European companies have worked with partners in the United States to develop laser-engraving systems for cutting cells into copper. Theoretically, a laser could generate up to 100,000 cells per second, a great improvement over electromechanical methods. In practice, however the reflectivity of the copper cylinder surface significantly reduced the efficiency of the laser engraver. The laser light energy intended to ablate copper to engrave a cell is instead reflected from the cylinder.

Attempts to replace copper with plastics or hardened epoxy for laser imaging have proven unsuccessful. To avoid the reflectivity problems associated with laser engraving of copper, the Max Daetwyler Corporation (MDC) developed a metal alloy with a "laser type-specific light absorption" (4). This system can reportedly engrave 70,000 cells per second.

OVERVIEW OF TODAY'S GRAVURE INDUSTRY

The gravure process is currently the third most common printing process used in the United States and the second most commonly used process in Europe and Asia. Three distinctly different market segments use the gravure process: publication, packaging, and specialty.

Publication gravure presses are designed to print web widths up to 142 inches and run at speeds up to three thousand feet per minute. The maximum cylinder circumference used in a publication gravure press is 76 inches. A typical publication gravure press consists of eight printing units, four for each side of the web. Gravure printed publications include magazines, Sunday newspaper supplements, catalogs, and newspaper advertising inserts.

Gravure packaging presses are designed to handle the specific substrates used in the packaging industry. Consequently, a packaging press is narrower and runs at a slower speed than a publication press. A packaging gravure press usually includes eight or more printing stations, and runs at a speed between 450 and 2000 feet per minute. The type of substrate printed or the speed of in-line finishing often limits press speeds. The gravure printing process can handle a wider range of substrates than any other printing process (with the possible exception of flexography). Gravure printed packaging products include folding cartons, usually printed on paperboard, flexible packaging, usually printed on polyethylene or polypropylene, and labels and wrappers.

The most interesting and diverse segment of gravure printing is known as the product or specialty segment. The press speeds and the web widths used for the various products manufactured by specialty gravure printers are diverse. Depending on the substrate, speeds vary from 30 to 1000 feet per minute, and widths vary from less than 20 inches to 12 feet. The following list includes many of the specialty products printed by gravure:

- Gift wrap
- Wallcoverings
- Swimming pool liners
- Shower curtains
- Countertops
- Vinyl flooring
- Candy and pill trademarking
- Stamps
- Cigarette filter tips
- Lottery Tickets

The strength of gravure derives from the simplicity of operation—fewer moving parts. This allows for a more stable and consistent production process. The improvements in gravure prepress have shortened cylinder lead times. Any successful breakthrough in plastic cylinder technology will make gravure competitive in short-run markets.

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GROUND PENETRATING RADAR

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INTRODUCTION

Ground-penetrating radar (GPR) is a geophysical method that can accurately map the spatial extent of near-surface objects or changes in soil media and produce images of those features. Data are acquired by reflecting radar waves from subsurface features in a way that is similar to radar methods used to detect airplanes in the sky (1). Radar waves are propagated in distinct pulses from a surface antenna; reflected from buried objects, features or bedding contacts in the ground; and detected back at the source by a receiving antenna. As radar pulses are being transmitted through various materials on their way to the buried target feature, their velocity changes, depending on the physical and chemical properties of the material through which they are traveling. When the travel times of the energy pulses are measured and their velocity through the ground is known, distance (or depth in the ground) can be accurately measured, producing a three-dimensional data set. In the GPR method, radar antennas are moved along the ground in transects, and two-dimensional profiles of a large number of periodic reflections are created, producing a profile of subsurface stratigraphy and buried

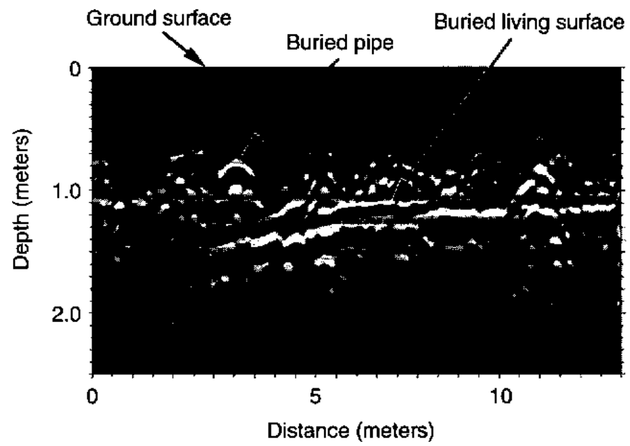


Figure 1. GPR reflection profile showing a vertical slice in the ground to 2.5 meters depth.

features along lines (Fig. 1). When data are acquired in a series of transects within a grid and reflections are correlated and processed, an accurate three-dimensional picture of buried features and associated stratigraphy can be constructed.

Ground-penetrating radar surveys allow for a wide aerial coverage in a short period of time and have excellent subsurface resolution of buried materials and geological stratigraphy. Some radar systems can resolve stratigraphy and other features at depths in excess of 40 meters, when soil and sediment conditions are suitable (2). More typically, GPR is used to map buried materials at depths from a few tens of centimeters to 5 meters in depth. Radar surveys can identify buried objects for possible future excavation and also interpolate between excavations and project subsurface knowledge into areas that have not yet been, or may never be excavated.

GPR surveys are most typically used by geologists, archaeologists, hydrologists, soil engineers, and other geoscientists. Ground-penetrating radar (GPR) was initially developed as a geophysical prospecting technique to locate buried objects or cavities such as pipes, tunnels, and mine shafts (3). The GPR method has also been used to define lithologic contacts (4–6), faults (7), bedding planes and joint systems in rocks (8–11). Ground-penetrating radar technology can also be employed to investigate buried soil units (12–17) and the depth to groundwater (14,18,19). Archaeological applications range from finding and mapping buried villages (20–25) to locating graves, buried artifacts, and house walls (26,27).

ENVIRONMENTS WHERE GROUND-PENETRATING RADAR IS SUCCESSFUL

The success of GPR surveys depends to a great extent on soil and sediment mineralogy, clay content, ground moisture, depth of burial, surface topography, and vegetation. It is not a geophysical method that can be immediately applied to any geographic or archaeological setting, although with thoughtful modifications in acquisition and data processing methodology, GPR can be adapted to many differing site conditions. In the past, it has been assumed that GPR surveys would be successful only in areas where soils and underlying sediment are extremely dry and nonconductive (28). Although radar wave penetration and the ability to reflect energy back to the surface are enhanced in a dry environment, recent work has demonstrated that dryness is not necessarily a prerequisite for GPR surveys, as good data have been collected in swampy areas, peat bogs, rice paddies, and even freshwater lakes. Modern methods of computer enhancement and processing have also proven that meaningful data can be obtained, sometimes even in these very wet ground conditions.

GROUND-PENETRATING RADAR EQUIPMENT AND DATA ACQUISITION

The GPR method involves transmitting high-frequency electromagnetic radio (radar) pulses into the earth and measuring the time elapsed between transmission, reflection from a buried discontinuity, and reception at a surface radar antenna. A pulse of radar energy is generated on a dipole transmitting antenna that is placed on, or near, the ground surface. The resulting wave of electromagnetic energy propagates downward into the ground where portions of it are reflected back to the surface at discontinuities. The discontinuities where reflections occur are usually created by changes in electrical properties of the sediment or soil, variations in water content, lithologic changes, or changes in bulk density at stratigraphic interfaces. Reflection can also occur at interfaces between anomalous archaeological features, buried pipes, and the surrounding soil or sediment. Void spaces in the ground, which may be encountered in burials, tombs, or tunnels, will also generate significant radar reflections due to a significant change in radar wave velocity.

The depth to which radar energy can penetrate and the amount of definition that can be expected in the subsurface are partially controlled by the frequency of the radar energy transmitted. The radar energy frequency controls both the wavelength of the propagating wave and the amount of weakening, or attenuation, of the waves in the ground. Standard GPR antennas propagate radar energy that varies in bandwidth from about 10 megahertz (MHz) to 1200 MHz. Antennas usually come in standard frequencies; each antenna has one center frequency but produces radar energy that ranges around that center by about two octaves. An octave is one-half and two times the center frequency.

Radar antennas are usually housed in a fiberglass or wooden sled that is placed directly on the ground (Fig. 2) or supported on wheels a few centimeters above the ground. When two antennas are employed, one is used as a transmitting antenna and the other as a receiving antenna. Antennas can also be placed separately on the ground without being housed in a sled. A single antenna can also be used as both a sender and receiver in what is called a monostatic system. In monostatic mode, the same antenna is turned on to transmit a radar pulse and then immediately switched to receiving mode to receive and measure the returning reflected energy.

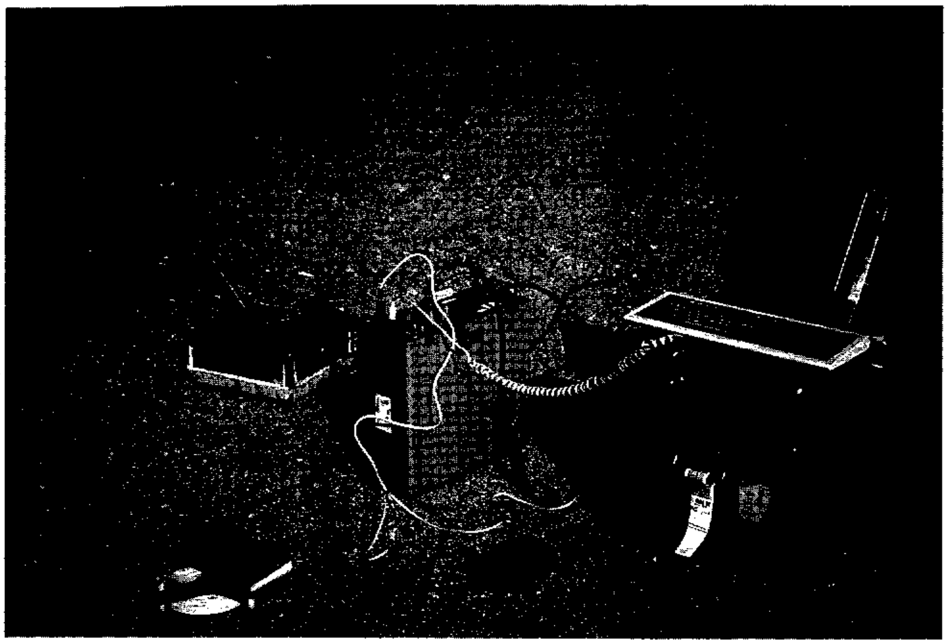


Figure 2. Typical GPR field acquisition set up. A 500 MHz antenna is on the left connected to the radar control unit and computer by a cable. A screen and keyboard for analysis in the field during collectiion is on the packing box on the right.

Antennas are usually hand-towed along survey lines within a grid at an average speed of about 2 kilometers per hour, or they can be pulled behind a vehicle at speeds of 10 kilometers per hour or greater. In this fashion, energy is being continuously transmitted and received as the antennas move over the ground. They can also be moved in steps along a transect instead of being moved continuously. During step acquisition, the smaller the spacing between steps, the greater the subsurface coverage. In the last few years, radar equipment manufacturers have been building their systems so that data can be collected by either method, depending on the preference of the user or because of site characteristics.

The most efficient method of subsurface radar mapping is establishing a grid across a survey area before acquiring the data. Usually rectangular grids are established with a line spacing of 50 centimeters or greater. Rectangular grids produce data that are easier to process and interpret. Other types of grid acquisition patterns may be necessary because of surface topography or other obstructions. Surveys lines that radiate outward from one central area have been sometimes used, for instance, to define a moat around a central fort-like structure (27). A rhomboid grid pattern has also been used with success within a sugarcane field on the side of a hill (20), where antennas had to be pulled between planted rows. Data from nonrectangular surveys are just as useful as those acquired in rectangular grids, although more field time may be necessary for surveying, and reflection data must be manipulated differently during computer processing and interpretation.

Occasionally GPR surveys have been carried out on the frozen surface of lakes or rivers (2,6,14,28). Radar waves will easily pass through ice and freshwater into the underlying sediment, revealing features on lake or river bottoms and in the subsurface. A radar sled can also be easily floated across the surface of a lake or river and onto the shore, all the while collecting data from the subsurface (29). These techniques, however, do not work in salt water because the high electrical conductivity of the saline water quickly dissipates the electromagnetic energy before it can be reflected to the receiving antenna.

If the antennas are pulled continuously along a transect line within a presurveyed grid, continuous pulses of radar energy are sent into the ground, reflected from subsurface discontinuities and then received and recorded at the surface. The movable radar antennas are connected to the control unit by cable. Some systems record the reflective data digitally directly at the antenna, and the digital signal is sent back through fiber optic cables to the control module (2). Other systems send an analog signal from the antennas through coaxial copper cables to the control unit where it is then digitized. Older GPR systems, without the capability of digitizing the reflected signals in the field, must record reflective data on magnetic tape or paper records.

The two-way travel time and the amplitude and wavelength of the reflected radar waves derived from the pulses are then amplified, processed, and recorded for immediate viewing or later postacquisition processing and display. During field data acquisition, the radar transmission process is repeated many times per second as the antennas are pulled along the ground surface or moved in steps. The distance along each line is also recorded for accurate placement of all reflections within a surveyed grid. When the composite of all reflected wave traces is displayed along the transect, a cross-sectional view of significant subsurface reflective surfaces is generated (Fig. 1). In this fashion, two-dimensional profiles that approximate vertical "slices" through the earth are created along each grid line.

Radar reflections are always recorded in "two-way time" because that is the time it takes a radar wave to travel from the surface antenna into the ground, to reflect from a discontinuity, travel back to the surface, and be recorded. One of the advantages of GPR surveys over other geophysical methods is that the subsurface stratigraphy and archaeological features at a site can be mapped in real depth. This is possible because the two-way travel time of radar pulses can be converted to depth, if the velocity of the radar wave travel through the ground is known (1).

The propagative velocity of radar waves that are projected through the earth depends on a number of factors; the most important is the electrical properties of the material through which they pass (30). Radar waves in air travel at the speed of light, which is approximately 30 centimeters per nanosecond (one nanosecond is one billionth of a second). When radar energy travels through dry sand, its velocity slows to about 15 centimeters per nanosecond. If the radar energy were then to pass through a water-saturated sand unit, its velocity would slow further to about 5 centimeters per nanosecond or less. Reflections would be generated at each interface where velocity changes.

Type of Data Collected

The primary goal of most GPR investigations is to differentiate subsurface interfaces. All sedimentary layers in the earth have particular electrical properties that affect the rate of electromagnetic energy propagation, as measured by the relative dielectric permittivity. The reflectivity of radar energy at an interface is primarily a function of the magnitude of the difference in electrical properties between the two materials on either side of that interface. The greater the contrast in electrical properties between the two materials, the stronger the reflected signal (31). The inability to measure the electrical parameters of buried units precisely usually precludes accurate calculations of specific amounts of reflectivity in most contexts, and usually only estimates can be made.

The strongest radar reflections in the ground usually occur at the interface of two thick layers whose electrical properties vary greatly. The ability to "see" radar reflections on profiles is related to the amplitude of the reflected waves. The higher the amplitude, the more visible the reflections. Lower amplitude reflections usually occur when there are only small differences in the electrical properties between layers.

Radar energy becomes both dispersed and attenuated as it radiates into the ground. When portions of the original transmitted signal are reflected toward the surface, they will suffer additional attenuation in the material through which they pass before finally being recorded at the surface. Therefore, to be detected as reflections, important subsurface interfaces must have sufficient electrical contrast at their boundaries and also must be located at shallow enough depths where sufficient radar energy is still available for reflection. As radar energy is propagated to increasing depths and the signal becomes weaker and spreads out over more surface area, less is available for reflection, and it is possible that only very low-amplitude waves will be recorded. The maximum depth of resolution for every site will vary with the geologic conditions and the equipment being used. Data filtering and other data amplification techniques can sometimes be applied to reflective data after acquisition that will enhance very low amplitude reflections to make them more visible.

Reflections received from deeper in the ground are usually gained, either during data collection in the field or during postacquisition processing. This data processing method exponentially increases the amplitudes of reflections from deeper in the ground and makes them visible in reflective profiles. The gaining process enhances otherwise invisible reflections, which have very low amplitude because the energy has traveled to a greater depth in the ground and become attenuated and spread out as waves radiate away from the transmitting antenna, leaving less energy to be reflected to the surface.

Production of Continuous Reflective Images

Most radar units used for geologic and archaeological investigation transmit short discrete pulses into the earth and then measure the reflected waves derived from those pulses as the antennas are moved along the ground. A series of reflected waves are then recorded as the antennas are moved along a transect. The amount of spatial resolution in the subsurface depends partially on the density of reflections along each transect. This spatial density can be adjusted within the control unit to record a greater or lesser number of traces along each recorded line, depending on the speed of antenna movement along the ground. If a survey wheel is being used for data acquisition, the number of reflective traces desired every unit distance can also be adjusted for greater or lesser resolution. If the step method of acquisition is used, the distance between steps can be lengthened or shortened, depending on the subsurface resolution desired.

As reflections from the subsurface are recorded in distinct traces and plotted together in a profile, a two-dimensional representation of the subsurface can be made (Fig. 1). One "trace" is a complete reflected wave that is recorded from the surface to whatever depth is being surveyed. A series of reflections that make up a horizontal or subhorizontal line (either dark or light in standard black-and-white or gray-scale profiles) is usually referred to as "a reflection." A distinct reflection visible in profiles is usually generated from a subsurface boundary such as a stratigraphic layer or some other physical discontinuity such as a water table. Reflections recorded later in time are usually those received from deeper in the ground. There can also be "point source reflections" that are generated from one feature in the subsurface. These are visible as hyperbolas on two-dimensional profiles. Due to the wide angle of the transmitted radar beam, the antenna will "see" the point source before arriving directly over it and continue to "see" it after it is passed. Therefore, the resulting recorded reflection will create a reflective hyperbola (Fig. 3), sometimes incorrectly called a diffraction, on two-dimensional profiles. These often can be produced from buried pipes, tunnels, walls, or large rocks.

Physical Parameters that Affect Radar Transmission

The maximum effective depth of GPR wave penetration is a function of the frequency of the waves that are propagated into the ground and the physical characteristics of the material through which they are traveling. The physical properties that affect the radar waves as they pass through a medium are the relative dielectric permittivity (RDP), the electrical conductivity, and the magnetic permeability (32). Soils, sediment or rocks that are "dielectric" will permit the passage of most electromagnetic energy without actually dissipating it. The more electrically conductive a material, the less dielectric it is. For maximum radar energy penetration, a medium should be highly dielectric and have low electrical conductivity.

The relative dielectric permittivity of a material is its capacity to store and then allow the passage of electromagnetic energy when a field is imposed upon it (33). It can also be thought of as a measure of a material's ability to become polarized within an electromagnetic field and therefore respond to propagated electromagnetic waves (30). It is calculated as the ratio of a material's electrical permittivity to the electrical permittivity in a vacuum (that is, one). Dielectric permittivities of materials vary with their composition, moisture content, bulk density, porosity, physical structure, and temperature (30).

The relative dielectric permittivity in air, which exhibits only negligible electromagnetic polarization, is approximately 1.0003 (34), usually rounded to one. In volcanic or other hard rocks, it can range from 6 to 16, and in wet soils or clay-rich units, it can approach 40 or 50. In unsaturated sediment, where there is little or no clay, relative dielectric permittivities can be 5 or lower. In general, the higher the RDP of a material, the slower the velocity of radar waves passing through it. In general, the higher the RDP of a material, the poorer its ability to transmit radar energy (1).

If data are not immediately available about field conditions, the RDP can only be estimated, but if the actual depth of objects or interfaces visible in reflective profiles is known, the RDP can be easily calculated using Eq. 1.

$$K^{1/2} = \frac{C}{V} \tag{1}$$

where K = relative dielectric permittivity (RDP) of the material through which the radar energy passes

C = speed of light (0.2998 meters per nanosecond)

V = velocity at which the radar passes through the material (measured in meters per nanosecond)

The relative dielectric permittivity of some common materials is shown in Table 1. These of course can be highly variable due to changes in clay content and type, the amount and type of salts, and especially moisture.

The greater the difference between the relative dielectric permittivity of materials in the subsurface, the larger the amplitude of the reflection generated. To generate a significant reflection, the change in dielectric permittivity between two materials must occur over a short distance. When the RDP changes gradually with depth, only small differences in reflectivity will occur every few centimeters, and therefore only weak or nonexistent reflections will be generated.

Table 1. Relative Dielectric Permittivities of Common Materials

Material	Relative Dielectric Permittivity
Air	1
Ice	3–4
Salt water	81–88
Dry sand	3–5
Saturated sand	20–30
Volcanic ash/pumice	4–7
Limestone	4–8
Shale	5–15
Granite	5–15
Coal	4–5
Dry silt	3–30
Saturated silt	10–40
Clay	5–40
Permafrost	4–5
Asphalt	3–5
Concrete	6

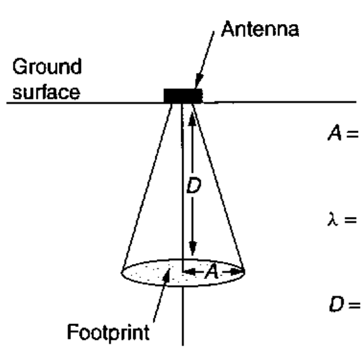
Magnetic permeability is a measure of the ability of a medium to become magnetized when an electromagnetic field is imposed upon it (35). Most soils and sediments are only very slightly magnetic and therefore have low magnetic permeability. The higher the magnetic permeability, the more the electromagnetic energy will be attenuated during its transmission. Media that contain magnetite minerals, iron oxide cement, or iron-rich soils can have high magnetic permeability and therefore transmit radar energy poorly.

Electric conductivity is the ability of a medium to conduct an electric current (35). When a medium through which radar waves pass has high conductivity, radar energy will be highly attenuated. In a highly conductive medium, the electric component of the electromagnetic energy is essentially conducted away into the earth and becomes lost. This occurs because the electric and magnetic fields are constantly "feeding" on each other during transmission. If one is lost, the total field dissipates. Highly conductive media include those that contain salt water and those that have high clay content, especially if the clay is wet. Any soil or sediment that contains soluble salts or electrolytes in the groundwater will also have high electrical conductivity. Agricultural runoff that is partially saturated with soluble nitrogen and potassium can raise the conductivity of a medium, as will wet calcium carbonate impregnated soils in desert regions. Radar energy will not penetrate metal. A metal object will reflect 100% of the radar energy that strikes it and will shadow anything directly underneath it.

RADAR ENERGY PROPAGATION

Many ground-penetrating radar novices envision the propagating radar pattern as a narrow pencil-shaped beam that is focused directly down from the antenna. In fact, GPR waves from standard commercial antennas radiate energy into the ground in an elliptical cone (Fig. 3) whose apex is at the center of the transmitting antenna (36–38). This elliptical cone of transmission occurs because the electric field produced by the antenna is generated parallel to its long axis and therefore usually radiates into the ground perpendicular to the direction of antenna movement along the ground surface. This radiative pattern is generated from a horizontal electric dipole antenna to which elements called shields, are sometimes added that effectively reduce upward radiation. Sometimes, the only shielding mechanism is a metal plate that is placed above the antenna to re-reflect upward radiating energy. Because of considerations of cost and portability (size and weight), the use of more complex radar antennas that might be able to focus energy more efficiently into the ground in a more narrow beam has been limited to date.

When an electric dipole antenna is located in air (or supported within the antenna housing), the radiative pattern is approximately perpendicular to the long axis of the antenna. When this dipole antenna is placed on the ground, a major change in the radiative pattern occurs due to ground coupling (39). Ground coupling is the ability of the electromagnetic field to move from transmission in the air to the ground. During this process, refraction that occurs as the radar energy passes through surface units changes the directionality of the radar beam, and most of the energy is channeled downward in a cone from the propagating antenna (32). The higher the RDP of the surface material, the lower the velocity of the transmitted radar energy, and the more focused (less broad) the conical transmission pattern becomes (24). This focusing effect continues as radar waves travel into the ground and material of higher and higher RDP is encountered. The amount of energy refraction that occurs with depth and therefore the amount of focusing is a function of Snell's law (35). In Snell's law the amount of reflection or refraction that occurs at a boundary between two media depends on the angle of incidence and the velocity of the incoming waves. In general the greater the increase in RDP with depth, the more focused the cone of transmission becomes. The opposite can also occur if materials of gradually lower RDP are encountered as radar waves travel into the ground. Then, the cone of transmission would gradually expand outward as refraction occurs at each interface.



$$A = \frac{\lambda}{4} + \frac{D}{\sqrt{K+1}} \quad (3)$$

A = Approximate long dimension radius of footprint

λ = Center frequency wavelength of radar energy

D = Depth from ground surface to reflection surface

K = Average relative dielectric permittivity (RDP) of material from ground surface to depth (D)

Figure 3. The conical transmission of radar energy from a surface antenna into the ground. The footprint of illumination at any depth can be calculated with equation 3.

Radiation fore and aft from the antenna is usually greater than to the sides, making the "illumination" pattern on a horizontal subsurface plane approximately elliptical (Fig. 3); the long axis of the ellipse is parallel to the direction of antenna travel (1). In this way, the subsurface radiative pattern on a buried horizontal is always "looking" directly below the antenna and also in front, behind, and to the sides as it travels across the ground. The radiative pattern in the ground also depends on the orientation of the antenna and the resulting polarization of the electromagnetic energy as it travels into the ground. If a standard GPR antenna is used, where the transmitting and receiving antennas are perpendicular to the direction of transport along the ground, the elliptical pattern of illumination will tend to be elongated somewhat in the direction of transport.

A further complexity arises due to polarization of waves as they leave the antenna and pass through the ground. The electric field generated by a dipole antenna is oriented parallel to the long axis of the antenna, which is usually perpendicular to the direction of transport across the ground. A linear object in the ground that is oriented parallel to this polarization would therefore produce a very strong reflection, as much of the energy is reflected. In contrast, a linear object in the ground perpendicular to the polarized electrical field will have little surface area parallel to the field with which to reflect energy therefore will reflect little energy, and may be almost invisible.

To minimize the amount of reflective data derived from the sides of a survey line, the long axes of the antennas are aligned perpendicular to the survey line. This elongates the cone of transmission in an in-line direction. Various other antenna orientations achieve different subsurface search patterns, but most of them are not used in standard GPR surveys (1).

Some antennas, especially those in the low-frequency range from 80–300 MHz, are sometimes not well shielded and therefore radiate radar energy in all directions. Using unshielded antennas can generate reflections from a nearby person pulling the radar antenna or from any other objects nearby such as trees or buildings (40). Discrimination of individual targets, especially those of interest in the subsurface, can be difficult if these types of antennas are used. However, if the unwanted reflections generated from unshielded antennas all occur at approximately the same time, for instance from a person pulling the antennas, then they can be easily filtered out later, if the data are recorded digitally. If reflections are recorded from randomly located trees, surface obstructions, or people moving about near the antenna, usually they cannot easily be discriminated from important subsurface reflections, and interpreting the data is much more difficult.

If the transmitting antenna is properly shielded so that energy is propagated in a mostly downward direction, the angle of the conical radiative pattern can be estimated, depending on the center frequency of the antenna used (1). An estimate of this radiative pattern is especially important when designing line spacing within a grid, so that all subsurface features of importance are "illuminated" by the transmitted radar energy and therefore can potentially generate reflections. In general, the angle of the cone is defined by the relative dielectric permittivity of the material through which the waves pass and the frequency of the radar energy emitted from the antenna.

An equation that can be used to estimate the width of the transmission beam at varying depths (footprint) is shown in Fig. 3. This equation (Eq. 3) can usually be used only as a rough approximation of real-world conditions because it assumes a consistent dielectric permittivity of the medium through which the radar energy passes. Outside of strictly controlled laboratory conditions, this is never the case. Sedimentary and soil layers within the earth have variable chemical constituents, differences in retained moisture, compaction, and porosity. These and other variables can create a complex layered system that has varying dielectric permittivities and therefore varying energy transmission patterns.

Any estimate of the orientation of transmitted energy is also complicated by the knowledge that radar energy propagated from a surface antenna is not of one distinct frequency but can range in many hundreds of megahertz around the center frequency. If one were to make a series of calculations on each layer, assuming that all of the variables could be determined and assuming one distinct antenna frequency, then the "cone" of transmission would widen in some layers, narrow in others, and create a very complex three-dimensional pattern. The best one can usually do for most field applications is to estimate the radar beam configuration based on estimated field conditions (1).

Antenna Frequency Constraints

One of the most important variables in ground-penetrating radar surveys is selecting antennas that have the correct operating frequency for the depth necessary and the resolution of the features of interest (41). The center frequencies of commercial GPR antennas range from about 10–1200 megahertz (MHz) (15,37). Variations in the dominant frequencies of any antenna are caused by irregularities in the antenna's surface or other electronic components located within the system. These types of variations are common in all antennas; each has its own irregularities and produces a different pulse signature and different dominant frequencies.

This somewhat confusing situation with respect to transmission frequency is further complicated when radar energy is propagated into the ground. When radar waves move through the ground, the center frequency typically "loads down" to a lower dominant frequency (39). The new propagative frequency, which is almost always lower, will vary depending on the electric properties of near-surface soils and sediment that change the velocity of propagation and the amount of "coupling" of the propagating energy with the ground. At present, there is little hard data that can be used to predict accurately what the "downloaded" frequency of any antenna will be under varying conditions. For most GPR applications, it is only important to be aware that there is a downloading effect that can change the dominant radar frequency and affect calculations of subsurface transmission patterns, penetration depth, and other parameters.

In most cases, proper antenna frequency selection can make the difference between success and failure in a GPR survey and must be planned for in advance. In general, the greater the necessary depth of investigation, the lower the antenna frequency which should be used. Lower frequency antennas are much larger, heavier and more difficult to transport to and within the field than high-frequency antennas. One 80-MHz antenna used for continuous GPR acquisition is larger than a 42-gallon oil drum, cut in half lengthwise, and weighs between 125 and 150 pounds. It is difficult to transport to and from the field, and usually must be moved along transect lines by some form of wheeled vehicle or sled. In contrast, a 500-MHz antenna is smaller than a shoe box, weighs very little, and can easily fit into a suitcase (Fig. 2). Lower frequency antennas used for acquiring data by the step method are not nearly as heavy as those used in continuous data acquisition but are equally unwieldy.

Low-frequency antennas (10–120 MHz) generate long wavelength radar energy that can penetrate up to 50 meters in certain conditions but can resolve only very large subsurface features. In pure ice, antennas of this frequency have been known to transmit radar energy for many kilometers. Dry sand and gravel or unweathered volcanic ash and pumice are media that allow radar transmission to depths that approach 8–10 meters, when lower frequency antennas are used. In contrast, the maximum depth of penetration of a 900-MHz antenna is about 1 meter or less in typical soils, but its generated reflections can resolve features as small as a few centimeters. Therefore, trade-off exists between depth of penetration and subsurface resolution. The depth of penetration and the subsurface resolution are actually highly variable and depend on many site-specific factors such as overburden composition, porosity, and the amount of retained moisture.

If large amounts of clay, especially wet clay, are present, then attenuation of the radar energy with depth will occur very rapidly, irrespective of radar energy frequency. Attenuation can also occur if sediment or soils are saturated with salty water, especially seawater.

SUBSURFACE RESOLUTION

The ability to resolve buried features is determined mostly by frequency and therefore the wavelengths of the radar energy transmitted into the ground. The wavelength necessary for resolution varies, depending on whether a three-dimensional object or an undulating surface is being investigated. For GPR to resolve three-dimensional objects, reflections from at least two surfaces, usually a top and bottom interface, need to be distinct. Resolution of a single buried planar surface, however, needs only one distinct reflection and therefore wavelength is not as important in resolving it.

An 80-MHz antenna generates an electromagnetic wave about 3.75 meters long when transmitted in air. When the wavelength in air is divided by the square root of the RDP of the material through which it passes, the subsurface wavelength can be estimated. For example, when an 80-MHz wave travels through material whose RDP is 5, its wavelength decreases to about 1.6 meters. The 300-MHz antenna generates a radar wave whose wavelength is 1 meter in air, and decreases to about 45 centimeters in material whose RDP is 5. To distinguish reflections from two parallel planes (the top and bottom of a buried object, for instance), they must be separated by at least one wavelength of the energy that is passing through the ground (1,2). If the two reflections are not separated by one wavelength, then the resulting reflected waves from the top and bottom will either be destroyed or will be unrecognizable due to constructive and destructive interference. When two interfaces are separated by more than one wavelength, however, two distinct reflections are generated, and the top and bottom of the feature can be resolved.

If only one buried planar surface is being mapped, then the first arrival reflected from that interface can be accurately resolved, independent of the wavelength. This can be more difficult when the buried surface is highly irregular or undulating. Subsurface reflections of buried surfaces that have been generated by longer wavelength radar waves tend to be less sharp when viewed together in a standard GPR profile, and therefore many small irregularities on the buried surface are not visible. This occurs because the conical radiation pattern of an 80-MHz antenna is about three times broader than that of a 300-MHz antenna (1). Therefore, the reflected data that are received at the surface from the lower frequency antenna have been reflected from a much greater subsurface area, which results in averaging out the low percentage of reflections from the smaller irregular features. Therefore, a reflective profile produced from reflections by an 80-MHz antenna produces an average and less accurate representation of a buried surface. In contrast, a 300-MHz transmission cone is about three times narrower than an 80-MHz radar beam, and its resolution of subsurface features on the same buried surface is much greater.

Radar energy that is reflected from a buried subsurface interface that slopes away from a surface transmitting antenna is reflected away from the receiving antenna and will be lost. This sloping interface would go unnoticed in reflective profiles. A buried surface of this orientation is visible only if an additional traverse is located in an orientation where that the same buried interface slopes toward the surface antennas. This is one reason that it is important always to acquire lines of data within a closely spaced surface grid.

The amount of reflection from a buried feature is also determined by the ratio of the object's dimension to the wavelength of the radar wave in the ground. Short wavelength (high-frequency) radar waves can resolve very small features but will not penetrate to a great depth. Longer wavelength radar energy will resolve only larger features but will penetrate deeper in the ground.

Some features in the subsurface may be described as "point targets," and others are similar to planar surfaces. Planar surfaces can be stratigraphic and soil horizons or large flat archaeological features such as pit-house floors or buried soil horizons. Point targets are features such as tunnels, voids, artifacts or any other nonplanar object. Depending on a planar surface's thickness, reflectivity, orientation, and depth of burial, it is potentially visible with any frequency data, constrained only by the conditions discussed before. Point sources, however, often have little surface area with which to reflect radar energy and therefore are usually difficult to identify and map. They are sometimes indistinguishable from the surrounding material. Many times they are visible only as small reflective hyperbolas visible on one line within a grid (Fig. 1).

In most geologic and archaeological settings, the materials through which radar waves pass may contain many small discontinuities that reflect energy. These can be described only as clutter (that is if they are not the target of the survey). Clutter depends totally on the wavelength of the radar energy propagated. If both the features to be resolved and the discontinuities that produce the clutter are of the order of one wavelength, then the reflective profiles will appear to contain only clutter, and there can be no discrimination between the two. Clutter can also be produced by large discontinuities, such as cobbles and boulders, but only when a lower frequency antenna is used that produces a long wavelength. In all cases, the feature to be resolved, if not a large planar surface, should be much larger than the clutter and greater than one wavelength.

Buried features, whether planar or point sources, also cannot be too small compared to their depth of burial, before they are undetectable. As a basic guideline, the cross-sectional area of the target to be illuminated within the "footprint" of the beam should approximate the size of the footprint at the target depth (Eq. 3 in Fig. 3). If the target is much smaller than the footprint size, then only a fraction of the reflected energy that is returned to the surface will have been reflected from the buried feature. Any reflections returned from the buried feature in this case may be indistinguishable from background reflections and will be invisible on reflective profiles.

Frequency Interference

Ground-penetrating radar employs electromagnetic energy at frequencies that are similar to those used in television, FM radio, and other radio communication bands. If there is an active radio transmitter in the vicinity of the survey, then there may be some interference with the recorded signal. Most radio transmitters, however, have quite a narrow bandwidth and, if known in advance, an antenna frequency can be selected that is as far away as possible from any frequencies that might generate spurious signals in the reflected data. The wide bandwidth of most GPR systems usually makes it difficult to avoid such external transmitter effects completely, and any major adjustments in antenna frequency may affect the survey objectives. Usually, this

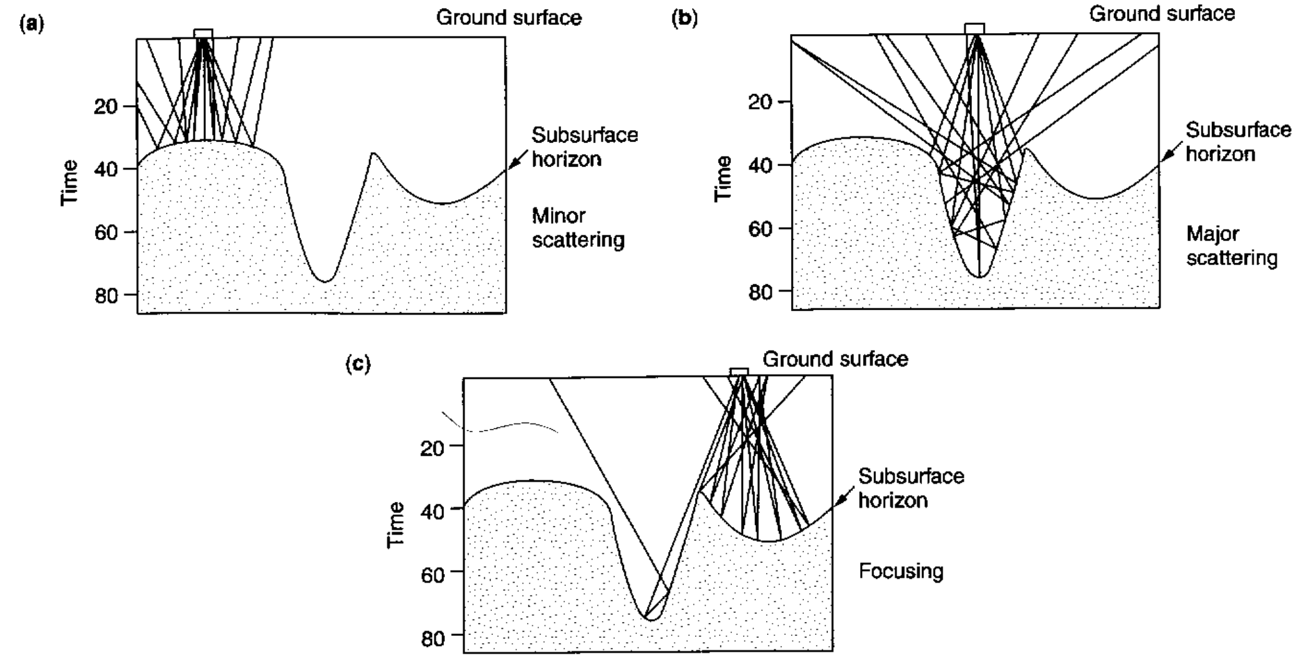


Figure 4. Ground-penetrating radar ray paths reflected from an undulating surface and a deep ditch. Convex upward surfaces scatter radar energy while concave upward focus. Very deep features tend to scatter most energy and are hard to detect using GPR.

becomes a problem only if the site is located near a military base, airport, or radio transmission antennas. Cellular phones and walkie-talkies that are in use nearby during the acquisition of GPR data can also create noise in recorded reflective data and should not be used during data collection. This type of radio "noise" can usually be filtered out during postacquisition data processing.

Focusing and Scattering Effects

Reflection from a buried surface that contains ridges or troughs can either focus or scatter radar energy, depending on its orientation and the location of the antenna on the ground surface. If a subsurface plane is slanted away from the surface antenna location or is convex upward, most energy will be reflected away from the antenna, and no reflection or a very low amplitude reflection will be recorded (Fig. 4). This is termed radar scatter. The opposite is true when the buried surface is tipping toward the antenna or is concave upward. Reflected energy in this case will be focused, and a very high-amplitude reflection derived from the buried surface would be recorded.

Figure 4 is an archaeological example of the focusing and scattering effects when a narrow buried moat is bounded on one side by a trough and on the other side by a mound. Both convex and concave upward surfaces would be "illuminated" by the radar beam as the antenna is pulled along the ground surface.

When the radar antenna is located to the left of the deep moat (Fig. 4) some of the reflections are directed to the surface antenna, but there is still some scattering, and a weak reflection will be recorded from the buried surface. When the antenna is located directly over the deep trough, there will be a high degree of scattering, and much of the radar energy, especially that which is reflected from the sides of the moat, will be directed away from the surface antenna and lost. This scattering effect will make the narrow moat invisible in GPR surveys. When the antenna is located directly over the wider trough to the right of the moat, there will be some focusing of the radar energy that creates a higher amplitude reflection from this portion of the subsurface interface.

TWO-DIMENSIONAL GPR IMAGES

The standard image for most GPR reflective data is a two-dimensional profile that shows the depth on the ordinate and the distance along the ground on the abscissa. These image types are constructed by stacking many reflective traces together that are obtained as the antennas are moved along a transect (Figs. 1 and 5). Profile depths are usually measured in two-way radar travel time, but time can be converted to depth, if the velocity of radar travel in the ground is obtained. Reflective profiles are most often displayed in gray scale, and variations in the reflective amplitudes are measured by the depth of the shade of gray. Color palettes can also be applied to amplitudes in this format.

Often, two-dimensional profiles must be corrected to reflect changes in ground elevation. Only after this is done will images correctly represent the real world. This process, which is usually important only when topographic changes are great, necessitates detailed surface mapping of each transect within the data grid and then reprocessing each transect by adjusting all reflective traces for surface elevation.

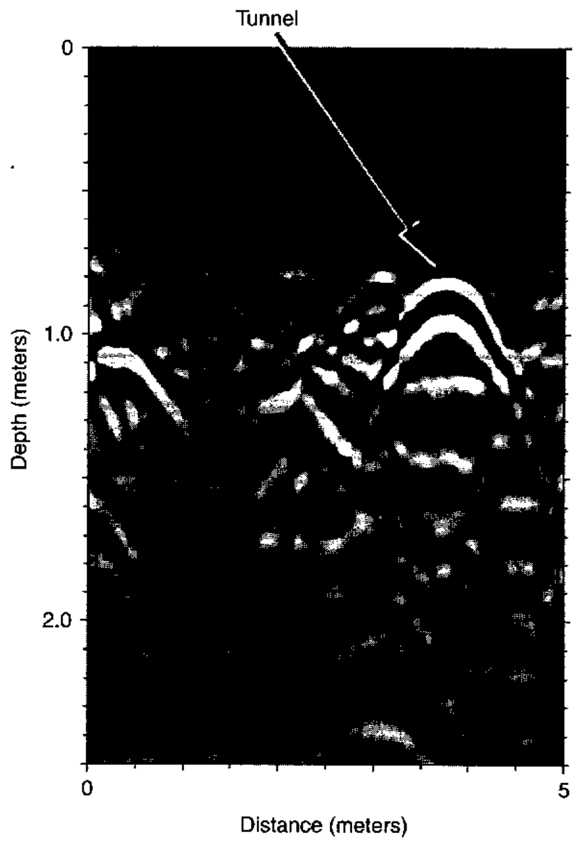


Figure 5. A vertical GPR profile perpendicular to a buried tunnel illustrating the hyperbolic reflection generated from a point source.

Standard two-dimensional images can be used for most basic data interpretation, but analysis can be tedious if many profiles are in the database. In addition, the origins of each reflection in each profile must sometimes be defined before accurate subsurface maps can be produced. Accurate image definition comes only with a good deal of interpretive experience. As an aid to reflection interpretation, two-dimensional computer models of expected buried features or stratigraphy can be produced, which creates images of what things should look like in the ground for comparative purposes (1,24).

THREE-DIMENSIONAL GPR IMAGING USING AMPLITUDE ANALYSIS

The primary goal of most GPR surveys is to identify the size, shape, depth, and location of buried remains and related stratigraphy. The most straightforward way to accomplish this is by identifying and correlating important reflections within two-dimensional reflective profiles. These reflections can often be correlated from profile to profile throughout a grid, which can be very time-consuming. Another more sophisticated type of GPR data manipulation is amplitude slice-map analysis that creates maps of reflected wave amplitude differences within a grid. The result can be a series of maps that illustrate the three-dimensional location of reflective anomalies derived from a computer analysis of the two-dimensional profiles. This method of data processing can be accomplished only with a computer using GPR data that are stored digitally.

The raw reflective data collected by GPR are nothing more than a collection of many individual traces along two-dimensional transects within a grid. Each of those reflective traces contains a series of waves that vary in amplitude, depending on the amount and intensity of energy reflection that occurred at buried interfaces. When these traces are plotted sequentially in standard two-dimensional profiles, the specific amplitudes within individual traces that contain important reflective information are usually difficult to visualize and interpret. The standard interpretation of GPR data, which consists of viewing each profile and then mapping important reflections and other anomalies, may be sufficient when the buried features are simple and interpretation is straightforward. In areas where the stratigraphy is complex and buried materials are difficult to discern, different processing and interpretive methods, one of which is amplitude analysis, must be used. In the past when GPR reflective data were often collected that had no discernible reflections or recognizable anomalies of any sort, the survey was usually declared a failure, and little if any interpretation was conducted. Due to the advent of more powerful computers and sophisticated software programs that can manipulate large sets of digital data, important subsurface information in the form of amplitude changes within the reflected waves has been extracted from these types of GPR data.

An analysis of the spatial distribution of the amplitudes of reflected waves is important because it is an indicator of subsurface changes in lithology or other physical properties. The higher the contrasting velocity at a buried interface, the greater the amplitude of the reflected wave. If amplitude changes can be related to important buried features and stratigraphy, the location of higher or lower amplitudes at specific depths can be used to reconstruct the subsurface in three dimensions. Areas of low-amplitude waves indicate uniform matrix material or soils, and those of high amplitude denote areas of high subsurface contrast such as buried archaeological features, voids, or important stratigraphic changes. To be correctly interpreted, amplitude differences must be analyzed in "time slices" that examine only changes within specific depths in the ground. Each time slice consists of the spatial distribution of all reflected wave amplitudes, which are indicative of these changes in sediments, soils, and buried materials.

Amplitude time slices need not be constructed horizontally or even in equal time intervals. They can vary in thickness and orientation, depending on the questions being asked. Surface topography and the subsurface orientation of features and the stratigraphy of a site may sometimes necessitate constructing slices that are neither uniform in thickness nor horizontal.

To compute horizontal time slices, the computer compares amplitude variations within traces that were recorded within a defined time window. When this is done, both positive and negative amplitudes of reflections are compared to the norm of all amplitudes within that window. No differentiation is usually made between positive or negative amplitudes in these analyses, only the magnitude of amplitude deviation from the norm. Low-amplitude variations within any one slice denote little subsurface reflection and therefore indicate the presence of fairly homogeneous material. High amplitudes indicate significant subsurface discontinuities and in many cases detect the presence of buried features. An abrupt change between an area of low and high amplitude can be very significant and may indicate the presence of a major buried interface between two media. Degrees of amplitude variation in each time slice can be assigned arbitrary colors or shades of gray along a nominal scale. Usually, there are no specific amplitude units assigned to these color or tonal changes.

EXAMPLES OF THREE-DIMENSIONAL GPR MAPPING USING TIME SLICES

Archaeological applications of GPR mapping have been expanding in the last decade, as the prices of data acquisition and processing systems have decreased and the image producing software has expanded. One area of archaeological success with GPR is the high plateau and desert areas of Colorado, Utah, New Mexico and Arizona, an area of abundant buried archaeological remains, including pit houses, kivas (semisubterranean circular pit features used for ceremonial activities), and storage pits. The climate and geological processes active in this area produce an abundance of dry sandy sediments and soil, an excellent medium for GPR energy penetration.

Traditional archaeological exploration and mapping methods used for discovering buried sites include visual identification of artifacts in surface surveys, random test pit excavation, and analysis of subtle topographic features; all of them may indicate the presence of buried features. These methods can sometimes be indicative of buried sites, but they are extremely haphazard and random and often lead to misidentification or nonidentification of features.

At a site near Bluff, Utah, a local archaeologist used some of these techniques to map what he considered was a large pit-house village. The area is located in the floodplain of the San Juan River, an area that was subjected to repeated floods during prehistoric time that often buried low lying structures in fluvial sediment. In a grid that was roughly 50 × 30 meters in dimension, surface surveys had located four or five topographic depressions that appeared to be subtle expressions of pit houses in what was presumably a small buried village. Lithic debris from stone tool manufacture as well as abundant ceramic sherds were found in and around these depressions and further enhanced this preliminary interpretation.

A GPR survey was conducted over this prospective area, using paired 500-MHz antennas that transmitted data to a maximum depth of about 2 meters (42). While data were being acquired, reflection profiles were viewed on a computer monitor and were recorded digitally. A preliminary interpretation of the raw data in the field showed no evidence of pit-house floors in the areas that contained the depressions. Surprisingly, a large distinct floor was located in one corner of the grid, an area not originally considered prospective (Fig. 6). Velocity information, obtained in a nearby pit being dug for a house foundation, was used to convert radar travel time to depth.

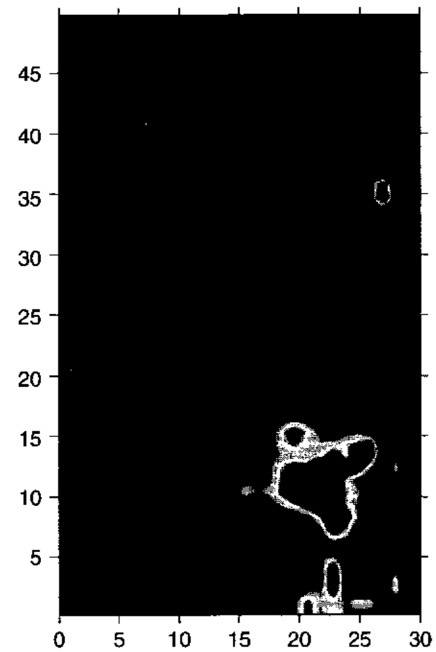


Figure 6. Amplitude slice-map of a layer from 1.2–1.5 meters in the ground. The anomalous high amplitude reflections in the bottom right are from the floor and features on the floor of a buried pit-house covered in river sediment.

An amplitude time-slice map was then constructed in a slice from about 1.2–1.5 meters deep, a slice that would encompass the pit-house floor and all subfloor features. A map of the high amplitudes in this slice shows an irregularly shaped floor that has a possible antechamber and an entrance at opposite sides of the pit structure (Fig. 6). To confirm this interpretation derived only from the GPR maps, nine core holes were dug on and around the feature. All holes dug within the mapped feature encountered a hard-packed floor covered with fire-cracked rock, ceramic sherds and even a small bone pendant at exactly the depth predicted from the GPR maps. Those cores, drilled outside the pit house and in the area of the shallow depressions originally considered the location of the houses, encountered only hard, partially cemented fluvial sediment without archaeological remains.

This GPR survey demonstrates the advantages of performing GPR surveys in conjunction with typical surface topography and artifact distribution mapping. The standard methods of site exploration indicated the presence of nearby pit houses, but both the artifact distributions and the subtle depressions pointed to the wrong area. If only these indicators were used as a guide to subsurface testing, it is doubtful that any archaeological features would have been discovered. Only when used in conjunction with the GPR data was the pit house discovered. It is not known at this time what may have created the subtle depressions that were originally interpreted as pit houses. It is likely that the artifact and lithic scatters noticed on the surface were produced by rodent burrowing, which brought these materials from depth and then concentrated them randomly across the site.

A cautionary lesson about how changing conditions can affect GPR mapping was learned at this site when a second GPR survey over the known pit house was conducted a few months later after a large rain storm. This survey produced no significant horizontal reflections in the area of the confirmed pit house, but many random nonhorizontal reflections throughout the grid; none of them looked like house floors. These anomalous reflections were probably produced by pockets of rainwater that had been differentially retained in the sediments.

At a well known archaeological site, also near Bluff, Utah, a second GPR survey was performed in an area where a distinct surface depression indicated the presence of a Great Kiva, a large semisubterranean structure typical of Pueblo II sites in the American Southwest (42). A 30 × 40 meter GPR survey, using both 300- and 500-MHz antennas, was conducted over this feature for use as a guide to future excavation. Individual GPR profiles of both frequencies showed only a bowl-shaped feature, which appeared to be filled with homogeneous material that had no significant reflection (Fig. 7). There were no discernible features within the depression that would correspond to floor features or possible roof support structures.

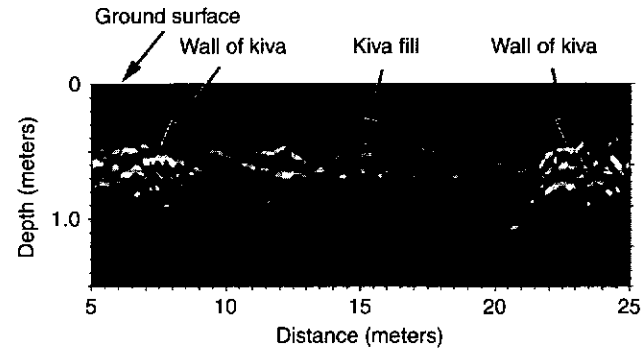


Figure 7. A vertical GPR profile across a buried kiva (semi-subterranean pit structure) in Utah, USA.

Amplitude time-slice maps were then produced for the grid in the hope that subtle changes in amplitude, not visible to the human eye in normal reflection profiles, might be present in the data. When this was completed, the slice from 1.33 to 1.54 meters in depth (Fig. 8) showed a square feature deep within the depression, which, it was later found in two excavation trenches, was the wall of a deeper feature within the depression (42).

The origin and function of this feature is not yet known. What can be concluded from this exercise in GPR data processing is that the computer can produce images of

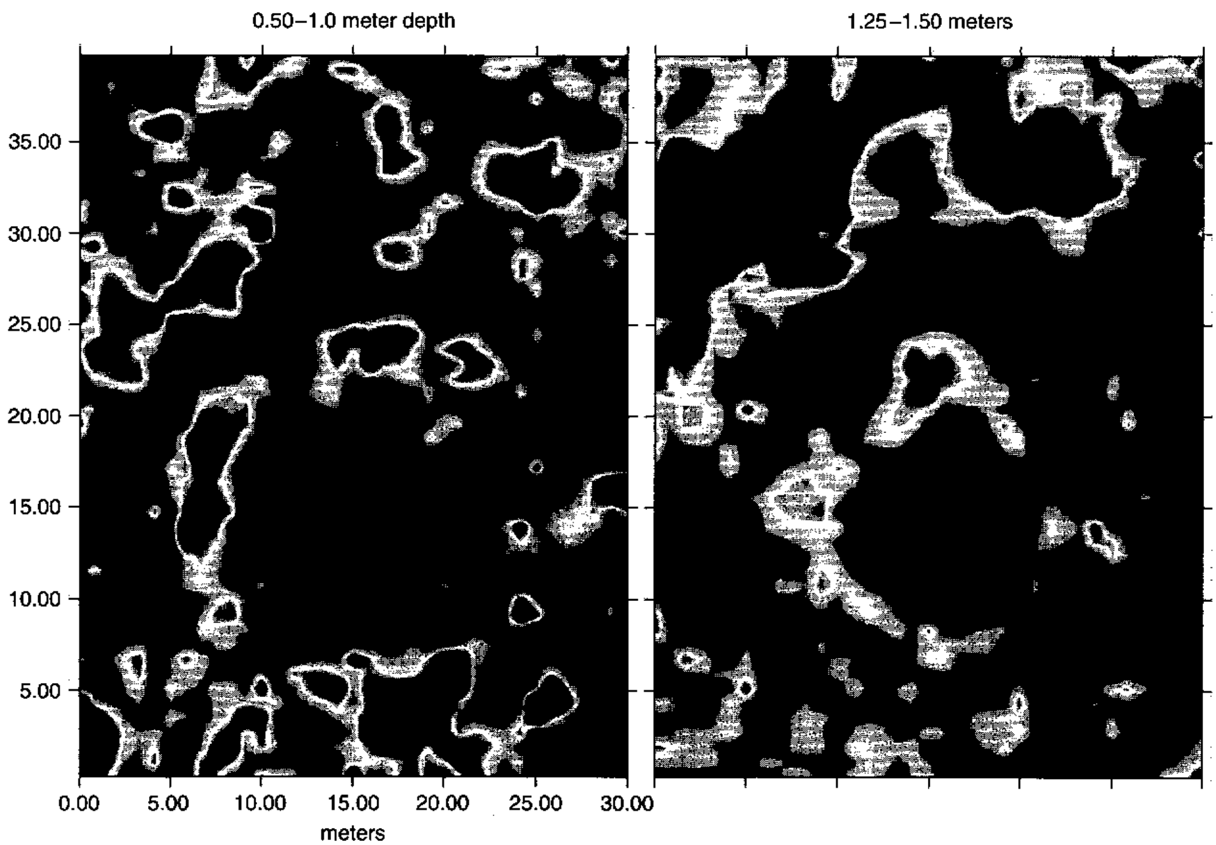


Figure 8. Two amplitude slice-maps across the buried kiva shown in Figure 7. The slice from .5–1.0 meters shows the circular wall of the kiva as high amplitude reflections. It is a discontinuous circle because the wall is partially collapsed. The slice from 1.25–1.5 meters shows a more square feature within the kiva that was found to be interior walls during excavations.

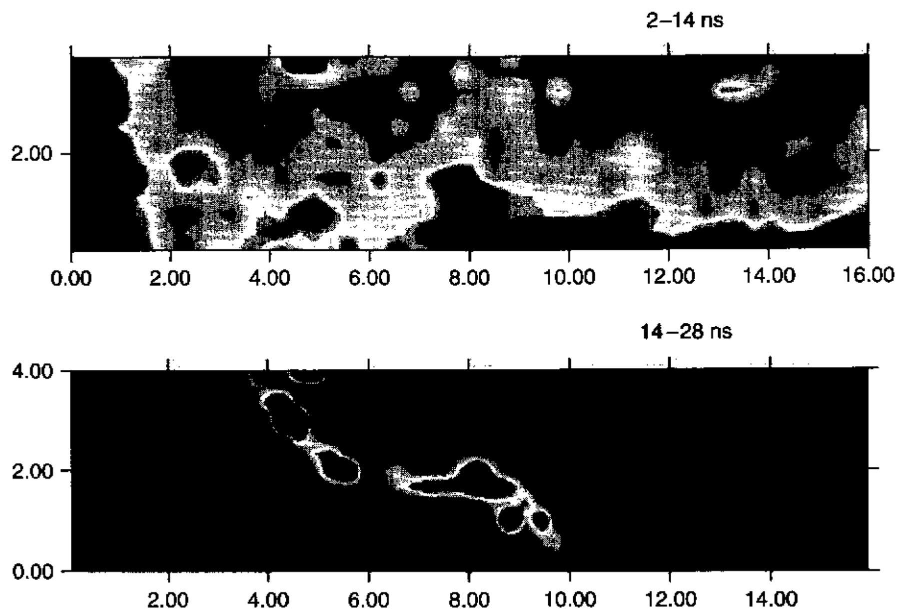


Figure 9. Two amplitude slice-maps showing a buried electrical cable. The slice from 2–14 nanoseconds shows only soil changes near the surface. From 14–28 nanoseconds the cable is clearly visible as high amplitude reflections.

subtle features that cannot be readily processed by the human brain. Without this type of GPR processing, this deep feature would most likely not have been discovered or excavated.

The most straightforward application of three-dimensional amplitude analysis is the search for buried utilities. Often near-surface metal water pipes or electrical conduit can be discovered by using metal detectors or magnetometers. But these methods will not work if the buried utilities are made of clay, plastic, or other nonmagnetic material. Because GPR reflections are produced at the contact between any two types of buried materials, reflections from many buried nonmagnetic pipes and conduits will occur. Tunnels and tubes filled with air are especially visible and produce very high-amplitude reflections.

In Fig. 9, two amplitude slices are shown in an area where it was thought that a buried electrical conduit existed. Records were available giving the approximate depth of burial, which was about 5 years before the GPR data were acquired. The actual location of the buried pipe and its orientation were not known. The conduit was immediately visible as a point-source hyperbola on the computer screen during acquisition when the antennas crossed it. Using the approximate depth from the old records and the measured radar travel time acquired in the field, an average velocity of radar travel through the ground was calculated. Amplitude slices were then constructed from the reflective data, and the lowest slice was most likely to include the buried conduit. The upper slices show only minor changes in amplitude, relating to changes in soil character. The pipe is easily discerned in the slice from 14 to 28 nanoseconds, and each bend is imaged. The image from this depth is somewhat complicated due to reflections from the side of the trench within which the conduit was placed.

CONCLUSIONS AND PROSPECTS FOR THE FUTURE

Ground-penetrating radar imaging of near-surface features is still very much in its infancy. Accurate three-dimensional maps can be made from two-dimensional reflective data, manually and using the amplitude slice-map method. But these maps are really constructed only from a series of two-dimensional data sets. Using only one transmitting and one receiving antenna (the acquisition method typical today) and an abundant amount of subsurface energy refraction, reflection, and scatter, it can sometimes be difficult to determine the exact source in the ground of many of the reflections recorded. A number of data acquisition and processing methods are being developed that may alleviate some of these problems.

One simple data processing method that offers a way to remove the unwanted tails of reflective hyperbolas is data migration. If the velocity of radar travel in the ground can be calculated, each axis of a hyperbola can be collapsed back to its source before producing amplitude slice maps. This process is standard procedure in seismic processing used by petroleum exploration companies. Good velocity analysis and a knowledge of the origin of hyperbolic reflections is necessary for this type of processing.

A very sophisticated data acquisition method is presently under development that will allow acquiring true three-dimensional reflective data. Also a modification from seismic petroleum exploration, this procedure would place many receiving antennas on the ground with a grid; each would simultaneously "listen" for reflected waves and then would record each of those received signals on its own channel. One transmitting antenna would then be moved around the grid in an orderly fashion, while the receiving antennas record the reflected waves from many different locations. In this way, real three-dimensional data are acquired in a method called tomography. The processing procedure, which can manipulate massive amounts of multichannel data, is still being developed.

Ever more powerful computers and the advancement of true three-dimensional data acquisition and processing will soon make it possible to produce rendered images of buried features. A number of prototype rendering programs have been developed, all of which show much promise. In the near future, clear images of buried features in the ground will be produced from GPR reflections, soon after data are acquired in the field; this will allow researchers to modify acquisition parameters, recollect data while the equipment is still on location, and produce very precise maps of subsurface materials.

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