acquire subsurface information. Energy is propagated downward into the ground from a transmitting antenna and is reflected back to a receiving antenna from subsurface boundaries between media possessing different EM properties. The reflected signals are recorded to produce a scan or trace of radar data. Typically, scans obtained as the antenna(s) are moved over the ground surface are placed side by side to produce a radar profile.

5.1.1 The vertical scale of the radar profile is in units of two-way travel time, the time it takes for an EM wave to travel down to a reflector and back to the surface. The travel time may be converted to depth by relating it to on-site measurements or assumptions about the velocity of the radar waves in the subsurface materials.

5.1.2 Vertical variations in propagation velocity due to changing EM properties of the subsurface can make it difficult to apply a linear time scale to the radar profile (Ulriksen **(31)**).

5.2 *Parameter Being Measured and Representative Values*:

5.2.1 *Two-Way Travel Time and Velocity*—A GPR trace is the record of the amplitude of EM energy that has been

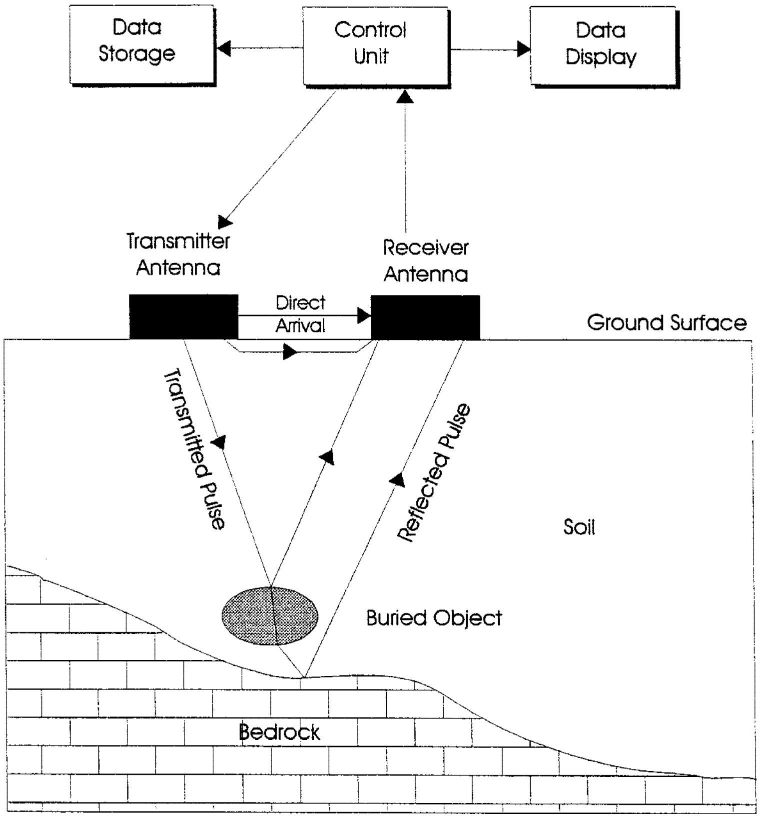


FIG. 1 Schematic Diagram of a Ground-Penetrating Radar System

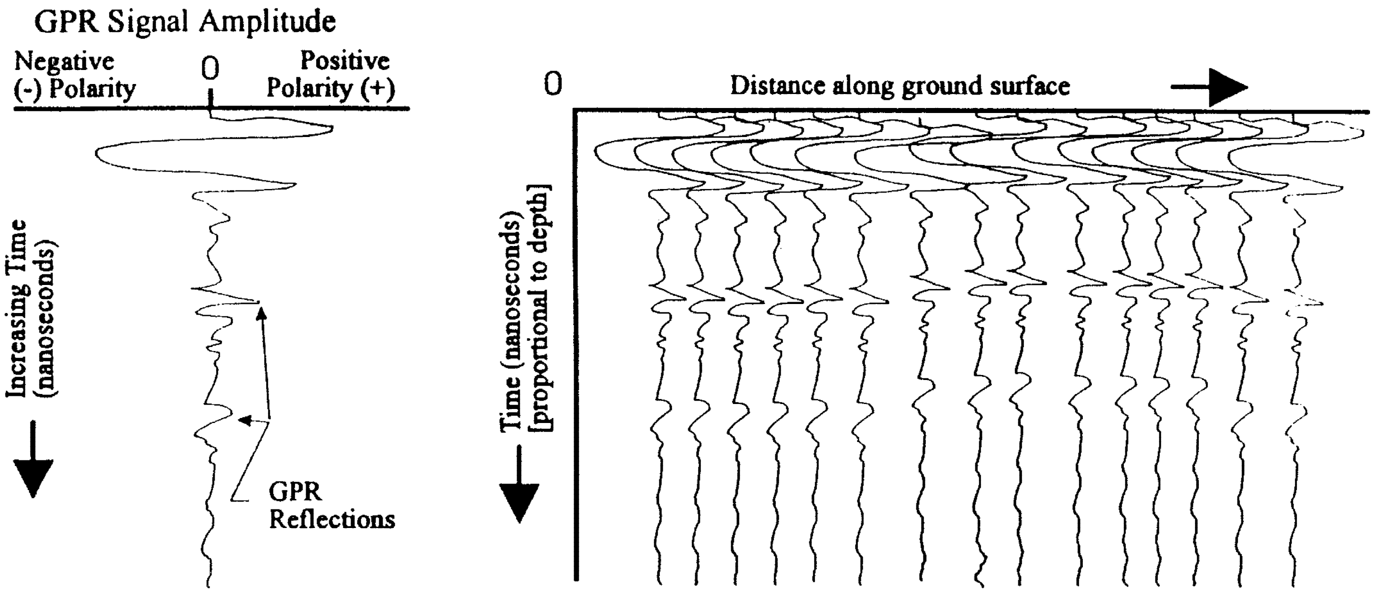


FIG. 2 Schematic Diagram Showing a Typical GPR Trace, and a Series of GPR Traces Collected at Specific Distances to Form a GPR Profile Line or Cross Section

reflected from interfaces between materials possessing different EM properties and recorded as a function of two-way travel time. To convert two-way times to depths, it is necessary to estimate or determine the propagation velocity of the EM pulses. The relative permittivity of the material (ϵ_r) through which the EM pulse propagates mostly determines the propagation velocity of the EM wave. The propagation velocity through the material is approximated using the following relationship (see full formula in Balanis **(32)**):

$$V_m = c/\sqrt{\epsilon_r} \tag{1}$$

where:

c = propagation velocity in free space (3×10^8m/s),
V_m = propagation velocity through the material, and
ϵ_r = relative permittivity.

It is assumed that the magnetic permeability is that of free space and the loss tangent is much less than 1.

5.2.1.1 Table 1 lists the relative permittivities (ϵ_r) *and radar propagation velocities for various materials. Relative permittivity values range from 1 for air to 81 for fresh water. For unsaturated earth materials,* ϵ_r *ranges from 3 to 15. Note that a small change in the water content of earth materials results in a significant change in the relative permittivity. For water-saturated earth material,* ϵ_r *can range from 8 to 30. These values are representative, but may vary considerably with temperature, frequency, density, water content, salinity, and other conditions.*

5.2.1.2 If the relative permittivity is unknown, as is normally the case, it may be necessary to estimate velocity or use a reflector of known depth to calculate the velocity. The propagation velocity, V_m, is calculated from the relationship as follows:

$$V_m = (2D)/t \tag{2}$$

where:

D = measured depth to reflecting interface, and
t = two-way travel time of an EM pulse.

TABLE 1 Approximate Electromagnetic Properties of Various Materials

NOTE 1—
d = function of density,
w = function of porosity and water content,
f = function of frequency,
t = function of temperature
s = function of salinity, and
p = function of pressure.

Material	Relative Permittivity, K	Pulse Velocities, m/Ns	Conductivity, mS/m
Air	1	0.3	0
Fresh water (f,t)	81	0.033	0.10 - 30
Sea water (f,t,s)	70	0.033	400
Sand (dry) (d)	4-6	0.15-0.12	0.0001 - 1
Sand (saturated) (d,w,f)	25	0.055	0.1 - 1
Silt (saturated) (d,w,f)	10	0.095	1 - 10
Clay (saturated) (d,w,f)	8-12	0.106-0.087	100 - 1000
Dry sandy coastal land (d)	10	0.095	2
Fresh water ice (f,t)	4	0.15	0.1 - 10
Permafrost (f,t,p)	4-8	0.15-0.106	0.01 - 10
Granite (dry)	5	0.134	0.00001
Limestone (dry)	7-9	0.113-0.1	0.000001
Dolomite	6-8	0.122-0.106	
Quartz	4	0.15	
Coal (d,w,f, ash content)	4-5	0.15-0.134	
Concrete (w,f, age)	5-10	0.134-0.095	
Asphalt	3-5	0.173-0.134	
Sea ice (s,f,t)	4-12	0.15-0.087	
PVC, epoxy, polyesters vinyls, rubber (f,t)	3	0.173	

5.2.1.3 Methods for measuring velocity in the field are found in 6.7.3. Note that measured velocities may only be valid at the location where they are measured under specific soil conditions. If there is lateral variability in soil and rock composition and moisture content, velocity may need to be determined at several locations.

5.2.2 *Attenuation*—The depth of penetration is determined primarily 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. Conductivity is primarily governed by the water content of the material and the concentration of free ions in solution (salinity). Attenuation also occurs due to scattering of the EM energy in unwanted directions by inhomogeneities in the subsurface. If the scale of inhomogeneity is comparable to the wavelength of EM energy, scattering may be significant (Olhoeft **(33)**). Other factors that affect attenuation include soil type, temperature (Morey **(34)**), and clay mineralogy (Doolittle **(35)**). Environments not conducive to using the radar method include high conductivity soils, sediments saturated with salt water or highly conductive fluids, and metal.

5.3 *Equipment*—The GPR equipment utilized for the measurement of subsurface conditions normally consists of a transmitter and receiver antenna, a radar control unit, and suitable data storage and display devices.

5.3.1 *Radar Control Unit*—The radar control unit synchronizes signals to the transmitting and receiving electronics in the antennas. The synchronizing signals control the transmitter and sampling receiver electronics located in the antenna(s) in order to generate a sampled waveform of the reflected radar pulses. These waveforms may be filtered and amplified and are transmitted along with timing signals to the display and recording devices.

5.3.2 Real-time signal processing for improvement of signal-to-noise ratio is available in most GPR systems. When working in areas with cultural noise and in materials causing signal attenuation, time varying gain is necessary to adjust signal amplitudes for display on monitors or plotting devices. Filters may be used in real time to improve signal quality. The summing of radar signals (stacking) is used to increase effective depth of exploration by improving the signal-to-noise ratio.

5.3.3 *Data Display*—The GPR data are displayed as a continuous profile of individual radar traces (Fig. 2). The horizontal-axis represents horizontal traverse distance and the vertical-axis is two-way travel time (or depth). Data are commonly presented in wiggle trace display, where the intensity of the received wave at an instant in time is proportional to the amplitude of the trace (see Fig. 2), or as a gray scale of color scale display, where the intensity of the received wave at an instant in time is proportional to either the intensity of gray scale (that is, black is high intensity, and white is low intensity; see Fig. 3) or to some color assignment defined according to a specified color-signal amplitude relationship.

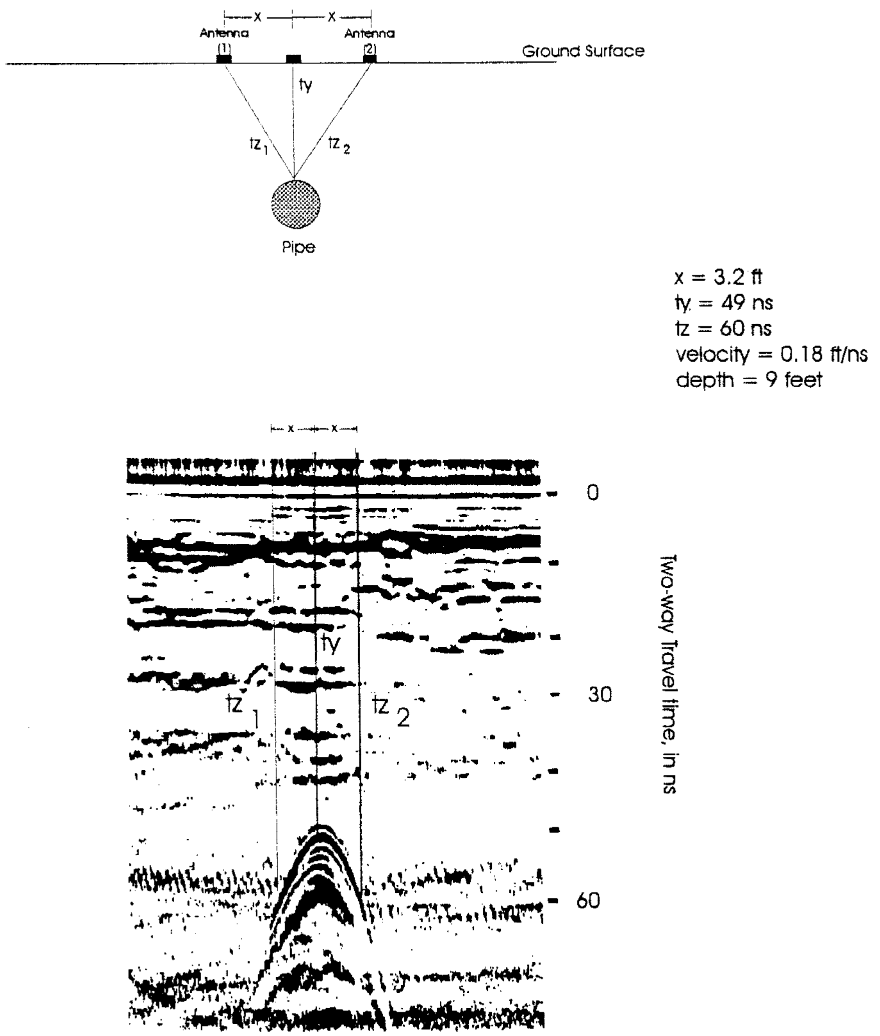


FIG. 3 Generalized Diagram of a Pipe Signature: GPR Record (300 MHz) Showing a Hyperbola from a Buried Pipe, and Computation of Depth and Velocity from that Target (see 8.4.1.2.2.2)

5.3.4 *Antennas and Control Cables*—The antennas used to transmit and receive radar signals are generally electric dipoles. A single-dipole antenna can be used to both transmit and receive signals in the monostatic mode. The bi-static mode uses separate antennas for transmitting and receiving. These antennas can be housed in a single enclosure where the distance between the two antennas are fixed, or in separate enclosures where the distance between the two antennas can be varied. The ability to vary the distance between the two antennas is helpful in optimizing the survey design for specific types of target detection.

5.3.4.1 Electromagnetic waves are three-dimensional vector fields where the orientation of the fields is described by the vector direction or polarization of the electrical and magnetic fields. Changing the polarization of a linearly polarized electric dipole antenna can cause maximum or minimum coupling to a scattering object. For example, alignment of the electric field axis (the long length of a dipole antenna) parallel to a pipe or wire will maximize the response of the pipe as a reflector scatterer, while a perpendicular alignment will minimize the pipe response. Typically, two antenna systems use the same orientation and polarization for both antennas, but sometimes the receive antenna will be oriented with its electric field perpendicular (orthogonal) to the transmit antenna, resulting in insensitivity to reflection from horizontal layers and linear features (like pipes) that are aligned to either antenna, but high sensitivity to off-alignment pipes.

5.3.4.2 Antennas are manufactured both with and without shielding (metal or high radar absorption material). Shielding reduces energy radiation from the sides and top of the antenna, which in turn reduces reflections from surface and above-ground targets. Low-frequency antennas (less than 100 MHz) are rarely shielded, whereas most high-frequency antennas are shielded.

5.3.4.3 The center frequency of commercially available antennas ranges from 10 to 3000 MHz. These antennas generate pulses which typically have 2 to 3 octaves of bandwidth. In general, lower-frequency antennas provide an increase in depth of penetration but have less resolution than higher-frequency antennas.

5.3.4.4 The selection of antenna frequency depends on the depth of penetration, spatial resolution, and system portability required for the study.

5.4 *Limitations and Interferences*:

5.4.1 *General Limitations Inherent to Geophysical Methods*:

5.4.1.1 A fundamental limitation of all geophysical methods lies in the fact that a given set of data cannot always be associated with a unique set of subsurface conditions. In most situations, surface geophysical measurements alone cannot resolve all ambiguities, and some additional information is required. Because of this inherent limitation in the geophysical methods, a GPR survey alone can not be considered a complete assessment of subsurface conditions. Properly integrated with other sources of knowledge or geophysical methods, GPR can be a highly effective, accurate, and cost-effective method of obtaining subsurface information.

5.4.1.2 In addition, all surface geophysical methods are inherently limited by decreasing resolution with depth.

5.4.2 *Limitations Specific to the GPR Method*:

5.4.2.1 The GPR method is site specific in its performance (depth of penetration and resolution), depending upon surface and subsurface conditions. Radar penetration of more than 30 m has been reported in geologic settings of water saturated sands (Morey **(34)**; Beres and Haeni **(2)**, Smith and Jol **(37)**, Wright et al **(1)**), 300 m in granite, 2000 m in dry salt (Unterberger **(38)**), and 5400 m in ice (Wright et al **(22)**). More commonly, penetration is on the order of 1 to 10 m. Limitations are discussed in the following section.

5.4.2.2 *Material Properties Contrast*—Reflection coefficients quantify the amplitude of reflected and transmitted signals at boundaries between materials. Reflection coefficients depend on the angle of incidence, the polarization of the incident field, and the EM property contrast. In addition to having sufficient velocity contrast, the boundary between the two materials needs to be sharp. For instance, it is more difficult to see a water table in fine-grained materials than in coarse-grained materials because of the different relative thicknesses of the capillary fringe for the same contrast.

5.4.2.3 *Attenuation*—Radar signal attenuation is caused by the effect of electrical conductivity, dielectric and magnetic relaxation, scattering, and geometric spreading losses (Olhoeft **(33)**).

(1) Electrical Conductivity Losses—Electrically conductive materials such as many mineralogic clays and free ions in solution attenuate the radar signal by converting EM energy to thermal energy (Olhoeft **33)**).

(2) Dielectric Relaxation Losses—Radar signals can also be attenuated by dielectric relaxation losses due to the rotational polarization of the liquid water molecule and chemical charge transfer processes on the surface of clay minerals. Attenuation due to dielectric relaxation losses arises from the conversion of EM energy to thermal energy (Olhoeft **(33)**).

(3) Geometric Scattering Losses—Scattering may be a dominant factor in signal attenuation when inhomogeneities in materials with grain sizes in the order of a radar wavelength (Table 2) are present (Olhoeft **(33)**).

5.4.2.4 *Polarization*—The type and alignment of polarization of the vector electromagnetic fields may be important in receiving responses from various scatterers. Two linear, parallel polarized, electric field antennas can maximize the response from linear scatters like pipes when the electric field (typically long axis of the dipole antenna) is aligned parallel with the pipe and towed perpendicular across the pipe. Similarly, alignment with the rebar in concrete will maximize the ability to map the rebar, but alignment perpendicular to the rebar will minimize scattering reflections from the rebar to see through or past the rebar to get the thickness of concrete. Similar arrangement may be made for overhead wires and nearby fences. Cross-polarized antennas (perpendicular to each other) minimize the response from horizontal layers.

TABLE 2 Radar Wavelengths (metres) for Various Antenna Frequencies (f) and Relative Permittivities (ϵ_r)

ϵ_r f	1	5	10	15	25	80
25 MHz	12.0	5.36	3.8	3.08	2.4	1.36
50 MHz	6.0	2.68	1.88	1.56	1.2	0.68
80 MHz	3.76	1.68	1.20	0.96	0.76	0.40
100 MHz	3.0	1.36	0.96	0.76	0.6	0.32
200 MHz	1.52	0.68	0.48	0.40	0.32	0.16
300 MHz	1.0	0.44	0.32	0.24	0.20	0.12
500 MHz	0.6	0.28	0.20	0.16	0.12	0.08
900 MHz	0.32	0.16	0.12	0.08	0.08	0.04

5.4.3 *Interferences Caused by Ambient, Geologic, and Cultural Conditions*:

5.4.3.1 Measurements obtained by the GPR method may contain unwanted signals (noise) caused by geologic and cultural factors.

5.4.3.2 *Ambient and Geologic Sources of Noise*—Boulders, animal burrows, tree roots, or other inhomogeneities can cause unwanted reflections or scattering of the radar waves. Lateral and vertical variations in EM properties can also be a source of noise.

5.4.3.3 *Cultural Sources of Noise*—Aboveground cultural sources of noise include reflections from nearby vehicles, buildings, fences, power lines, lampposts, and trees. In cases where this kind of interference is present in the data, a shielded antenna may be used to reduce the noise.

(1) Scrap metal at or near the surface can cause interference or ringing in the radar data. The presence of buried structures such as foundations, reinforcement bars (rebar), cables, pipes, tanks, drums, and tunnels under or near the survey line may also cause unwanted reflections (clutter).

(2) In some cases, EM transmissions from nearby cellular telephones, two-way radios, television, and radio and microwave transmitters may induce noise on the radar record.

(3) Other Sources of Noise—Other sources of noise can be caused by the EM coupling of the antenna with the earth and decoupling of the antenna to the ground due to rough terrain, heavy vegetation, water on the ground surface, or other changes in surface conditions.

5.4.3.4 *Summary*—All possible sources of noise present during a survey should be noted so that their effects can be considered when processing and interpreting the data.

5.4.4 *Alternate Methods*—The limitations previously discussed may prohibit the effective use of the GPR method, and other methods or non-geophysical methods may be required to resolve the problem (see Guide D 6429).

6. Procedure

6.1 *Qualification of Personnel*—The success of a radar survey, as with most geophysical techniques, is dependent upon many factors. One of the most important is the competency of the person(s) responsible for planning, carrying out the survey, and interpreting the data. An understanding of the theory, field procedures, and methods for interpretation of GPR data along with an understanding of the site geology are necessary to successfully complete a GPR survey. Personnel not having specialized training and experience should be cautious about using this technique and solicit assistance from qualified practitioners.

6.2 *Planning the Survey*—Successful use of subsurface GPR measurements depends to a great extent on proper planning. Without careful and detailed planning, the GPR method may not yield data significant to interpret.

6.2.1 *Objectives of the GPR Survey*:

6.2.1.1 Planning and design of a GPR survey should be done with due consideration to the objectives of the survey and the characteristics of the site, because they will determine the equipment to be used, level of interpretation, and the level of effort and budget necessary to achieve the desired results. Factors that need to be considered include geology, depth of investigation, geometry of the target, EM properties of the target and of the host material, topography, and access to the site. The presence of sources of noise (natural or cultural) as well as operational constraints must also be considered. It is good practice to obtain as much of the relevant information as possible about the site (soil type, electrical conductivity, and depth to water table) prior to mobilization to the field, including data from any previous GPR or electrical resistivity work, boring logs, geophysical logs in the study area, and a site map or aerial photo.

6.2.1.2 The purpose of the radar survey may be for reconnaissance of subsurface conditions or detailed subsurface investigations. In reconnaissance surveys, the spacing between radar lines is large, few transects are used, and elevations are obtained from topographic maps or by hand-held readings from the field. In a detailed survey where the targets are small, the spacing between radar transects are small and elevations and locations of points along the radar lines are accurately determined.

6.2.2 *Assess Depth of Penetration*:

6.2.2.1 Another critical element in planning a GPR survey is the determination of whether or not the target is within the anticipated penetration depth irrespective of any unusual target characteristics.

6.2.2.2 The penetration depth of a radar signal is determined primarily by attenuation caused by the sum of electrical conductivity, dielectric relaxation, scattering, and geometric spreading losses as well as the dynamic range of the radar system (Olhoeft **(33)**), and sources of noise. Electrical conductivity is controlled by the water content, the concentration of ions in solution, and the mineralogic (that is, montmorillonite) clay present. An engineering size fraction clay (“rock flour”) is not a problem for GPR since it does not produce relaxation losses, as do mineralogical clays.

6.2.3 *Assess EM Property Contrast*:

6.2.3.1 One of the most critical elements in planning a GPR survey is the determination of whether or not there is an adequate property contrast between geologic units or buried objects of interest. Assuming that no previous GPR surveys have been made in the area, one is forced to rely on knowledge of the geology, published and unpublished references containing radar velocities, relative permittivities, and magnetic permittivities of earth materials and reports of GPR studies done in similar hydrogeologic settings (see Table 1).

6.2.3.2 A simple model of the subsurface EM properties at the site may be useful. By using this geoelectric model and forward modeling methods (Powers et al **(39)**), the applicability of the GPR method may be assessed.

6.2.3.3 One method of estimating whether there is a sufficient contrast in electrical properties is to use the expression for power reflectivity :

$$Pr = ((\sqrt{\epsilon_r \text{ Host}} - \sqrt{\epsilon_r \text{ Target}}) / (\sqrt{\epsilon_r \text{ Host}} + \sqrt{\epsilon_r \text{ Target}}))^2 \tag{3}$$

where ϵ_r= relative permittivity.

6.2.4 Two conservative estimates for predicting whether a target can be detected are as follows:

6.2.4.1 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 ϵ_r Target $\rightarrow\infty$ in the above equation)

6.2.4.2 Second, the ratio of the target depth to smallest lateral target dimension should not exceed 10:1.

6.3 *Selection of the Approach*:

6.3.1 The objective of the study determines the specific mode of operation for the radar study. Two modes of operation are normally used in conducting radar surveys, and both are referred to as the reflection profiling method (Fig. 4).

6.3.1.1 In the first mode, data are acquired as the antenna(s) are towed along the survey line.

6.3.1.2 In the other mode, the radar data are collected at specific points along the survey line both with fixed transmitter/receiver separation.

6.3.1.3 A third less commonly used method is to collect common midpoint (CMP) data at points along the profile (varying transmitter-receiver separation). A three-dimensional perspective view can be constructed by obtaining data on a grid. The choice of operational mode depends upon the characteristics of the target, the field conditions, and purpose of the study.

6.4 *Survey Design*:

6.4.1 *Location of Survey Lines*—It is preferable to have an on-site visit to help design the site survey. If this is not possible, preliminary location of survey lines can be done with the aid of topographic maps and aerial photos. The degree of accuracy of the location and elevation of transect positions varies with the objective of the survey. The datum for GPR data is the ground surface. In areas where significant changes in elevation occur, elevations along the survey lines should be obtained. In addition to the preceding, consideration should be given to:

6.4.1.1 Need for data at a given location,

6.4.1.2 Accessibility of the area,

6.4.1.3 Proximity of wells or test holes for control data, and

6.4.1.4 Extent, location, and impact of any surface features such as concrete, buried structures and utilities, and other

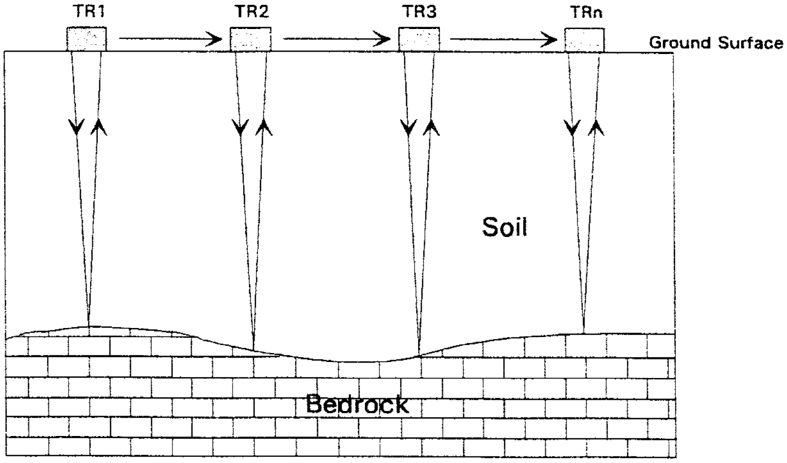


FIG. 4 Schematic Diagram of the Reflection Profiling Method

sources of cultural noise that prevent measurements from being made.

6.4.2 *Coverage*—The area of survey should be larger than the area of interest so that measurements are taken in both "background" conditions and over the area of interest. Survey lines should be laid out over the site. The issue of whether lines will be run perpendicular to one another or parallel to one another should be considered. The survey lines should be oriented perpendicular to any linear feature (buried channel, pipeline, tank, trenches, faults, and fractures) that is expected. Line spacing should be adjusted according to the size of the target. In special cases, consideration of the antenna polarization (orientation) may be needed to optimize or minimize reflections from subsurface targets.

6.5 *Survey Implementation*:

6.5.1 *On-site Check of the Plan*—A systematic visual inspection of the site should be made upon arrival to determine if the plan developed is reasonable. At this point, modifications to the field plan may be required.

6.5.1.1 Often a set of initial GPR measurements is made to confirm whether adequate radar depth of penetration exists. The initial measurement(s) also can be used to assess the signal-to-noise ratio of the site relative to the various antenna frequencies. On-site assessment of initial results may result in changes to the survey plan. Assess the need for antenna shielding and penetration depth. Set range, gains, and filters. Record a trial transect along a test line that is representative of average site conditions to evaluate the system set up parameters and make necessary changes. Generally, it is good practice to establish radar system control settings and then maintain these settings throughout a given line or area depending upon site conditions and survey objectives. However, sometimes one set of control settings is inadequate, such as at a survey site partially covered by two different materials (that is, bare soil and asphalt) where antenna coupling might change enough to require two different settings (and two different surveys). If site conditions change, additional duplicate surveys may need to be run with different radar system control settings.

6.5.2 *Survey Lines*—When laying out survey lines, the following should be considered:

6.5.2.1 Lay out the survey lines in a straight line if possible.

6.5.2.2 Place station marks at equal intervals along the survey line using survey flags and tape, measuring wheel, electronic measuring device, global positioning system, or other location system.

6.5.2.3 Note the distances so that corrections can be made to the data.

6.5.2.4 The survey lines should be referred to a permanent location so the grid can be revisited at a later date if necessary.

6.6 *Quality Control (QC)*—Quality-control practices are applicable to the field procedures, processing, and interpretation phases of the work. Quality-control procedures require that reasonable guidelines are followed and appropriate documentation of the survey is made.

6.6.1 The following items are used to provide QC of field operations:

6.6.1.1 Run a test line to establish system settings and record all system settings and parameters.

6.6.1.2 Maintain a field log that records the equipment, system settings, and field operational procedures used for the project.

6.6.1.3 Document any changes to the planned field procedures.

6.6.1.4 Record any changes in GPR control settings that are made, and the locations in the survey where they were made.

6.6.1.5 Document any conditions (weather conditions and natural and cultural noise) that could impact survey results.

6.6.1.6 Note any problems with the equipment, what steps were taken to correct the problem, and how the problem could affect the data.

6.6.1.7 Review data as soon as possible, if the data are being recorded (by a computer or digital-acquisition system) with no visible means of observing the data.

6.6.1.8 Rerun test line(s) as needed to confirm that the system is running properly.

6.6.2 *Calibration and Standardization*—In general, the manufacturer's recommendation is followed for calibration and standardization. Conduct an operational check of equipment before each project and before starting fieldwork each day. A routine check of equipment should be made on a periodic basis and after each problem.

6.7 *Interpretation of Ground Penetrating Radar Data*:

6.7.1 The level of effort involved in the interpretation depends upon the objectives of the survey and the detail desired.

6.7.1.1 A problem inherent in all geophysical studies is the nonunique correlation between possible geologic models and a single set of field data. This ambiguity can only be resolved through the use of geologic, geophysical, and other available information along with the experience of the interpreter.

6.7.1.2 Preliminary interpretation of field data should be labeled as draft or preliminary because it is easy to make errors in an initial field interpretation and a preliminary analysis is never a complete and thorough interpretation. Preliminary analysis in the field is done mostly as a means of QC.

6.7.2 *Methods of Converting Travel Time to Depth*:

6.7.2.1 *Travel Time*—Determining the travel time to a horizon or target involves measuring the travel time on the GPR record from time zero to the reflector. This measurement is the two-way travel time from the surface to the reflector and back to the surface. The point of zero time, that is, the time at which the transmit pulse starts to radiate into the ground, is established several ways. For GPR systems with a monostatic antenna configuration, the zero crossing (polarity) of the transmitted radar signal can be used. Another way to set the zero-time position for a given antenna is to make measurements against a metal surface located at several different distances from the antenna. Then, by regression, the zero-time position is determined (Ulriksen **(31)**). For bistatic antenna configurations, zero time must be measured in the field. In this case, zero time is determined by conducting common midpoint (CMP) or wide angle reflection (WAR) soundings, and projecting the air and ground waves on the time versus antenna separation graph back to their intersection at zero time. A consistent approach to picking the time intervals must be applied to minimize errors.

6.7.2.2 *Compute the Depth*—Compute the depth (*D*) to a reflector, it is necessary to know the velocity (*V*) of the EM waves within the material(s). The reflection times recorded on a GPR record are the two-way travel times, where depth = two-way travel time × velocity / 2.

6.7.2.3 *Velocities*—Velocities can be estimated, calculated, or measured using the following techniques. If there is significant lateral variability in the soil EM properties moisture content in the subsurface, or both, the velocity may only be valid at the single point of calibration.

(1) Estimated Approach—If the velocity of the EM wave in the material is not known, it can be sufficient to estimate the velocity based on the material type present. Table 1 gives estimated velocities and relative dielectric permittivities for various materials.

(2) Measured Approach—There are three ways to measure EM wave velocities: velocity sounding, hyperbolic geometry, and the depth to the known reflector methods.

(2a) Velocity Sounding—The velocity sounding method uses two separate antennas (one for transmitting and one for receiving) over a horizontal subsurface interface. The antennas are sequentially moved away from their original positions and in the opposite directions at known distance increments. This method results in a measurement of reflection times over known distances through the medium of unknown velocity. With knowledge of the zero offset ($x = 0$), travel time and the travel times observed for several antenna positions at known separation distances the effective propagation velocity in the medium is given by:

$$V_m = x / \sqrt{(t_x^2 - t_d^2)} \tag{4}$$

where:

x = horizontal distance between the transmitting and receiving antennas,
t_x = two-way travel time of a reflection from an interface at x antenna separation, and
t_d = two-way travel time to the reflecting interface when $x = 0$.

There are two modes of operation for conducting velocity soundings. In the common midpoint (CMP) sounding (Fig. 5), both the antennas are moved equidistant from a fixed location. In a wide-angle reflection (WAR) sounding (Fig. 6), one antenna is held fixed while the other is moved away. The WAR sounding is only valid when the subsurface reflector is flat.

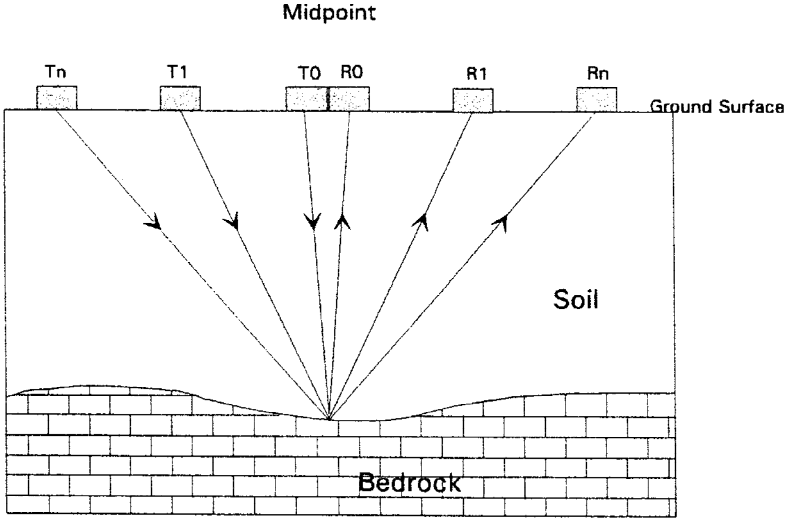


FIG. 5 Schematic Diagram of a Common Midpoint (CMP) Sounding

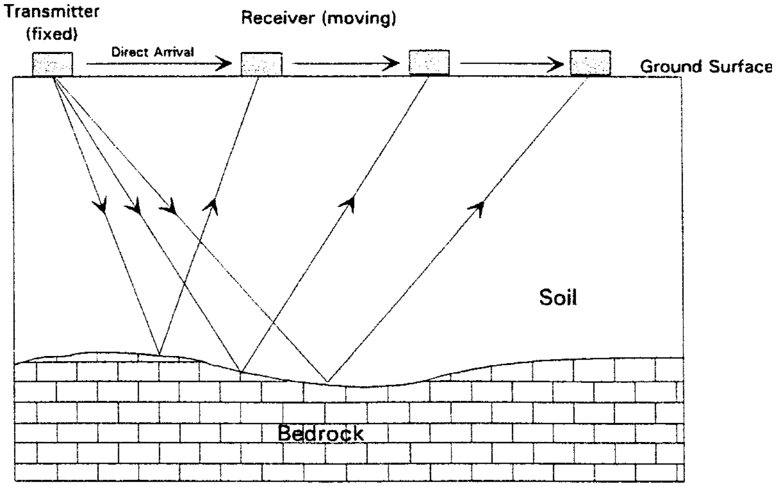


FIG. 6 Schematic Diagram Showing a Wide Angle Reflection Sounding

(2b) Hyperbolic Geometry-Hyperbolic geometry uses reflections from point reflectors (targets) such as pipes, tanks, or boulders that result in a hyperbolic pattern on the radar record. Fig. 3 illustrates a hyperbolic pipe signature from a buried pipe. This information can be used to find the depth to the pipe when a distance along the ground (x) is known and two-way travel time (t_z and t_y) to an object, which is scaled from the data.

$$\text{Depth} = x / \sqrt{((t_z/t_y)^2 - 1)} \text{ and } v = (2/t_y)\,(x / (\sqrt{((t_z/t_y)^2 - 1)})) \tag{5}$$

where:
x = distance along ground,
t_z = two-way travel time or “slant range” to pipe, ns,
t_y = two-way travel time to pipe when antenna is directly over pipe, ns, and
v = velocity in m (ft)/ns.

(*1*) An example of these computations on field data from a 300-MHz antenna is shown in Fig. 3. The modeling program by Powers and Olhoeft **(39)** can be used to accomplish this, as well as several commercial processing packages.

(*2c*) *Known Depth to Reflector*-Another way to determine the velocity at a given point at a site is to use the travel time to a reflector of known depth. Reflectors can include utilities, tanks, the water table in coarse-grained soils, clay layers, or other geologic reflectors that have a known depth at the site. Using the travel time from the GPR record and the known reflector depth, the average velocity of the radar signal can be determined from the formula:

$$V = d/t \tag{6}$$

where t = ½ total time and the antenna(s) are directly over the known target.

6.8 *Interpretation of Results*:

6.8.1 Interpretation of radar data may involve some or all of the following steps depending upon the purpose of the survey

6.8.2 *Recognition of Noise*—Continuous horizontal signals (banding) throughout a GPR record are generally indicative of coherent system noise, and may be indicative of a system malfunction or an unusually flat stratum. Such banding may also be the result of antenna ringing from poor coupling to the ground. Reflections from building foundations, bridge supports, trees, or overhead objects may also cause errors in interpretation if these are not accounted for in the interpretation of the survey.

6.8.3 *Point Reflectors*—Point reflectors are identified by their characteristic hyperbolic shapes (Fig. 3). Typical point reflectors in the subsurface include pipes, drums, tanks, old foundations, graves, boulders, cavities, fractures, faults, and vertical geologic structures. Hyperbolas in radar records can also be from tree limbs and powerlines overhead and trees and buildings off to the side, but these can be recognized by the hyperbola being broader than those underground and fitting a velocity for the speed of light in air (relative permittivity = 1 and velocity = 0.3 m/s).

6.8.4 *Lateral Changes*—Lateral changes in amplitude, phase, or reflection patterns in the radar record can be caused by changes in rock or soil type, moisture content, the presence of contaminants and other human artifacts.

6.8.5 *Integrating Information for Multiple Lines*—In some cases, information from a single GPR survey line transect is sufficient to meet the objective of the survey. Radar data collection from multiple transects is needed to fully map a subsurface anomaly. If two-way travel times are converted to depth, contour maps of the tops of various reflectors (interpreted as a subsurface layer) can be generated much as can be done with seismic reflection data (Annan, 1993). When GPR data are collected on closely spaced two-dimensional lines (1 to 3 ft), these data can be used to generate three-dimensional perspective views of radar data (Daniels et al **(40)**; Knoll and Haeni, **(41)**); and fence diagrams (Olhoeft **(42, 43)**).

6.8.6 All other available information about the site should be used when interpreting the radar data. This information can include site maps, aerial photos, soil survey reports, well logs, geotechnical, geologic and hydrogeologic reports, and geologic information.

6.9 *Data Processing*:

6.9.1 For most surveys, interpretation of the radar record is accomplished without processing of the data.

6.9.2 *Filtering*—Filtering of radar data is used in an attempt to remove unwanted noise and correctly position reflectors on the radar record. Filtering processes include, but are not limited to, stacking, deconvolution, finite and infinite impulse filters, Hilbert transforms, migration, and spectrum transforms (Yilmaz **(44)** and Fisher et al **(45)**). Care must be used when processing radar data because artifacts can be inadvertently introduced into the data. Commercial programs for processing radar data are available from equipment manufacturers and software vendors.

6.9.2.1 A variety of filtering methods may be used to remove or minimize noise in GPR data.

6.9.2.2 Ringing from poor antenna-ground coupling may be removed by an average of all scans in the data set being subtracted from each scan (background removal).

6.9.2.3 Radio frequency interference from cellular telephones and other nearby radio transmitters may be removed with a medium gradient filter (Olhoeft **(29)**).

6.9.3 Variations in surface elevation can have a major impact on radar data. The standard process for topographic correction is to apply a static time shift to each radar trace before plotting (Fig. 7). The time shift is a product of elevation change and knowledge of near-surface wave velocity. Most interpretation programs accomplish this if altitude and position of the antennas are recorded, and if the velocity of the near surface can be estimated or measured.

6.9.4 Since it is impossible to tow a radar antenna at a constant speed, the data on the resulting record section are not spaced at even distance increments. Rubber sheeting (rubber

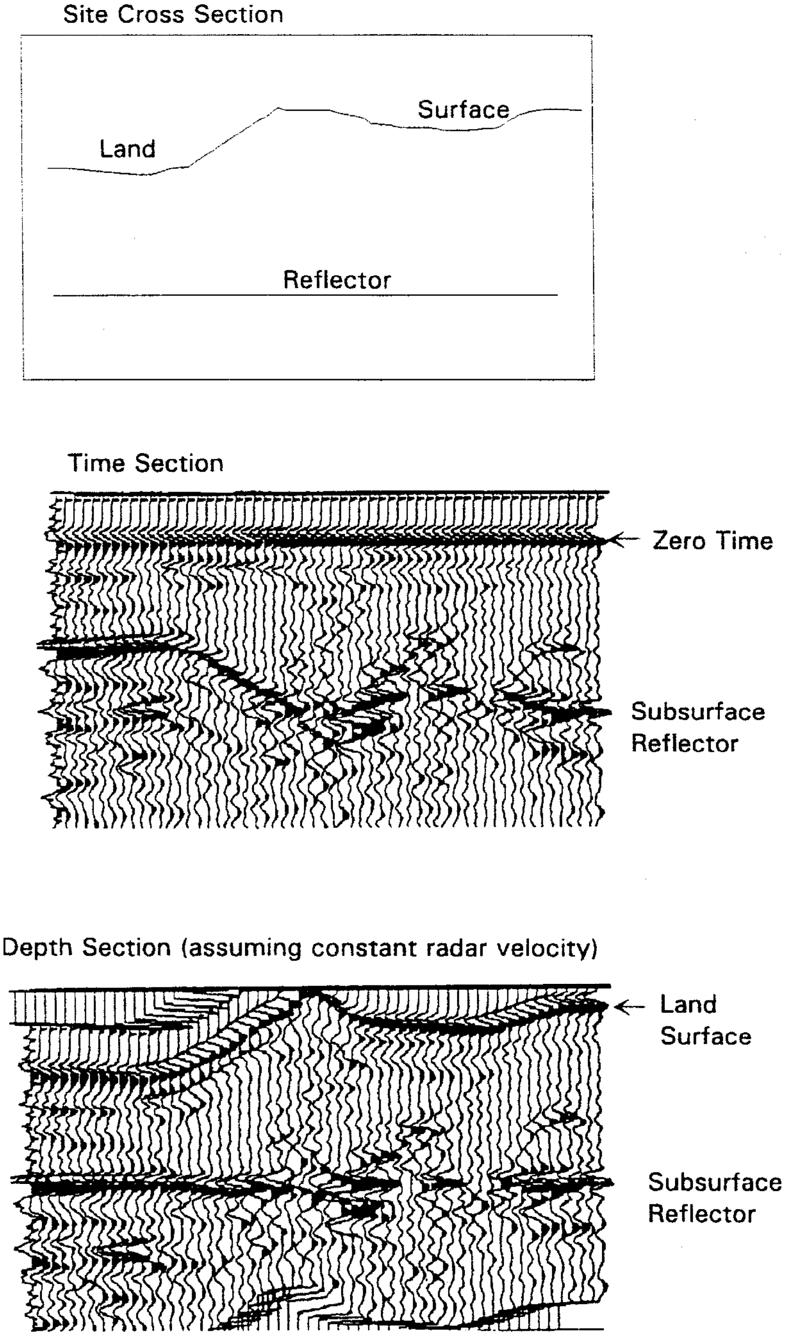


FIG. 7 Illustration of the Effect of Elevation Changes on GPR Data (Modified from Geophysical Survey Systems, Inc., 1992, not to scale)

banding) is the process of stretching or compressing the radar record horizontally so that the data are spaced at even distance increments. The "before" and "after" process of rubber sheeting is illustrated in Fig. 8. Generally, rubber sheeting compression is achieved by removing scans, while rubber sheeting stretching is achieved by inserting duplicate adjacent scans or interpolating scans to expand the record (Bochiccio **(46)**).

7. Report

7.1 The following is a list of the key items that should be contained within most formal reports. In some cases, there is no need for an extensive formal report.

7.2 Report the following information:

7.2.1 Purpose and scope of the GPR survey,

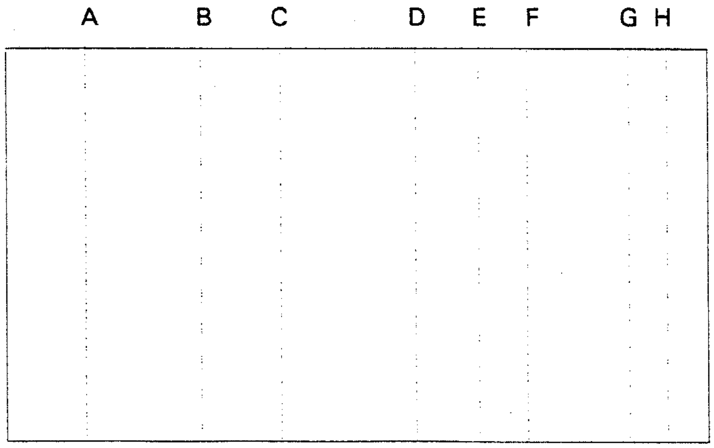
7.2.2 Geologic setting,

7.2.3 Limitations of the GPR survey (sources of noise, interferences, logistical constraints),

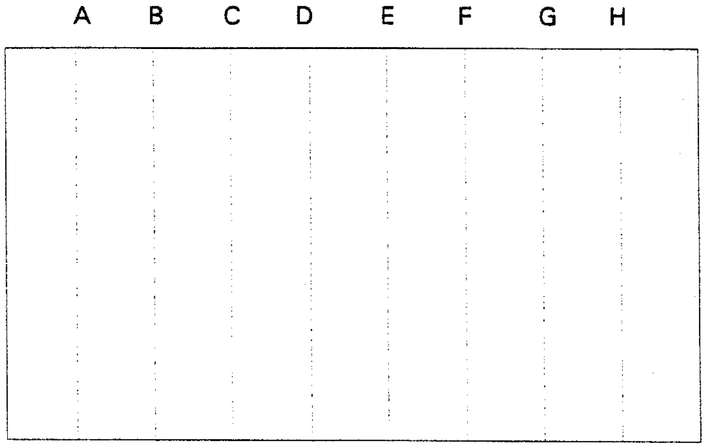
7.2.4 Assumptions made,

7.2.5 Field approach used along with a description of the equipment and the data acquisition and display parameters, such as date of acquisition, gains, filters, antenna frequency, and geometry,

7.2.6 Location of radar transects on a site map, directions of antenna motion along transects, and orientation of antenna polarizations,



Before Rubbersheeting



After Rubbersheeting

Distance Markers

FIG. 8 Spacing of Scans with Respect to Actual Horizontal Distance, Before and After Rubber Sheeting (modified from Bochiccio, 1988)

7.2.7 Corrections applied to field data and justification for their use,

7.2.8 Measured results,

7.2.9 How depths to reflectors were determined,

7.2.10 What software program(s) and steps for processing and interpretation were used,

7.2.11 Interpreted results and qualifications and possible alternate interpretations, and

7.2.12 Appropriate references or comments for supporting data used in the interpretation.

7.3 *Presentation of Data and Interpretations*:

7.3.1 In some cases, there is little if any need for a formal presentation of data or interpreted results. A statement of findings may be sufficient. If the original data are to be provided to the client, the data and related survey grid maps should be labeled.

7.3.2 The final GPR interpretation generally leads to a conceptual model of the site conditions (geologic, hydrologic, or cultural). A conceptual model is a simplified characterization of a site that incorporates all the essential features of the physical system under study. The conceptual model is usually represented as a cross-section and contour map, along with other drawings to illustrate the general geohydrologic conditions and cultural condition along with any anomalous conditions at a site.

7.4 *Quality Assurance*—It is generally accepted practice to have the data interpretation and report reviewed by a person who was not directly involved with the project, but has a general knowledge of the geologic/cultural setting and expertise in the use and interpretation of GPR data.

8. Precision, Bias, Calibration, and Resolution

8.1 *Precision*—For the purposes of this guide, precision is a measure of the repeatability between measurements. Precision can be affected by the location of the antennas, the tow speed, the coupling of the antennas to the ground surface, the variations in soil conditions, and the ability and care involved in picking reflections. Assuming that soil conditions remain the same (that is, soil moisture), repeatability of radar measurements is can be 100 %.

8.2 *Bias*—For the purposes of this guide, bias is defined as a measure of the closeness to the truth. The accuracy of the GPR survey is dependent upon picking travel times, processing and interpretation, and site-specific geologic limitations, such as unknown changes in radar velocities (lateral or vertical) or the presence of steeply dipping layers.

8.3 *Calibration*—A determination of velocity is only valid at the point where that velocity is calculated. Extrapolation beyond the point of measurement, or interpolation between two or more measurement points, should be done with caution since subtle changes in moisture and soil/rock properties can easily cause significant changes in radar velocity (travel time).

8.3.1 Travel times must be picked as accurately as possible using the onset of the pulse. An error of 10 ns (two-way travel time) translates into an error of approximately 0.6 m in unsaturated sediments, 0.3 m in saturated sediments, and 0.6 m in many rocks.

8.3.2 The accuracy of a GPR survey is commonly based on how well the reflection depths agree with boring data. In general, when there is a significant change in physical properties such as a sand clay interface or a soil rock interface, the radar data and boring data should be expected to agree. In some cases, there will be considerable disagreement between the GPR and boring data. While the GPR measurements may be accurate in themselves, the results may disagree with the depth obtained from drilling for the following reasons.

8.3.2.1 *Fundamental Differences Between GPR Data and Drilling Data*—The GPR method is based upon a measure of travel time of the EM pulses. In order to measure depth to an interface, such as that between soil and rock, there must be a a significant change in velocity at the interface. The GPR method gives an average depth over an area defined by the Fresnel zone.

8.3.2.2 In contrast, when the top of rock is defined by drilling it is usually based upon refusal, blow counts, or the first evidence of rock fragments. Differences between GPR measurements and drilling in defining the top of rock can account for differences between the two types of measurements. In addition, the drilling results are valid for only a sampling area of a few square centimetres.

8.3.2.3 *Positioning Differences*—The GPR survey and the drill hole may not be located in the same location. In cases where the drill rig cannot easily get to the GPR line, the lateral offset may account for significant discrepancies in depth, up to several metres, where the top of rock is highly variable such as karst terrain.

8.4 *Resolution*:

8.4.1 *Lateral Resolution*—The antenna frequency, the rate at which scans are recorded, and the speed at which the antenna is moved determine lateral resolution of a continuous GPR survey. Lateral resolution of a station-by-station GPR survey is determined primarily by the antenna frequency and station spacing. Lateral resolution is also controlled by the antenna patterns and the Fresnel zone, which get larger (poorer resolution) with increasing depth.

8.4.2 *Vertical Resolution*—Vertical resolution can be considered in two ways: (*1*) how small a change in depth can be determined by the GPR method and (*2*) how thin a layer can be detected by the GPR method.

8.4.3 The answers to both of the questions are a complex function of the amplitude and wavelength of the transmitted pulse, the properties and electromagnetic propagation characteristics of the host material and the target, the complexity of the geology, noise from man-made and natural objects at or near the surface, and the depth, shape, and size of the target.

8.4.4 Resolution of a few centimetres can be obtained with high-frequency antennas (1 GHz) at shallow depths, while lower frequency antennas (10 MHz) may have resolution of approximately one metre at greater depths (Table 3).

9. Keywords

9.1 civil engineering; environmental site characterization; geological engineering; geology; geophysics; ground penetrating radar; ground water; subsurface investigation; surface geophysics

TABLE 3 Resolution Limits (metres) for Various Antenna Frequencies (f) and Relative Permittivities (ϵ_r) Based on 1/4λ

ϵ_r f	1	5	10	15	25	80
25 MHz	3.00	1.34	0.95	.0.77	0.60	0.34
50 MHz	1.50	0.67	0.47	0.39	0.30	0.17
80 MHz	0.94	0.42	0.30	0.24	0.19	0.10
100 MHz	0.75	0.34	0.24	0.19	0.15	0.08
200 MHz	0.38	0.17	0.12	0.10	0.08	0.04
300 MHz	0.25	0.11	0.08	0.06	0.05	0.03
500 MHz	0.15	0.07	0.05	0.04	0.03	0.02
900 MHz	0.08	0.04	0.03	0.02	0.02	0.01

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