3

GPR Theory and Practice

RADAR ENERGY GENERATION AND PROPAGATION

Radar waves that move in both the air and the ground are a form of electromagnetic energy composed of cojoined oscillating electrical and magnetic fields (figure 3.1). These waves are produced when an electric current oscillates back and forth in a conductive body, producing a subsidiary magnetic field (Kraus 1950; Rojansky 1979). Electromagnetic waves are then generated that propagate outward from the source, with the electrical portion of the waveform moving perpendicular to the magnetic. If either the magnetic or electrical component of the field is lost (attenuated, absorbed, or conducted away), the wave will cease propagating and die. Propagation of radar waves occurs readily in air or space, and unless they encounter a medium that absorbs or reflects them, they will travel an infinite distance. Radar waves are capable of penetrating up to a few meters or more in some ground conditions before they are attenuated and the energy is lost.

Radar energy used in GPR is produced at an antenna, the simplest of which is a copper wire or plate on which an oscillating electrical current is applied. Depending on the frequency of the oscillation (measured in cycles per second), different wavelengths of propagating radar waves are produced. The higher the oscillation frequency, the shorter the wavelength of electromagnetic energy produced, and vice versa. To generate long radar wavelengths, larger antennas with a lower oscillation frequency are necessary. Each wavelength of propagating energy will behave differently in different media within the ground, with longer wavelength energy usually propagating deeper with less reflection from small objects and shorter wavelengths

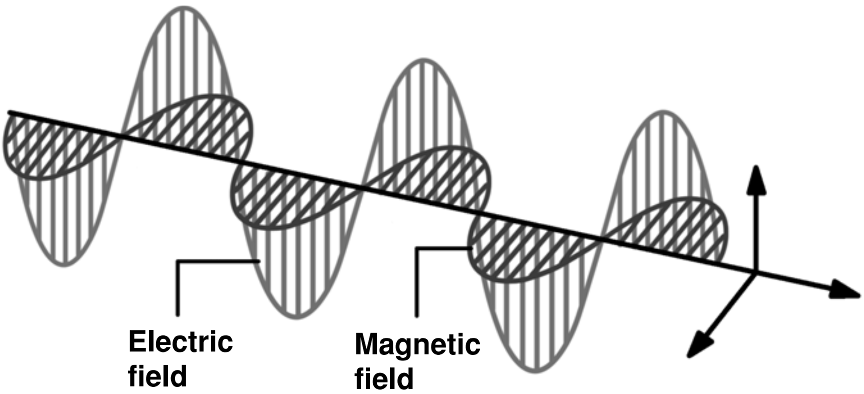


FIGURE 3.1
Electromagnetic Wave Propagation. An electromagnetic wave consists of cojoined electrical and magnetic waves that feed on themselves during propagation.

penetrating to only shallow depths, but reflecting much more readily from smaller buried discontinuities. The shorter wavelengths penetrate less deeply because they are more readily attenuated by most ground conditions (Leckebusch 2003).

There are many different designations assigned to electromagnetic waves, each defined by its wavelength (which is determined by the frequency of the oscillating source that produces them). Visual light is the most commonly recognizable electromagnetic wave, as are X rays, ultraviolet and infrared radiation, TV, radio and cellular phone transmissions, gamma rays, and many more. Radar waves used by most GPR systems occupy a specific portion of the radio spectrum (figure 3.2).

Frequency of propagating radar waves is measured in units of hertz, which is defined as cycles per second. Gamma rays, X–rays, and visual light have very high frequencies of oscillation on the order of 10^{12} to 10^{17} cycles per second. These very high frequencies produce extremely short wavelength energy, measured in fractions of millimeters. Radio waves, a subset of which are radar waves, have much lower frequencies, with wavelengths of propagating energy that vary from a few centimeters to at most a few tens of meters in length. The radar energy used in most GPR applications has frequencies ranging between about 10 and 1,500 megahertz (figure 3.2). This energy occupies a portion of the same electromagnetic spectrum as television and FM radio, cellular phones, and other personal communications devices (figure 3.2), which has recently been the cause of some (mostly irrational) concern by government regulators who are worried about possible GPR antenna interference with communication transmissions (Chignell 2004).

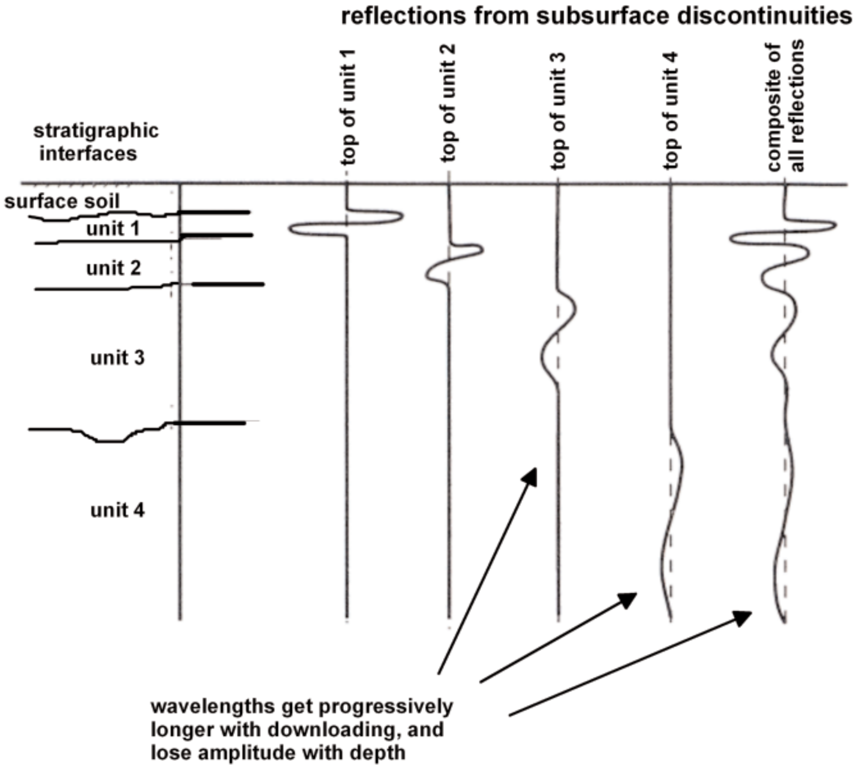


FIGURE 3.2
The GPR Frequency Distribution. Most GPR antennas operate within the frequency band used by many communication devices. There can be a good deal of interference of these usages with some GPR antennas, especially in the 500- to 1,000-MHz frequencies that often overlap television, cellular phone, and pager transmissions.

The GPR method is based on the transmission of electromagnetic pulses, which then propagate as waves, into the ground and measuring the time elapsed between their transmission, reflection off buried discontinuities, and reception back at a surface radar antenna. Each physical or chemical change in the ground through which the radar waves pass will cause some of that energy to be reflected back to the surface, while the remainder continues to propagate deeper until it finally dissipates. Buried discontinuities where reflections occur are usually created by changes in the electrical or magnetic properties of the rock, sediment or soil, variations in their water content, lithologic changes, or changes in bulk density at stratigraphic interfaces (VanDam and Schlager 2000). Reflections also are generated when radar energy

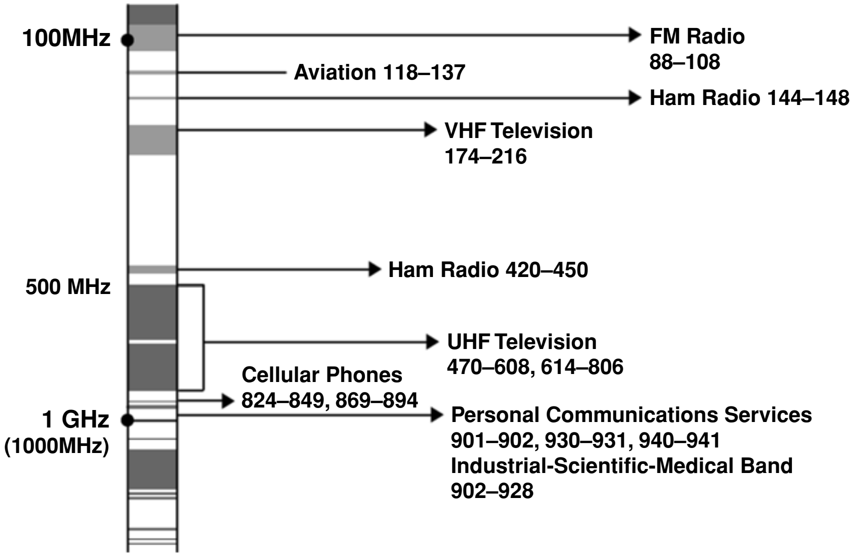


FIGURE 3.3
The Generation of a Waveform. A waveform is a composite reflection trace produced by recording a number of wavelets generated at many subsurface interfaces in the ground.

passes across interfaces between archaeological features and the surrounding matrix. Void spaces in the ground, which may be encountered in burials, tombs, tunnels, caches, or pipes, will also generate significant radar reflections because of a similar change in radar wave propagation velocity. Many bed boundaries and other discontinuities in the ground will reflect a *wavelet* of energy (a positive and negative amplitude wave) back to the surface to be recorded (figure 3.3). A composite of many wavelets that are recorded from many depths in the ground produces a series of reflections generated at one location, called a *reflection trace* (figure 3.3).

GENERATION AND RECORDING OF GPR WAVES

To collect GPR reflections, paired antennas are moved along the ground in transects (figure 3.4). One antenna generates propagating radar waves, and a second paired antenna records the reflection traces generated from reflections below. When many hundreds or even thousands of reflection traces are stacked sequentially as they are collected along an antenna transect, a reflection profile is produced, as in figure 2.1. With the aid of a computer, reflections from thousands of traces within many profiles in a grid can be converted to depth in the ground,

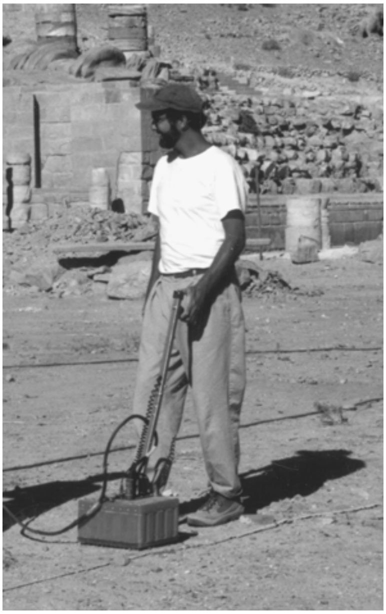


FIGURE 3.4
GPR Antennas Collecting Data. Reflection profiles are collected by moving antennas in transects. This fiberglass box houses paired transmitting and receiving 400 MHz antennas. Energy is transferred to and from the control system by means of a cable.

and the strength of the reflected waves can be analyzed, producing images that portray the nature of materials in the ground in three dimensions.

Radar antennas are usually housed in a fiberglass or plastic sled that is placed directly on the ground (figure 3.4) or supported on wheels a few centimeters above the ground. Commercial GPR systems can have antennas that are mounted in a number of different ways, but all attempt to place them at or near the ground surface. When two antennas are employed, which is almost always the case, one is used as a transmitter and the other as a receiving antenna. This is called *bistatic mode*. A single antenna can also be used as both a transmitter and receiver, in what is called a *monostatic* system. In this type of data collection, the same antenna is turned on to transmit a radar pulse and then immediately switched to receiving mode in order to measure the returning reflected energy received from within the ground. There are some multichannel GPR systems commercially available that can send and receive from multiple antennas simultaneously, but so far they have not been commonly applied to archaeology because of their size, expense, and the complexity of data processing. Researchers are also developing antenna arrays that can potentially receive reflections at tens or even hundreds of surface antennas to produce accurate three-dimensional images of the subsurface, but these also have seen limited archaeological application (Leckebusch 2000).

Antennas are usually hand-towed along survey transects (figure 3.4) at about the speed that someone can walk, but they can also be pulled behind a vehicle, towed by a boat on a lake (Leckebusch 2003), or even suspended from a helicopter. Most GPR systems are capable of generating and collecting reflection traces at a very high rate and can be pulled behind vehicles on a roadway at quite high speeds, but this collection mode is usually not practical or desirable for most archaeological applications.

Ground-penetrating radar systems also have the ability to collect individual reflection traces in steps along a transect instead of being moved continuously. During step acquisition, the smaller the spacing between steps, the greater the number of reflection traces recorded per unit distance, with a corresponding increase in subsurface coverage and therefore resolution. The step acquisition method, however, necessitates more field time because the antennas must be manually moved to each step for each reflection trace to be recorded and therefore less data can be acquired in a given amount of time. Most systems can be programmed to collect data with a survey wheel, or some similar device that can measure where the antennas are in distance along each transect, which can expedite data processing as all recorded reflection traces can be assigned a specific surface location (figure 3.5). A number of prototype systems that are in the experimental stage use global positioning systems or self-tracking laser theodolites to measure distance and location of the antennas on the ground, but they have not as yet been commonly used in archaeology (Lehmann and Green 1999).

ACQUISITION PROCEDURES

Usually antennas are placed directly on the ground surface or as close to the ground as possible. If antennas are located too far above the ground surface, energy will not effectively couple with and then penetrate into it. When this happens, much of the transmitted energy is reflected back to the receiving antenna from the air–ground interface, leaving little to penetrate more deeply.

Although the source of the transmitted energy can be thought of as one distinct radar pulse generated from the surface antenna, this perception is not technically correct. Most GPR systems transmit radar pulses at extremely high rates ranging from 25,000 to 50,000 pulses per second, and digitizers in most systems are not fast enough to sample reflected waves received from any one of these distinct pulses (Leckebusch 2003). To overcome this problem, radar control systems use incremental sampling methods that produce a composite reflection trace by recording the first digital sample within a trace from reflected energy that arrives from the first transmitted pulse. The second sample is recorded from the second pulse and so on until one complete reflection trace is constructed. It may, therefore, take 512 or more samples, from the

FIGURE 3.5
An Antenna Survey Wheel. Antennas can be attached to survey wheels, which can be programmed to collect a given number of reflection traces every programmed distance along a transect.

same number of consecutively produced pulses, to compile the record of one complete reflection trace (figure 3.6). Most GPR users collect a minimum of 512 digital samples to record each reflection trace, although more or less can be defined in most system setup commands.

In continuous data acquisition, if the antennas are moving across the ground at an average walking speed, incremental sampling will create some averaging of the recorded reflections as conditions change in the subsurface. This averaging procedure is usually negligible because it is occurring very quickly and would affect the recorded data only if the subsurface features and layers were extremely variable or the antennas were moving at a high speed along the ground.

The step method of data acquisition uses the same general method, except discrete reflection data in one reflection trace are received and recorded at every step interval. When the antennas are moved to the next step, a reflection trace is again acquired and recorded digitally as 512 or more samples. If the antennas are set up for acquisition in the step method, a beeper or some other form of notice

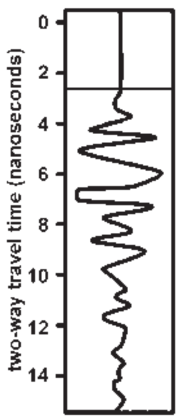


FIGURE 3.6
A Reflection Trace. This reflection trace shows the ground surface at about 2.5 nanoseconds, with the waveform losing amplitude with time, as energy is attenuated in the ground; 512 digital samples are recorded to define this one reflection trace.

is given after each reflection trace is acquired at a station, telling the antenna handler to move the antennas to the next station along a presurveyed transect.

The movable radar antennas are often connected to the GPR control unit by cable (figure 3.4). Some systems record the reflection data digitally directly at the antenna, and the digital signal is sent through fiber optic cables back to the control module (Davis and Annan 1992). Others send an analog signal from the antennas, through coaxial cables, to the control unit where the reflection waveforms are digitized and stored. In the near future, wireless transmission of data from the antennas to a base station will also be possible, allowing all cables to be dispensed with. Many manufacturers are marketing systems that can be used by one person, with the GPR control unit, power sources, and antennas all placed on a wheeled cart or carried on a backpack for nontethered transport within a grid (figure 3.7).

To create a vertical display of the subsurface reflections, all recorded reflection traces, no matter what the acquisition method, are displayed in a format where the two-way travel time or approximate depth of the reflected waves is plotted

FIGURE 3.7
A One-Person GPR System. Some GPR systems can be mounted on a cart for one-person operation.

on the vertical axis with the surface location on the horizontal axis (figure 2.1). In standard two-dimensional reflection profiles that are produced by moving the antennas continuously across the ground, pulses of radar energy are generated at a set time interval, and the horizontal scale will vary because of changes in the speed at which the antennas are moved. Depending on variability in the speed at which the antennas are pulled along the ground, the number of reflection traces collected per unit of distance covered will also vary, making the horizontal scale nonlinear. When data are collected in this fashion, manual markers are placed in the data string at known distances along the transect, and the horizontal scale of the profiles can be adjusted later (Shih and Doolittle 1984). These location markers placed in the recorded reflection data are called *fiducial marks*. Computer processing methods (discussed in chapter 6) can correct the horizontal scale, interpolating between the fiducial marks and either expanding or contracting the spacing of reflection traces between these known locations to create a linear evenly spaced horizontal scale. In the step acquisition or survey wheel method, the horizontal scale is set by the distance between acquisition stations, or the number of traces programmed to be collected per unit distance along the ground, and no horizontal adjustment is usually necessary during postacquisition processing.

The vertical scale in all GPR profiles is measured in two-way travel time, but it can be converted to approximate depth if the velocity of radar energy in the ground is known. Postacquisition computer processing, discussed in chapter 6, typically adjusts both vertical and horizontal scales to create profiles with any desired vertical or horizontal scale or exaggeration. If there is significant elevation variation along a survey transect, topographic corrections should also be made that will adjust the recorded reflections for surface irregularities (figure 3.8). This can only be accomplished if a ground surface topographic survey is made.

Three people are the optimum number of workers usually necessary to conduct a GPR survey, although with newer, more portable systems, one person can sometimes do it alone, with lots of bending over to move and straighten survey tapes as antenna transects are moved within a grid. If more than one person is available, one helper is usually assigned to pull the antennas, or move them in steps, along the surveyed grid transects. Another can stay at the control unit to view the reflection data coming across the computer screen and make notes of significant reflections as they are recorded. If neces-

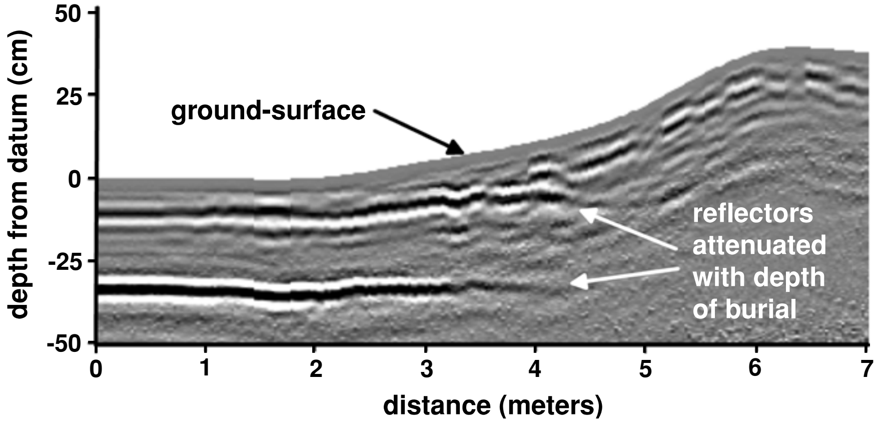


FIGURE 3.8
Topographically Corrected Reflection Profile. This is a reflection profile where radar travel times have been converted to depth and then adjusted for a sloping ground surface. The energy that produced two high-amplitude reflections in this profile is greatly attenuated with progressive depth of burial.

sary, the person at the control unit can also activate a surface location marker button by a command from the person pulling the sled to note the location of obstacles or distance markers along antenna transects. A third person comes in handy to make sure antenna cables do not snag on surface obstacles, help maneuver the antennas when necessary, clear surface debris away from transects, and move tape measures or survey lines for each transect. Some of this labor can be saved if a cart or backpack is used to move the control system with the antennas.

The most tedious, but also important, part of a GPR survey is performed by the person moving the antennas. This job is most difficult during continuous data acquisition because the person pulling the sled must not only walk backward but must also make sure that the antennas are moving parallel to the designated transect line marked by a tape measure or survey rope. If data are being acquired in continuous acquisition mode, where radar pulses are being generated at a programmed number per second, the antenna puller must also pay attention to when the antennas move past designated surface markers. At each presurveyed location, a marker button on the antenna handle must be pushed to place fiducial marks in the reflection records. When a survey wheel is used or antennas are moved in steps, manual marks of this sort are not necessary, and antenna pulling is an easier task. Another important aspect of moving the antennas along the ground is making sure that the antennas are in the same orientation and the same distance above the ground or are directly touching it at all times. Changes in antenna orientation with respect to the ground can potentially cause variations in the recorded reflections that can be confused with "real" material variations in the ground. This phenomenon is called *coupling loss*, and its ramifications will be discussed later in this chapter.

Prior to acquiring reflection data along a transect, the person working the control unit needs to note in a field book the transect number in the grid and the corresponding file number to which the reflection data will be saved. This task cannot be understated because even the most sophisticated computer storage systems can sometimes mysteriously "lose" data (usually because of operator error), and only a handwritten record will reconstruct the procedures used in the field. Surface obstructions that might be encountered, and large trees or other features both on the surface and in the ground that could possibly reflect radar energy, also need to be documented for each transect and their approximate location noted. Many other acquisition procedures more common to geologic studies are discussed by Jol and Bristow (2003).

COLLECTION OF TRANSECTS IN GRIDS

Most archaeological applications necessitate the acquisition of GPR data in a rectilinear grid over the area to be surveyed (Doolittle and Miller 1991). If the grid is oriented to the north, then survey transects can be acquired in either north-south or east-west orientations (or both, if desired). The grid should be situated so that surface obstacles are avoided, and it should be located on the most even and horizontal ground possible. Unless data are being collected on a paved parking lot or mowed field, this is rarely the case. When surface obstructions are present, a grid pattern with survey transects of different lengths can also be easily constructed to avoid the obstacles, creating a complex grid pattern. Computer programs are available that will process reflection data from any grid pattern, as long as the antenna transects are parallel or perpendicular to each other. If buried pipes, tunnels, or electrical cables are known to be present, their location should also be identified in advance, and the grid should be located so as to avoid them. When this is not possible, their location can often be determined by identifying reflections derived from them when the data are interpreted.

Rectangular or rectilinear grids are preferable to other grid designs for a number of important reasons. Digital reflection data collected as parallel or perpendicular transects in a grid can easily be exported to computer display and imaging processing programs that are almost always preset for this gridding method. In this way, the data can be quickly processed and interpreted without time-consuming transect surveying and spatial rectification. In addition, with a rectangular grid, important reflections in each profile can be immediately correlated to others, and reflections can be visually "tied" to parallel or perpendicular transects throughout the grid. In all cases, a sketch of the grid with notes on the transect length, orientation, and beginning and end locations of each transect should be made.

Simple rectilinear grid patterns are not always possible or desirable when conducting some GPR surveys. In some cases, surface conditions or time constraints may necessitate a series of separate nonparallel transects that can still yield good subsurface coverage. Care must be taken when setting up a nonrectangular grid so that the locations of all transects are accurately surveyed and the acquired reflection data can be accurately mapped in three dimensions. When grids of this sort are collected, reflection data must usually be manually interpreted, and map making can be both time-consuming and tedious. Important results can still be obtained, however. Surveys transects that radiate outward from one central area have been sometimes used—for instance, to define a moat around a central fort-like structure (Bevan 1977). A rhomboid grid pattern has also been used with success in Central America within a sugarcane field on the side of a hill where antennas, by necessity, had to be pulled between planted cane rows (Conyers 1995). Sinuous reflection profiles, none of which were either straight or parallel to each other, were collected as antennas were towed over the surface of a lake in Switzerland (Leckebusch 2003). A very complicated grid of sinuous profiles was the product of the boat drifting away from floating survey lines, which necessitated some complex spatial adjustment before interpretation. Although all these non-rectilinear surveys necessitated additional data-processing time to spatially rectify all recorded reflections, they ultimately proved just as useful as those acquired in rectangular grids.

All grids must be accurately surveyed and placed within an overall site map using some type of surveying technique either before or after the acquisition of the GPR data. At the very minimum, the corners of each grid (if rectangular) must be accurately located, and care must be taken so that all transects are parallel or perpendicular to each other within it. This part of the GPR acquisition process can sometimes be the most time-consuming and tiresome part of a survey, but it is extremely important. In the near future, it will be possible to survey grids in a more cursory fashion and use a global positioning system (GPS) to automatically record the location of survey transects (Czarnowski et al. 1996). In this way, the exact coordinates of each transect, and the elevation of the ground surface along them, will be automatically recorded as digital data on a separate channel during acquisition. This technology, which is becoming more common in geological data acquisition, is just beginning to be applied to GPR systems, and at present, traditional survey methods conducted with a transit and rod, laser theodolite, or tape and compass must still be used.

When the ground surface is rough, uneven, or sloping, closely spaced topographic elevations along each survey transect must be obtained so that corrections of subsurface reflections can be made during postacquisition processing (Sun and Young 1995). If the ground is evenly sloping, it may only be necessary to survey the beginnings, ends, and a few elevations along each transect, or at each change of slope, and then interpolate elevations in between to save surveying time. When surface irregularities are numerous, elevation surveying must be done at more frequent intervals (perhaps every meter or less), and data processing becomes more of a chore. The location of any surface feature that could conceivably reflect radar energy should also be mapped at the same time. Trees, overhead branches, houses, or other objects must be accurately located and placed on survey maps so that when the reflection data are later processed, reflections that might have been generated from them can be factored out.

Occasionally there is a need to immediately determine the location of important subsurface reflections with no real need to produce a regional map of the site. If this were the case, raw reflection profiles could be collected and interpreted immediately as the antennas are randomly pulled across the ground. It may not even be necessary to set up a grid, and one could conceivably just wander around a site, producing reflection records until a reflection anomaly is visible on the computer screen. This method is commonly used for buried utility detection at construction sites. Significant reflection locations could then be marked on the ground with pin flags or chalk as they are identified on the computer screen. This is an extremely easy way to conduct a GPR survey (and quite fun, as one gets instant results) but it is full of pitfalls in most archaeological contexts. For the most part, it is difficult to immediately identify important reflection anomalies in raw reflection profiles as they are appearing on the computer screen or on paper printouts. Often important reflections do not appear (or are not recognizable) until the antennas have moved past the subsurface feature producing them, and then one must estimate their location after the fact. This "instant results" type of data acquisition and reflection profile interpretation method should never be used in place of the more standard data acquisition method, which is to collect straight profiles in rectilinear grids for later processing.

Radar energy will easily pass through ice and fresh water into the underlying sediment, revealing features on and below lake or river bottoms (Annan and Davis 1977; Fuchs et al. 2004; Jol and Albrecht 2004; Leckebusch 2003). Radar antennas can also be easily floated across the surface of a lake or river and directly on to the shore, all the while collecting data from the subsurface or even towed from a cable car over a river (Haeni et al. 2000). These techniques, however, will not work in salty or even slightly brackish water because the high electrical conductivity of the saline water will quickly dissipate the propagating electromagnetic energy as it enters the water column, leaving no energy to be transmitted to depth or reflected back to the surface. A few recent GPR surveys were conducted by hanging antennas from a low-flying helicopter. In this method, a distinct reflection was recorded from the ground and less distinct but still recognizable reflections from within the ground.

For expediency, during both continuous and step data acquisition, antenna transects acquired in a rectangular grid are usually collected in a sinuous pattern. One antenna transect is collected moving in one direction in the first transect and then in the opposite direction on the next parallel transect, offset some distance away. This collection pattern, with a standard transect offset, is then continued until all transects in a grid are acquired. Perpendicular cross-transects can be surveyed in the same fashion within the same grid, if necessary. If the reflection data are being stored digitally, simple computer programs can later reverse all the recorded traces for half of the acquired transects so that all reflection profiles produced within a grid have the same orientation with respect to a surveyed datum or baseline.

DATA RECORDING

For most standard GPR data collection, the elapsed time between radar pulse generation, reflection from interfaces in the ground, and final recording of the reflected wave at the receiving antenna is measured. The amplitude and wavelength of the reflected radar waves received back at the surface are also amplified, processed, and digitally recorded for immediate viewing on a computer screen and stored on some kind of digital medium for later postacquisition processing and display. Radar reflections are always recorded in *two-way time* because that is the time it takes a radar wave to travel from the surface transmitting antenna into the ground, be reflected off a discontinuity, and then travel back to the surface to be detected at another surface antenna and recorded.

Some of the earlier model GPR systems were only able to record reflection data on paper by means of a graphic recorder (Batey 1987; Fischer et al. 1980; Loker 1983). These systems use electrosensitive paper that moves across an electrically charged moving stylus, and all reflections in profiles are printed out on long rolls of paper as the antennas are moved along the ground in a transect. The stylus is fed the amplified incoming reflection data from the receiving antenna, with higher amplitudes printed as very dark shades of gray, while areas of little subsurface reflection remain white. A depth scale (in two-way travel time measured in nanoseconds) is also usually printed on the paper profiles. When using a graphic recorder, the operator can vary the speed of the paper and the sensitivity of the moving stylus to produce a wide variety of profile styles and exaggerations (Batey 1987; Fischer et al. 1980). This type of data recording has been almost totally superseded by digital recording systems, but a few of these systems are still in operation.

In other antiquated GPR units, reflected waves can be recorded on magnetic tape as small voltage changes around an arbitrary mean for later printout or digitization (Loker 1983). This kind of recorded data can be reprocessed later in order to convert the analog signal to digital data using a computer digitizer (Conyers 1995; Conyers and Spetzler 2002). Paper printouts of reflection profiles that are the only recorded archive of a GPR survey have even been digitized using a scanner, which assigns digital values to different shades of gray, approximating amplitudes of reflected waves in the ground. One would have to be very desperate to process an extremely important data set in this fashion, because it is not only laborious but also quite inexact.

In the early 1980s, GPR units were developed that recorded GPR reflections internally as digital data (Annan and Davis 1992; Geophysical Survey Systems 1987). With these units a computer is usually built into the control unit that allows reflection data to be easily processed, filtered, and spatially corrected as they are recorded. Digital units have now become the standard equipment in almost all GPR surveys, although good data can sometimes be acquired with the older analog units that have been converted to digital systems. Data are then saved to a computer hard drive or digital tape and most recently to flash memory chips.

ANTENNA VARIABLES

One of the most important variables in GPR surveys is the selection of antennas with the correct operating frequency for the depth necessary and the resolution of the features of interest (Huggenberger et al. 1994; Smith and Jol 1995). Commercial GPR antennas used in most archaeological applications range from 10- to 1,500-megahertz center frequency (Annan and Cosway 1994; Fenner 1992; Malagodi et al. 1996; Olson and Doolittle 1985; Jol and Bristow 2003). General-purpose GPR systems use dipole antennas that typically have a two-octave *band width*, meaning that the frequencies vary between one half and two times the center frequency. For example, a 300-megahertz center-frequency antenna generates radar energy with wavelengths ranging from about 150 to 600 megahertz. The frequency distribution of an idealized 500-megahertz wave, which is a bell-shaped distribution around a mean frequency, is shown in figure 3.9. In reality, depending on the electrical components and design of each individual antenna, the frequency distribution is rarely bell shaped but often an asymmetrical “spiky” distribution around a mean or median frequency. Figure 3.9 illustrates the actual frequency distribution derived from a radar pulse created from a 500-megahertz “bow tie” antenna that shows spikes in a number of frequencies with a mean frequency of about 505 megahertz. These variations in frequencies may be caused by irregularities in the antenna’s surface (a bow tie–shaped copper plate), other electronic components located within the antenna system, or noise within the GPR system itself. Variations of this sort are common in all antennas, and each has its own irregularities, producing a different pulse signature and different dominant frequencies. Most important, just because a manufacturer identifies an antenna as having one frequency doesn’t necessarily mean that it will produce radar energy with a center at exactly that frequency. If there is any question as to an antenna’s frequency, a frequency distribution test should be performed that will yield a distribution curve like that shown in figure 3.9, prior to collecting data.

A primary goal of all antenna manufacturers is to produce a clean pulse of one wavelength in duration that can be transmitted into the ground. No antennas, however, produce perfectly clean pulses, and somewhat noisy reflection

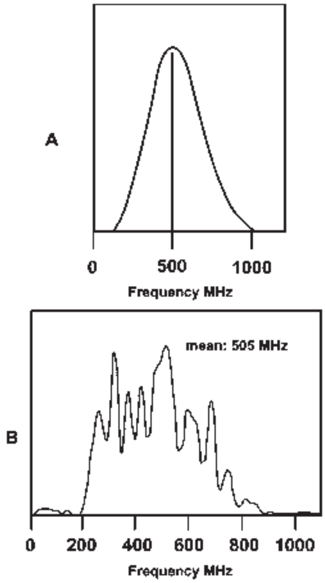


FIGURE 3.9
Antenna Frequency Distribution. Most antennas used in archaeology transmit at frequencies that vary about one octave around a mean center frequency. The theoretical distribution of energy transmitted from a 500-MHz antenna should take on a bell shape, with energy varying between 250 and 1,000 MHz (A). The actual frequency distribution of a 500-MHz antenna (B) when tested in the laboratory was found to have a mean of 505 MHz and a very uneven frequency distribution that varied between about 200 and 900 MHz.

records generated from noisy transmitted pulses are always the norm. A test was done on a 500-megahertz antenna (figure 3.10), and it was found that the transmitted pulse recorded in a noise-free environment is inherently noisy with the beginning of one strong pulse, recorded at 2 nanoseconds, followed by antenna “ringing” and other system noise after about 6 nanoseconds, making the transmitted energy one large pulse followed by many smaller-amplitude

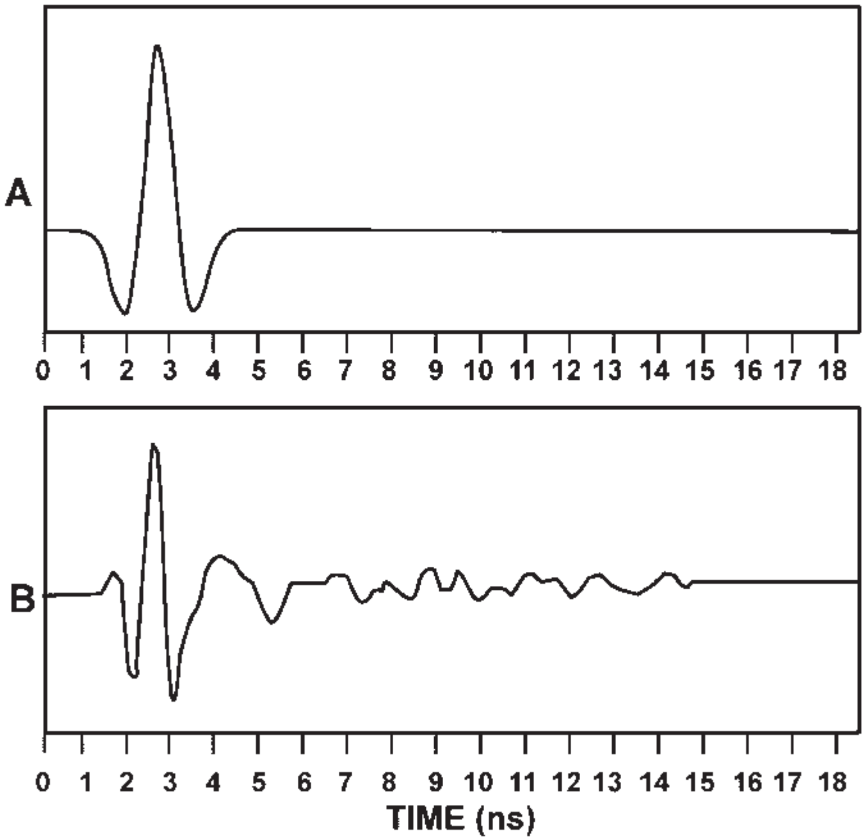


FIGURE 3.10
Radar Pulses. Antenna engineers strive to manufacture antennas that produce one pulse (A), but most antennas actually produce energy that is much noisier than desired due to imperfections in manufactured components and the addition of system and external noise (B).

waves. This antenna test is anything but the clean idealized pulse desired, which is almost always the case with commercially manufactured antennas. Postacquisition data processing can often "clean up" the noisy reflections recorded by most antennas.

Proper antenna center frequency selection can in most cases make the difference between success and failure of a GPR survey and must be planned for in advance. In general, the greater the depth of investigation, the lower the antenna frequency (longer transmitted wavelength) that is necessary (Smith and

Jol 1995). Lower-frequency antennas are for the most part much larger, heavier, and more difficult to transport to and within the field than high-frequency antennas. An older model 80-megahertz 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. Other newer-model low-frequency antennas can sometimes be moved by more than one person with the aid of tubular plastic supports (figure 3.11). These low-frequency antennas not only are difficult to transport to and from the field but must be moved along transect lines using some form of wheeled vehicle or sled. Often low-frequency antennas are so cumbersome that they must be used to collect data only in the step method, record-

FIGURE 3.11
Low-Frequency Antennas. Very low-frequency antennas are almost always unshielded and must be carried across the ground by one or more people. This antenna can produce center frequency energy of between 16 and 80 MHz depending on how it is configured.

ing one discrete reflection trace at each location as they are moved along a transect. In contrast, a 900-megahertz antenna is smaller than a shoe box, weighs very little, and can easily fit into a suitcase (figure 3.12).

Electrical engineers are continually modifying their antenna components and design parameters to more effectively produce “cleaner” and higher-power radar energy into the ground (Arcone 1995). Early GPR antennas, shaped like bow ties, were dipole antennas constructed of copper. In these antennas, an electrical current is applied to the center of a bow tie–shaped copper plate, which then radiates energy outward to its edges producing an electromagnetic field. One distinct pulse, like that shown in figure 3.10, is then created at the apex of the two arms of the bow tie, which propagates into space. To keep the electromagnetic field from oscillating many times within the antenna and creating many complex propagating waves instead of one distinct pulse, resistors are placed at the outer edges of the copper plate.

FIGURE 3.12
High-Frequency Antennas. A 900-MHz center frequency antenna system is very small and can be easily maneuvered across the ground.

Smaller, higher-frequency antennas are usually shielded, which allows energy propagation downward into the ground, but not upward or to the sides where it could be reflected off surface features, the antenna cables, or even the people pulling the antennas (Lanz et al. 1994). Shielding material that absorbs radar energy is usually placed on top and to the sides of the antenna, allowing energy to propagate only in a downward direction. When unshielded antennas are used, many reflections can be collected from objects on or above the ground surface and discrimination of individual targets in the ground can be difficult. However, if the unwanted reflections recorded from unshielded antennas all occur at approximately the same time—for instance, off a person pulling the antennas—then they can be easily filtered out later, if the data are recorded digitally (Leckebusch 2003). If reflections are recorded from randomly located trees, surface obstructions, or people moving about near the antenna, they usually cannot easily be discriminated from important subsurface reflections, and interpretation of the data is much more difficult unless noted specifically in field notes.

Most larger, lower-frequency antennas are more difficult to shield and therefore have the potential to receive many extraneous reflections from surface objects, and they can thus be quite "noisy." Bow tie antennas especially tend to "ring," which means that the oscillating electromagnetic field is not effectively dampened at the edges of the copper plate, producing a radar pulse that is less than perfect in its geometry. If a larger voltage were applied in an attempt to get more powerful electromagnetic energy into the ground, and produce a radar wave with higher amplitude, the antennas would tend to ring even more, producing a very noisy transmitted wave.

More recent antenna designs have abandoned the classic bow tie design and produce a cleaner radar pulse of higher amplitude, without extensive ringing. For instance, the GSSI 400-megahertz antenna creates a powerful, higher-amplitude pulse, which can travel deeper in the ground than the older 500-megahertz bow tie antenna, with greater subsurface resolution. The energy is also transmitted in a narrower beam as it moves in the ground, focusing more energy downward and creating "crisper" reflection profiles. Unfortunately, recent government regulations pertaining to radio bandwidth transmissions have necessitated that manufacturers to produce antennas of lower power, negating some of these advances in antenna design. Fortunately, many of the newer antennas manufactured by most GPR firms are also smaller in size than earlier comparable models and therefore are easier to transport to and within the field.

RADAR PROPAGATION AND REFLECTION IN THE GROUND

Measurements of Radar Propagation and Reflection

The primary goal of most GPR investigations in archaeology is to differentiate and spatially map important subsurface interfaces. Any time radar energy crosses a contact between two materials in the ground with different physical or chemical properties, the velocity of the passing waves will change, and some energy will be reflected back toward the surface (figure 3.3). All sedimentary layers and other buried materials in the ground have particular properties that affect the velocity of electromagnetic energy propagation and therefore the strength of the reflected waves (Van Dam et al. 2002). Often the amount of reflection that occurs at buried interfaces is a function of differing retained or distributed water, which can be directly related to the physical properties of the buried units (Conyers 2004). The measurable properties of materials that affect radar propagation and reflection are electrical conductivity (related to the amount of retained water) and, to a lesser extent, magnetic permeability (Olhoeft 1981; Reynolds 1998: 688; Van Dam and Schlager 2000). If these are known (which is rarely the case for most sites, as detailed laboratory analyses must be conducted on soil and sediment samples), the amount of reflection at buried interfaces can be predicted.

Relative dielectric permittivity (RDP), also called the *dielectric constant*, takes the electrical and magnetic properties of buried materials into account and is a measure of the ability of a material to store a charge from an applied electromagnetic field and then transmit that energy (ASTM International 2003 von Hippel 1954; Wensink 1993). It is usually determined empirically from measurements in the field but can be directly measured in the laboratory, as will be discussed in chapter 5. In general, the greater the RDP of a material, the slower radar energy will move through it (figure 3.13). Relative dielectric permittivity is a general measurement of how well radar energy will be transmitted to depth. It therefore measures velocity of propagating radar energy and also its strength. For most archaeological applications, RDP values and measurements of the velocity of radar travel in the ground are used synonymously, as it is very difficult to measure or predict most of the other components of radar wave behavior used in the complex calculation of RDP.

For most archaeological studies, RDP and velocity are used interchangeably as a way to determine velocity of radar wave propagation in the ground. For instance, the RDP of fresh water is very high (about 80), but radar energy can easily be transmitted through it without being attenuated (especially when in a solid

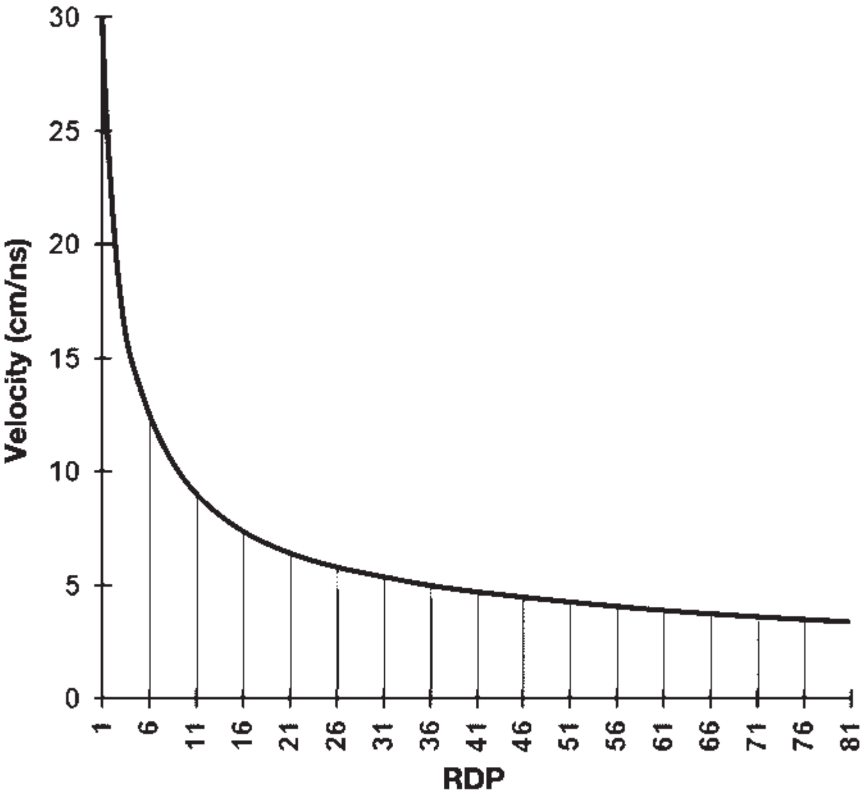


FIGURE 3.13
Graph of the Relative Dielectric Permittivity–Velocity Relationship. RDP is inversely related to radar travel velocity.

state—frozen), only at a very slow velocity. A bed of peat, which is composed almost wholly of organic material and fresh water, also has a high RDP but will also allow radar transmission to great depths, just at much slower speeds than in saturated sand or other materials (Clarke et al. 1999; Worsfold et al. 1986).

It is usually difficult to calculate RDP in the field, but it can be estimated using a number of field procedures discussed in chapter 5. It is always important to have some understanding of the RDP (or velocity) of the material in the ground at each site being studied, as it will be used to convert radar travel times to depth. Without this crucial understanding of how fast energy is traveling in the ground, many other preacquisition calibration procedures necessary for optimal data acquisition discussed in chapter 4 can be potentially compromised.

The relative dielectric permittivity of air, which exhibits only negligible electromagnetic attenuation, is approximately 1.0003 (Dobrin 1976) and is usually rounded to 1. Most soils and sediments found at archaeological sites have RDP values that range between 3 and about 25 (table 3.1). In a totally dry state, most naturally occurring materials in the ground have an RDP that varies little, usually between about 3 and 5. But if just a small amount of water is added to the material (which is almost always the case in natural conditions, even in the driest of deserts), the RDP will increase, sometimes dramatically (Conyers 2004). Take, for instance, sand (with an RDP of 3; see table 3.1) that is totally saturated with fresh water (with an RDP of 80). The overall RDP of this material can be estimated by taking the water-filled sand porosity of 30 percent and multiplying it by the RDP of water, which is 80. This is then added to the RDP of the sand (about 3) that makes up the other 70 percent of the total volume (calculated by taking 70 percent of 3). The RDP of the total volume would then estimated at 26.1: $([0.30 \times 80] + [0.70 \times 3])$. In real field conditions, this easy calculation is

Table 3.1. Typical Relative Dielectric Permittivities (RDPs) of Common Geological Materials

Material	*RDP*
Air	1
Dry sand	3–5
Dry silt	3–30
Ice	3–4
Asphalt	3–5
Volcanic ash/pumice	4–7
Limestone	4–8
Granite	4–6
Permafrost	4–5
Coal	4–5
Shale	5–15
Clay	5–40
Concrete	6
Saturated silt	10–40
Dry sandy coastal land	10
Average organic-rich surface soil	12
Marsh or forested land	12
Organic-rich agricultural land	15
Saturated sand	20–30
Fresh water	80
Sea water	81–88

Modified from Davis and Annan (1989) and Geophysical Survey Systems (1987).

rarely possible, because almost all materials in the ground contain many other constituents such as clay and organic matter that can interact chemically or physically with the pore water, producing a complex blend of materials, each of which have different RDP values. Many volcanic and other hard rocks and moist sand and gravel can have RDPs that range from 6 to 16. Wet soils and clay-rich sediments or soils (Wensink 1993) often have RDPs which can approach 40 or 50 (table 3.1). In unsaturated sediment, with little or no mineralogical clay, RDPs are usually 5 or lower.

The RDP values shown in table 3.1 are very approximate and can vary greatly over a site and with depth of burial. If data about the types of material in the ground are not immediately available, the RDP of the ground can only be estimated using a number of field methods discussed in chapter 5. Equation 3.1, which relates RDP and radar velocity of a material, is shown below:

$$K = \left(\frac{C}{V}\right)^2$$

K = relative dielectric permittivity (RDP) of the material through which the radar energy passes
C = speed of light (.2998 meters per nanosecond)
V = velocity of the material through which the radar passes (in meters per nanosecond)

EQUATION 3.1
Relative dielectric permittivity and radar velocity relationship in GPR.

To generate a significant radar reflection, the change in RDP between two bounding materials must occur over a short distance. When the RDP changes gradually with depth, only small differences in reflectivity will occur every few centimeters in the ground, and very weak or no reflections at all will be generated (Van Dam and Schlager 2000). The amplitude of reflections generated at an interface between two materials with known RDPs can be calculated using equation 3.2 (Sellmann et al. 1983; Walden and Hosken 1985; Van Dam et al. 2002). But the inability to precisely measure the physical and chemical parameters of buried units in the field usually precludes accurate calculations of specific amounts of reflectivity in most archaeological contexts, and usually only estimates can be made.

$$R = \left(\sqrt{K_1} - \sqrt{K_2}\right)\left(\sqrt{K_1} + \sqrt{K_2}\right)$$

R = coefficient of reflectivity at a buried surface
K_1 = RDP of the overlying material
K_2 = RDP of the underlying material

EQUATION 3.2
The coefficient of reflectivity at an interface between materials of differing relative dielectric permittivity. The higher the coefficient, the higher the amplitude of reflected waves at the interface.

The highest-amplitude radar reflections usually occur at an interface of two relatively thick layers that have greatly varying properties. For instance, a difference of this sort might be between a compacted clay floor of a buried pit house and overlying sand or gravel layer that covers it (e.g., figure 2.1). Often other important stratigraphic interfaces or buried archaeological features of interest will also produce high-amplitude reflections, but not always. If the target archaeological features are composed of almost exactly the same substance as the material surrounding them, or if those materials have about the same physical and chemical properties, there will no variation RDP between them, and little or no reflection will occur at their interface. Calculations other than equation 3.2 that can be used to quantify reflectivity, and therefore the amplitudes or reflected waves at interfaces, are discussed in greater detail later.

Dispersion and Attenuation of Radar Energy in the Ground

Another factor that affects the depth of penetration and amplitude of reflected radar waves in the ground is dispersion and energy attenuation. These occur because most ground is at least slightly electrically conductive, which dissipates and absorbs propagating waves as they move through it. As energy moves more deeply in the ground, less is therefore available for reflection and amplitudes of reflections at buried interfaces also decrease (figure 3.3). When what remains of the original transmitted energy is finally reflected back toward the surface from deep within the ground, that remaining energy will suffer additional attenuation within the materials through which it passes before finally reaching the receiving antenna. As a result, radar energy is always progressively weakened as it moves through the ground. Reflections must therefore be generated at subsurface interfaces that have sufficient RDP contrast and also must be located at a shallow enough depth where sufficient radar energy is still available to be reflected. Sometimes filtering and wave amplification techniques, which will be discussed in chapter 6, can be applied to very weak reflections after acquisition that can enhance their very low amplitudes in order to make them more visible. However, there is always a maximum depth of radar energy penetration and therefore potential reflection, which is different for every site, no matter what antenna frequency is used or postacquisition processing techniques are employed.

The maximum effective depth of penetration of GPR waves 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 pass (Annan et al. 1975; Batey 1987; Geophysical Survey Systems 1987; Keller 1988; Olhoeft 1981). Soils, sediment, or rocks that are termed *dielectric* will permit the passage of a great deal of electromagnetic energy without dissipating it. The more electrically conductive a material, the less dielectric it is, and the larger amount of energy will attenuate at a shallower depth. In a highly conductive medium, the electrical component of the propagating electromagnetic wave is rapidly conducted away, and when this happens, the wave as a whole dissipates. This occurs because for propagation to occur, the electrical and magnetic waves must constantly "feed" on each other during transmission (figure 3.1).

Highly electrically conductive media include those that contain salt water and some that have certain types of electrically conductive clay, especially if that clay is wet. Any soil or sediment that contains soluble salts or electrolytes in the groundwater will also create a medium with a high electrical conductivity. Agricultural runoff that is partially saturated with soluble nitrogen and potassium can potentially increase the electrical conductivity of a medium, as will moist calcium carbonate impregnated soils in arid regions. Often desert soils, even if they appear to be extremely dry and therefore should readily allow radar transmission, contain hydrous salts in their interstices, which conduct electricity. In these types of soils, radar energy will often become attenuated at a shallow depth.

Soil chemistry, especially the types and structures of different clay minerals, also plays a role in radar energy transmission, but this mechanism is still poorly understood (Rhoades et al. 1976; Walker et al. 1973; Wensink 1993). Some common soils are composed of mineralogic clays with a high ionic displacement such as montmoriollionite, smectite, and bentonite (Birkeland 1999). These are three-layer clays that are generally termed swelling clays. All have the ability to both hold water in their atomic structure (and therefore swell when wet). Their molecular structure, when it contains water, allows the easy movement of ions, making them good electrical conductors. In comparison, two-layer clays such as kaolonite and three-layer nonswelling clays such as illite are relatively resistive, and their presence in a soil, even when wet, will often not greatly impede radar energy transmission.

It used to be assumed that wet clay, no matter what type, would attenuate radar waves, and it was therefore unsuitable for GPR surveys (Leckebusch 2003). While this is often the case, good radar reflections have been recorded at a depth of more than 2 meters with a 400-megahertz antenna in western Oregon, in ground composed almost entirely of saturated clay (figure 3.14). This unusual success was a mystery at the time, and only after returning from the field and analyzing the soil and sediment samples collected at the site was it discovered that the clay was not mineral clay. The ground was actually sediment composed of rock fragments that were of clay size, which had not yet undergone diagenesis into mineral clays (Birkeland 1999); therefore, the material did not have the high electrical conductivity properties of many clay minerals discussed earlier. How one would readily determine in the field whether clay at a survey area was mineral clay or just sediment composed of clay-sized rock fragments, without detailed sedimentological and mineralogical analysis, is unknown.

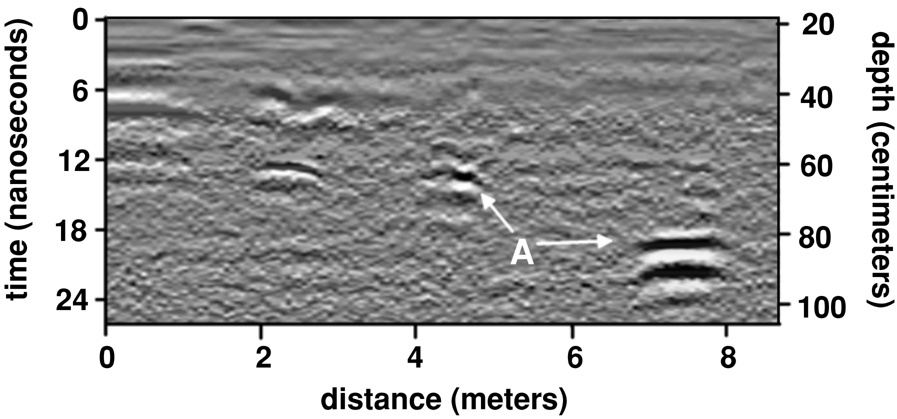


FIGURE 3.14

Reflection Profile in Wet Clay. Good radar reflections (A) were recorded at more than 25 nanoseconds in a homogeneous saturated clay in western Oregon. Laboratory tests of this material showed it to have a low conductivity but a high RDP, and therefore energy traveled within it with little attenuation, but at a relatively slow velocity.

It was also interesting that this saturated clay, with a porosity of about 40 percent, had a very high RDP, because of the amount of retained water. Radar energy therefore readily traveled within it (but at a low velocity) because it was a relatively nonconductive medium. In contrast, the same 400-megahertz antenna was used to collect data at a site in southern Colorado, in extremely dry sandy silt. The maximum depth of radar penetration there was only about 50 centimeters (figure 3.8). Only after the GPR survey was complete, and a mineralogical analysis of the sediment made, was the presence of bentonite clay found in the medium. This water-holding clay made the otherwise dry sediment electrically conductive, explaining the rapid radar energy attenuation at such a shallow depth.

Another similar survey in coastal Peru, with presumably dry sandy soil (it had not rained in that area for decades), also had a very high electrical conductivity, and therefore radar energy was also attenuated at a very shallow depth. In this case, electrically conductive salts were bound with clay in the sand, making the medium as a whole highly electrically conductive and therefore nondielectric.

These examples illustrate how the old GPR adage that dry sandy soils are good for radar penetration while wet clay is bad can be very misleading, as there are many other more important factors controlling radar propagation (Conyers 2004; Gerber et al. 2004). The most important is electrical conductivity, which is often difficult to predict in advance of conducting a GPR survey.

Undecomposed organic matter, such as peat, is often relatively nonconductive, even when wet. The high percentage of water in these sediments, however, will drastically slow radar travel times. Peat will therefore have a high RDP (low propagation velocity), while still allowing radar wave transmission to sometimes great depths (Clarke et al. 1999; Leopold and Volkel 2003). Decomposing organic matter, however, sometimes accumulates metals, especially in a chemically reducing environment, and those metals can increase the material's overall electrical conductivity (Van Dam et al. 2002). This type of wet organic material will also increase the overall acidity in the ground, creating mobile hydrogen ions, which also allow the greater passage of electricity and an increase in the conductivity in some cases.

Other minerals in the ground, especially those that can dissolve in water, will create free ions, which allow for greater electrical conductivity. Sulfates, carbonate minerals, iron, salts of all sorts, and any charged elemental species of mineral will create a highly conductive ground and readily attenuate radar energy at shallow depths (Van Dam et al. 2002). Under the very unfavorable conditions of wet (with slightly saline water), calcareous sediment or soils that contain certain clay-rich minerals, the maximum depth of GPR penetration in the ground can be much less than a meter.

Barring detailed soil chemistry studies at sites prior to data acquisition, the best method of determining an area's conduciveness for GPR studies is to collect GPR data and visually determine depth of energy penetration in reflection profiles. Some researchers have attempted to use electromagnetic conductivity meters (EMs) to measure near-surface ground conductivity, as those readings will generally determine whether GPR energy will successfully be transmitted to the depth desired. Care must be taken using this method, because EM tools must be correctly calibrated to a known media first, or conductivity measurements can be invalid. This method also necessitates a trip to the site first for EM data collection. If GPR equipment were also available, it would probably be better to just collect a radar profile or two at a prospective site to see how deeply energy will penetrate, which would yield more definitive results.

Research is still ongoing to devise an instrument that will quickly and accurately measure soil conductivity of samples, which can then be used to determine the efficacy of GPR in a survey area prior to going to the field. Some have attempted to use devices that were developed to determine the moisture content in grain shipped to storage elevators, which also use dielectric methods. Others have resorted to simple direct current devices that pass an electrical current from one electrode to another in the ground, measuring electrical resistivity, which is the inverse of conductivity. Both have had marginal success in predicting radar transmission because they are measuring either just one sample, which may not be indicative of the ground as a whole, or an electrical current whose pathway in the ground cannot be readily determined. To date, there is no really good way to accurately measure electrical conductivity in the ground as it affects radar transmission, outside of some calibrated EM devices and laboratory tests of samples.

Magnetic permeability also affects radar penetration depth in a medium. It is a measure of the ability of a medium to become magnetized when an electromagnetic field is imposed upon it (Sheriff 1984). Most soils and sediments are only slightly magnetic and therefore usually have a low magnetic permeability. The higher the magnetic permeability, the more electromagnetic energy will be attenuated during its transmission. When this occurs, the magnetic portion of the EM wave is destroyed, just as when electrical conductivity is increased, the electrical component is lost. Media that contain magnetite minerals, iron oxide cement, or iron-rich soils can all have a high magnetic permeability and therefore often transmit radar energy poorly (Van Dam et al. 2002). Poor radar energy penetration caused by this physical property has been encountered in basaltic sands in Hawaii (Olhoeft 1998) and unweathered granite outwash sediments in Arizona, both of which contain large amount of magnetite and other slightly magnetic iron-rich minerals. But in Iceland basalt seems to be capable of transmitting energy to many meters with low-frequency antennas (Cassidy et al. 2004).

Radar energy will not penetrate metal. A metal object will reflect all of the radar energy that strikes it and will "shadow" anything directly underneath. Buried metal objects are quite easy to see in GPR reflection profiles because they usually create multiple reflections stacked on top of one another below the metal object (figure 3.15). This is caused by radar energy reflecting off the metal object, traveling back to the ground surface to be reflected again from the ground–air interface, back to the metal object, and then again to the surface. When this occurs, many reflections of this sort are often stacked on top of each other, a good indicator of buried metal. Other materials besides metal

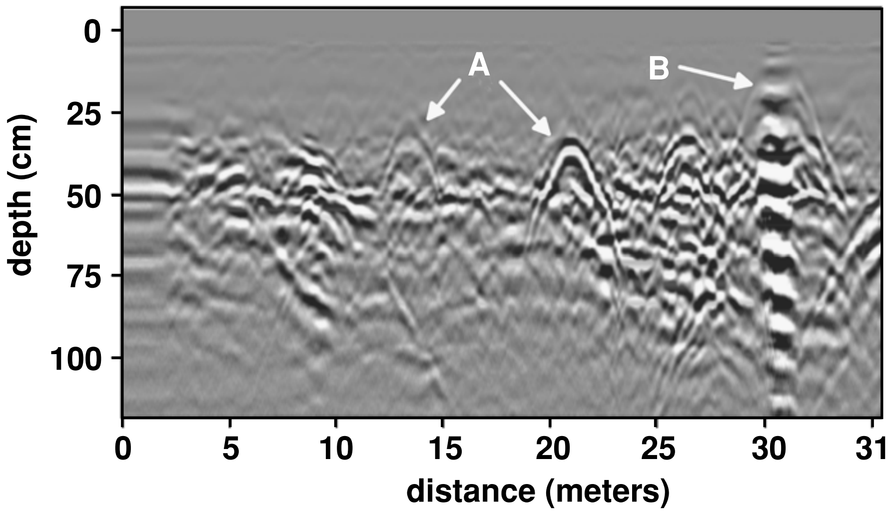


FIGURE 3.15
Point Source Hyperbolas. Buried pipes (A) have generated reflection hyperbolas in profile. The hyperbola on the right was generated from a metal pipe and the lower-amplitude hyperbola on the left from a plastic pipe. The series of high-amplitude reflections that are stacked vertically at location B were generated by a large piece of metal near the ground surface.

are also highly reflective, such as baked clay or some plastic objects, so multiple stacked reflections as shown in figure 3.15 do not indicate solely metal objects.

The depth of radar energy penetration and subsurface resolution is actually highly variable, depending on many site-specific factors such as overburden composition, porosity, and the amount of retained moisture. It is important to remember that in ground conditions that are highly conductive, radar energy will become attenuated at shallow depths, no matter what its wavelength. There is a common misconception that if a high-frequency antenna (say, a 500-megahertz) is only capable of transmitting energy to about 50 centimeters in the ground, then a lower-frequency antenna will transmit deeper. If a 300-megahertz antenna was also tried, and its maximum depth of penetration was about the same, then the ground is almost surely highly electrically conductive, and no antenna, no matter what frequency or how powerful, would be able to transmit to a greater depth.

At very high frequencies, usually greater than 1,500 megahertz, some geologic materials containing water will exhibit higher than normal energy attenuation due to energy loss from molecular relaxation (Annan and Cosway 1994; Olhoeft 1994b). This is usually not a problem in most archaeological applications, but due to the wide bandwidth of commercial antennas, some of the radar energy produced from center-frequency antennas of 800 megahertz or greater might be affected. Molecular relaxation occurs because water molecules are bipolar and will rotate and become aligned within an imposed electromagnetic field. This rotation causes the radar energy to be converted to mechanical energy, which is then dissipated as heat, much like how a microwave oven works (ASTM International 2003). Energy loss of this sort, which is frequency-dependent, is referred to as *dielectric relaxation*, and usually becomes a factor only if a GPR survey is being conducted in a very wet environment with a high-frequency antenna, which is rare.

Reflection Types

A series of reflection traces collected along a transect that are produced from a buried layer will generate a horizontal or subhorizontal line in profiles (either dark or light in gray scale reflection profiles) that is referred to simply as a *planar reflection* (as in the pit house floor in figure 2.1). These types of distinct reflections are usually generated from a subsurface boundary such as a stratigraphic horizon or some other physical discontinuity such as the water table, a buried soil horizon, or a horizontal feature of archaeological interest. There can also be *point source reflections* that are generated from one distinct aerially restricted feature or object in the subsurface (figure 3.15). The buried materials that generate these types of point source reflections could be individual rocks, metal objects, pipes that are crossed at right angles, and a great variety of other smaller things of this sort. They are visible in two-dimensional profiles as reflection hyperbolas, even though they were generated from a "point," or aerially restricted feature in the ground. A large number or density of hyperbolas in a reflection profile can often make interpretation difficult because many closely spaced hyperbolic reflections produce very complex and "busy" profiles (figure 3.16).

Point source reflection hyperbolas, sometimes termed *diffractions*, are generated because most GPR antennas produce a transmitted radar beam that propagates downward from the surface in a conical pattern, radiating outward as energy travels to depth (figure 3.17). Radar energy will therefore be reflected

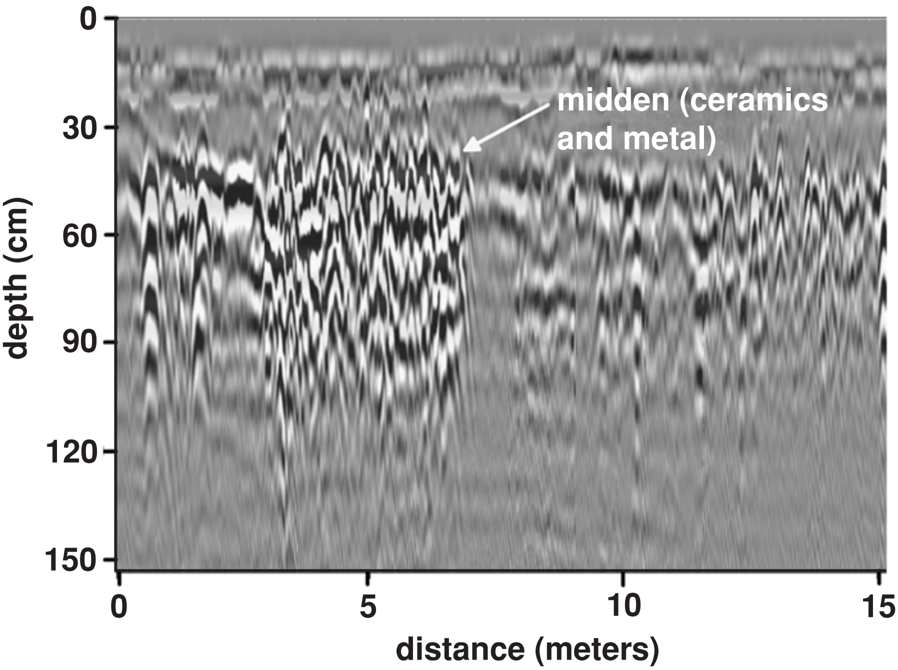


FIGURE 3.16
Many Small Hyperbolas. A cluttered group of many hyperbolas can be generated from small artifacts, such as these that were generated by small pieces of metal and broken ceramics, creating a complex reflection profile. This feature was excavated along the San Gabriel River in southern California, and found to be a nineteenth-century household midden.

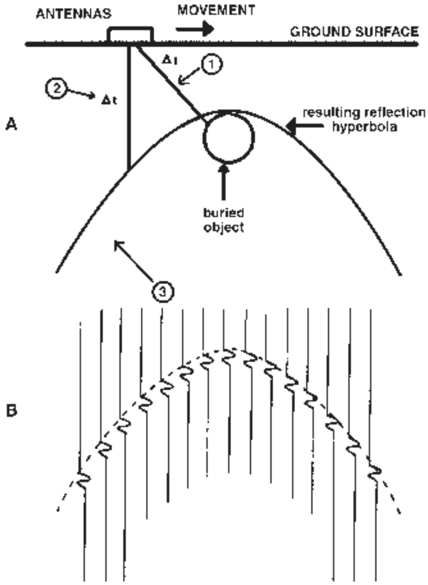


FIGURE 3.17
Generation of a Reflection Hyperbola. The conical projection of radar energy into the ground will allow radar energy to travel in an oblique direction to a buried point source (1) as seen in A. The two-way time (Δt) is recorded and plotted in depth directly below the antenna where it was recorded (2). When many such reflections are recorded as the surface antennas move toward and then away from a buried object, the result is a reflection hyperbola (3), when all traces are viewed in profile, as seen in B.

from buried features that are not located directly below the transmitting antenna but are still within the "beam" of propagating waves. Oblique radar wave travel paths to and from the ground surface are longer (as measured in radar travel time), but reflections generated from objects not located directly below the antennas will still be recorded as if they were directly below, but just deeper in the ground. As the surface antenna moves closer to a buried point source, the receiving antenna will continue to record reflections from the buried point source prior to arriving directly on top of it and continue to "see" it after it has passed. A reflection hyperbola is then generated because the time it takes for the energy to move from the antenna to the object along many oblique paths is greater the farther the antenna is away from the source of the reflection. As the antenna moves closer to the buried object, the reflection from it is recorded closer in time until the antenna is directly on top of it. The same phenomena is repeated in reverse as the antenna passes away from the source, resulting in a hyperbola where only its apex denotes the actual location of the buried reflection source, with the arms of the hyperbola creating a record of reflections that traveled the oblique wave paths. In some cases, only half of a hyperbola may be recorded, if just the corner or edge of a more planar feature is causing a discrete reflection, such as the edge of a buried house floor or platform of some sort.

The presence of reflection hyperbolas is considered by some geophysicists to be a distraction during data interpretation because they are not denoting the "real" location of buried features but are the product of the complex geometry of radar wave travel paths in the ground. Their presence, however, can aid in interpretation because hyperbolas are easily identified in reflection profiles and denote a specific size and possible geometry of objects in the ground. Most important, their utility in determining velocity (discussed in chapter 5) cannot be overemphasized. If it later becomes necessary to remove reflection hyperbolas from profiles, software programs (discussed in chapter 6) can "collapse" the hyperbola arms to their apex using data migration procedures. This is often necessary when performing more complex spatial analysis and mapping buried features in three dimensions where many hyperbola "tails" can create false anomalies, tending to blur the location of some objects in maps and three-dimensional images.

Resolution of Subsurface Features

Subsurface resolution is mostly a function of the wavelength of propagating radar energy and the geometry of the buried materials in the ground of interest. Low-frequency antennas (those of 10 to 120 megahertz) generate long-wavelength radar energy that can penetrate up to 50 meters or more in certain conditions but are capable of resolving only very large subsurface features. In pure ice, antennas of this frequency have been known to transmit radar energy many kilometers, and they are commonly used to determine the thickness of glacial ice or the orientation of subice bedrock surfaces (Bogorodsky et al. 1985; Delaney et al. 2004). In contrast, the penetration depth of a 900-megahertz antenna is about 1 meter, and often less, in typical ground conditions, but its generated reflections can resolve features down to a few centimeters in diameter. A trade-off therefore exists between depth of penetration and subsurface resolution. Table 3.2 shows the dominant wavelength for different center-frequency antennas, and how those wavelengths change as energy moves through materials of differing RDP.

The ability to resolve buried features is largely a function of the wavelength of energy reaching them at the depth they are buried. A "rule of thumb" is that the minimum object size that can be resolved is about 25 percent of the downloaded wavelength reaching them in the ground. *Downloading* of radar energy always occurs as energy passes in the ground (Jol and Bristow 2003) and decreases in frequency, increasing the propagating wavelength of the radar waves. For instance, a 400-megahertz center-frequency antenna will generate energy with a wavelength of 75 centimeters in air (table 3.2). When that energy downloads as it moves into the ground, its dominant frequency decreases to about 300 megahertz, which is a wavelength of about 100 centimeters. It is almost impossible to calculate what the downloaded wavelengths of any radar energy transmitted from an antenna would be, and it is usually sufficient to be aware of the downloading phenomenon.

Determining what the wavelength of any frequency radar wave might be in the ground is further complicated by additional changes in wavelength as energy passes through materials with different RDPs. In all cases, radar waves moving in the ground will decrease their wavelength from the downloaded energy. For instance, a 300-megahertz antenna generates a wavelength of about 1 meter in air (table 3.2). This frequency energy would download to about 200 megahertz or so in the ground, which would produce wavelengths of propagating waves of about 1.5 meters. But as the energy passes progressively through materials with increasing RDP (say, an RDP of 5), those same radar waves would then decrease their wavelength to about 0.67 meters (table 3.2). If they were then to travel even deeper in the ground and pass through material of even higher RDP, the wavelength would likely decrease even further. Although difficult to calculate and know for sure, an estimation of these wavelength changes is important because an object much smaller than about 25 percent of the wavelength of radar energy intersecting them would in all likelihood not be resolvable in reflection profiles. In the prior example, therefore, an object smaller than about 75 percent of 0.67 meters (about 17 centimeters in diameter) would probably not be resolvable using a 300-megahertz antenna.

Unfortunately, it is often not known in advance what the target depth of archaeological features of interest is, their dimensions, or often the ground conditions and their physical properties. Most important, the ability to transmit radar energy to the depth necessary is often not known until one actually collects some reflection profiles. The best one can usually do prior to going to the field is to make some rough calculations from the best knowledge available, and then take the antennas that will hopefully be necessary for the task. Antenna choice can therefore be a difficult decision. As a general rule, if the target features are within about 1 meter of the ground surface, antennas between 400 and 900 megahertz will be adequate to transmit energy to that depth and to resolve most features and associated stratigraphy (table 3.2). If target features are small, and greater resolution is needed, the higher frequencies antennas in this range should be used. If the target depth is between 1 and 3 meters, antennas from 500 to 200 megahertz or so are probably optimal. Radar energy with a frequency higher than about 500 megahertz will rarely transmit energy to greater than 2 meters in the ground, except in exceptionally dielectric media. Targets buried deeper than about 3 or 4 meters will require antennas with frequencies lower than 200 megahertz, but it is important to remember that the wavelengths generated from these frequencies are only capable of resolving fairly large features. Also, the deeper in the ground the energy must penetrate, the more spreading of the transmission

Table 3.2. Wavelength (in meters) of Radar Waves in Media of a Given RDP and Frequency

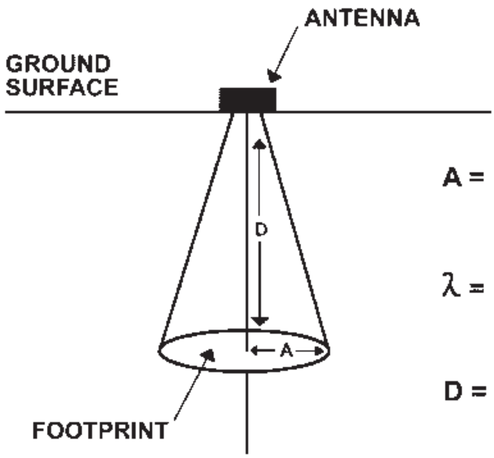
	Frequency (MHz)									
RDP	*100*	*200*	*300*	*400*	*500*	*600*	*700*	*800*	*900*	*1,000*
1 (air)	2.998	1.499	0.999	0.750	0.600	0.500	0.428	0.375	0.333	0.300
2	2.120	1.060	0.707	0.530	0.424	0.353	0.303	0.265	0.236	0.212
3	1.731	0.865	0.577	0.433	0.346	0.288	0.247	0.216	0.192	0.173
4	1.499	0.750	0.500	0.375	0.300	0.250	0.214	0.187	0.167	0.150
5	**1.341**	**0.670**	**0.447**	**0.335**	**0.268**	**0.223**	**0.192**	**0.168**	**0.149**	**0.134**
6	1.224	0.612	0.408	0.306	0.245	0.204	0.175	0.153	0.136	0.122
7	1.133	0.567	0.378	0.283	0.227	0.189	0.162	0.142	0.126	0.113
8	1.060	0.530	0.353	0.265	0.212	0.177	0.151	0.132	0.118	0.106
9	0.999	0.500	0.333	0.250	0.200	0.167	0.143	0.125	0.111	0.100
10	**0.948**	**0.474**	**0.316**	**0.237**	**0.190**	**0.158**	**0.135**	**0.119**	**0.105**	**0.095**
11	0.904	0.452	0.301	0.226	0.181	0.151	0.129	0.113	0.100	0.090
12	0.865	0.433	0.288	0.216	0.173	0.144	0.124	0.108	0.096	0.087
13	0.831	0.416	0.277	0.208	0.166	0.139	0.119	0.104	0.092	0.083
14	0.801	0.401	0.267	0.200	0.160	0.134	0.114	0.100	0.089	0.080
15	**0.774**	**0.387**	**0.258**	**0.194**	**0.155**	**0.129**	**0.111**	**0.097**	**0.086**	**0.077**
16	0.750	0.375	0.250	0.187	0.150	0.125	0.107	0.094	0.083	0.075
17	0.727	0.364	0.242	0.182	0.145	0.121	0.104	0.091	0.081	0.073
18	0.707	0.353	0.236	0.177	0.141	0.118	0.101	0.088	0.079	0.071
19	0.688	0.344	0.229	0.172	0.138	0.115	0.098	0.086	0.076	0.069
20	**0.670**	**0.335**	**0.223**	**0.168**	**0.134**	**0.112**	**0.096**	**0.084**	**0.074**	**0.067**
30	0.547	0.274	0.182	0.137	0.109	0.091	0.078	0.068	0.061	0.055
40	0.474	0.237	0.158	0.119	0.095	0.079	0.068	0.059	0.053	0.047
50	0.424	0.212	0.141	0.106	0.085	0.071	0.061	0.053	0.047	0.042
60	0.387	0.194	0.129	0.097	0.077	0.065	0.055	0.048	0.043	0.039
70	0.358	0.179	0.119	0.090	0.072	0.060	0.051	0.045	0.040	0.036
80	**0.335**	**0.168**	**0.112**	**0.084**	**0.067**	**0.056**	**0.048**	**0.042**	**0.037**	**0.034**

beam, and the more energy attenuation, so it may not be possible to get good reflections from deeper than 3 or 4 meters in most ground conditions, no matter what the antenna frequency. If targets are buried deeper than 5 meters or so, antennas with frequencies lower than about 100 megahertz are usually necessary, and ground that is dielectric enough to allow radar penetration to that depth is uncommon. Usually it must be exceptionally dry and lacking in conductive clay or salts, dry unweathered volcanic ash or perhaps permafrost, or very deeply frozen soil.

Another way to determine if features of a certain size are resolvable in reflection profiles is to calculate how much of a propagating beam of radar energy will illuminate them. As a basic guideline, the cross-sectional area of the target to be detected should approximate the size of the energy illumination pattern at the target depth or a little smaller (figure 3.18). If the radiating antenna is properly shielded so that energy is being propagated in a mostly downward direction, this elliptical *illumination pattern* (also called the *footprint*) on a horizontal surface (figure 3.18) can be calculated (Annan and Cosway 1992). If the target is much smaller than the footprint size, then only a fraction of the transmitted energy that intersects it within the cone of transmission will be reflected to the surface. The small number of reflections returned from a very small buried feature in this case would probably be indistinguishable from background reflections generated elsewhere within the transmission cone and therefore be invisible in reflection profiles. Small features of this sort might still be detectable if they create very high-amplitude reflections or after raw reflection data are computer processed to increase resolution, discussed in chapter 6.

An estimation of footprint size is also important when designing transect spacing within a grid so that all subsurface features of importance are illuminated by the transmitted radar energy and can therefore generate reflections. In general, the angle of the transmission cone, and therefore the size of the footprint, varies as a function of the relative dielectric permittivity of the material through which the waves pass, and the frequency of the radar energy emitted from the antenna. Equation 3 in figure 3.18 can be used to estimate the width of the transmission beam at varying depths. This equation can only be used as a rough approximation of real-world conditions because it assumes a consistent dielectric permittivity of the medium through which the radar energy passes and one single antenna frequency. Outside strictly controlled laboratory conditions, this is never the case. Sedimentary and soil layers within the ground almost always have variable chemical constituents, differences in retained moisture, compaction, and porosity. These and other variables create a complex layered system with varying relative dielectric permittivities and therefore energy transmission patterns, which are often difficult to define precisely.

Higher-frequency antennas, such as the 900-megahertz or higher, have quite narrow cones of propagation, while the 200- and 300-megahertz-frequency antennas can spread energy outward a meter or more at depths of only about one or two meters below the ground surface (figure 3.18). The cones of radar transmission in the ground are in reality more elliptical than circular in geometry because the electrical field produced by the antenna is generated parallel to its long axis and is therefore usually radiating into the ground perpendicular to the direction of antenna movement along the ground surface. If the antenna dipoles are positioned perpendicular to the direction of movement along



Equation 3

$$A = \frac{\lambda}{4} + \frac{D}{\sqrt{K+1}}$$

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 3.18
Conical Spreading of Radar Energy in the Ground. Radar energy spreads out in a conical projection as it travels into the ground. The approximate size of the radiation footprint at a depth in the ground can be estimated from the antenna frequency and the RDP of the ground through which the energy passes.

a transect (the usual orientation), the cone of propagation is more elongated parallel to the direction of transport. This will cause a greater propagation outward both in front and behind the antennas, and less to the sides.

The illumination footprint is much larger in dimension when radar energy travels through a material with a low RDP (figure 3.19). Higher-RDP material tends to focus the beam of transmission, decreasing the radius of the subsurface footprint. Therefore, when conducting a survey in ground with a high RDP, transect lines should be more closely spaced in order to make sure all subsurface features are illuminated with (and therefore can potentially reflect) radar energy.

Any estimation of the orientation of transmitted energy is also complicated by the knowledge that radar energy propagated from most surface antennas is not one distinct frequency but can range many hundreds of megahertz around

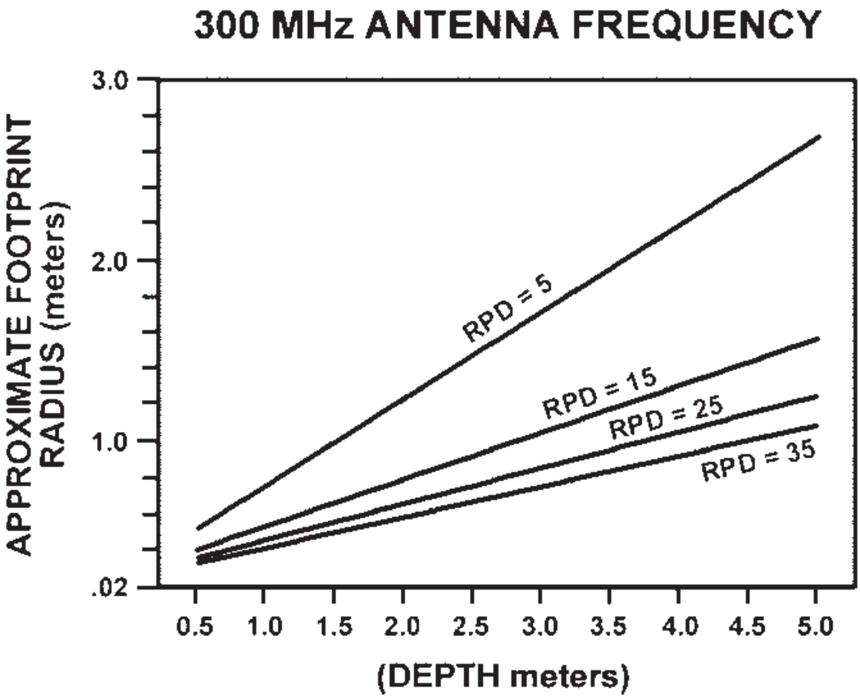


FIGURE 3.19
Radiation Footprint Differences with Differing Ground RDP. The cone of transmission is much broader (and therefore the footprint radius greater) with depth when the RDP of the material is low. In high-RDP material, the transmission cone is narrower, and its footprint radius at any one depth is much smaller.

a center frequency. If one were to make a series of calculations on each layer in the ground (assuming all the soil and sediment physical and chemical variables could be quantified), and if one distinct antenna frequency was assumed, then the "cone" of transmission would be seen to widen in some layers, narrow in others, and create a very complex three-dimensional pattern. The best one can usually do for most archaeological applications is to estimate the radar beam geometry and footprint size based on approximate field conditions and the center frequency of the antenna to be used. Some determination of the propagation beam dimensions, however, is always important prior to conducting a survey so that grid lines can be spaced at distances smaller than the maximum footprint dimension at the depth necessary to delineate the features of interest (equation 3 in figure 3.18). Any wider spacing of survey transects may allow important subsurface features to go undetected.

Recent field studies have shown that the amount of radar energy emitted from an antenna is greater directly under the antenna, and it tends to decrease in the more splayed portion of the cone of radiation (Leckebusch 2003; Neubauer et al. 2002). For this reason, survey line transects should be spaced as closely together as field conditions, equipment, and time allow (Jol and Bristow 2003). Comparisons of maps produced in grids containing variously spaced transects indicate that the highest-resolution images of buried features will always result from reflection data acquired in more closely spaced transects (Conyers et al. 2002; Neubauer et al. 2002).

Resolving a sequence of buried horizontal surfaces in the ground is even more complicated than determining whether individual objects might be visible in reflection profiles. To distinguish radar reflections generated from two parallel buried layers (e.g., the top and bottom of a large planar object), the two interfaces must be separated by at least one wavelength of the energy that is encountering them (Davis and Annan 1989). If the two reflections generated are not separated by that distance, then the resulting reflected waves from both the top and bottom will be either destroyed or unrecognizable due to constructive and destructive interference, as illustrated in figure 3.20. When two interfaces are separated by greater than one wavelength, two distinct reflections are generated from each interface, and both the top and bottom of the feature can potentially be resolved.

If only one buried planar surface is being mapped, then the first arrival reflected from that interface can usually be resolved, independent of the wavelength. Reflections generated from buried surfaces using longer-wavelength

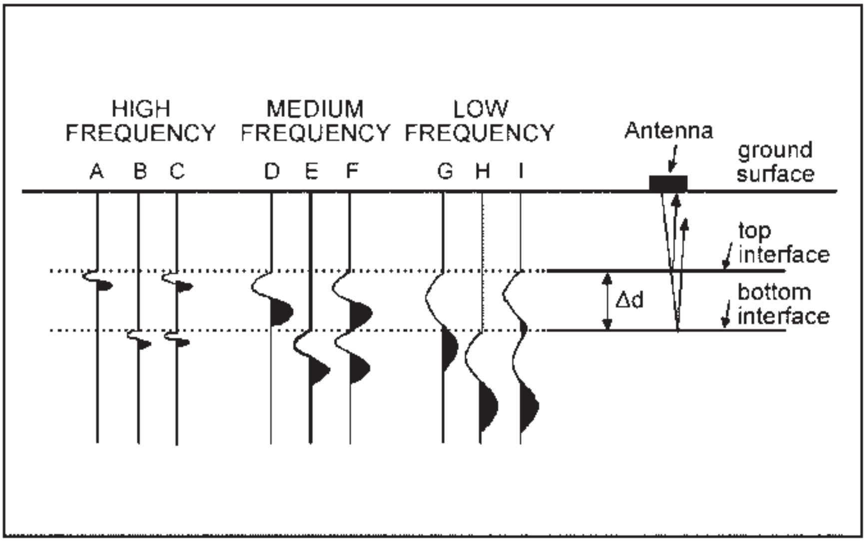


FIGURE 3.20
Resolution of Interfaces. Depending on the frequency of energy transmitted into the ground and the distance between two planar interfaces (Δd), reflections from the top and bottom of a layer may or may not be visible in a reflection profile. High-frequency energy will generate a small enough wavelength so that the top (A) and bottom (B) will produce a reflection, and the composite reflection trace of the two (C) can define both interfaces. Medium-frequency antennas with a longer wavelength will just barely have enough definition from the top and bottom (D and E) to produce a composite reflection trace (F) that exhibits both interfaces. Low-frequency antennas may produce a wave that will reflect off both interfaces (G and H), but the composite reflection trace is affected by constructive and destructive interference of the two waves, and only the top of the interface is visible in the composite reflection trace (I).

radar energy tend to be less sharp than those from higher-frequency antennas, when viewed in a standard reflection profile (Annan and Cosway 1992). This is because the longer wavelength energy tends to spread out more as it travels in the ground (figure 3.19) and is therefore reflected from more surface area (a larger footprint) than would occur with higher-frequency energy. As a result, small irregularities on the buried surface would not be visible, as they would likely be "averaged out" in the recorded reflection traces derived from a wider cone of transmission. This results in an averaging of many reflections from the buried surface and a more blurry composite reflection generated from the buried interface. In contrast, a high-frequency antenna produces a transmission cone that is much narrower, and its resolution of subsurface features on the same buried surface will be much greater as reflections received at the ground surface were generated from much less of the buried surface area. The trade-off, however, is that the higher-frequency waves will not propagate as far into the ground. This phenomenon is demonstrated in figure 3.21 where differing buried stratigraphic horizons are visible in both 300- and 500-megahertz center-frequency reflection data along the same traverse. A very different set of buried layers is detectable in both profiles because of variations in the depth of energy propagation, the resolution of those buried interfaces due to the wavelength differences of the energy reflected, and the footprint size on the reflection surfaces. In the step collection method the spacing of races also affects subsur-

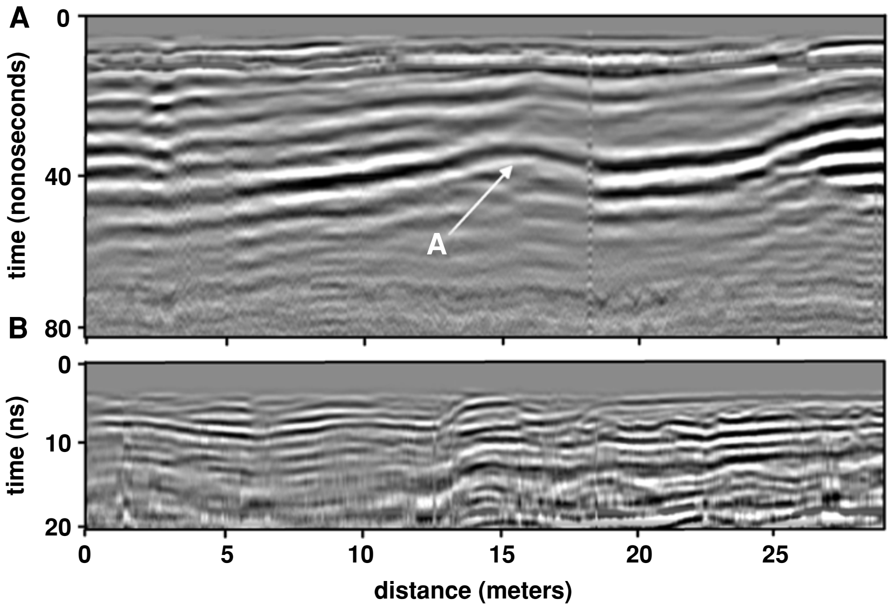


FIGURE 3.21
Resolution of Stratigraphy as a Function of Frequency. A 300-MHz reflection profile (profile A) generated energy that penetrated to about 50 nanoseconds and reflected off a number of subsurface interfaces. It exhibits relatively poor stratigraphic resolution in the upper 10 nanoseconds or so. In contrast, a 500-MHz profile along the same transect (profile B) exhibits high-definition reflections to only about 20 nanoseconds, but with good shallow resolution, showing many stratigraphic layers not visible in the lower-frequency profile. The upward bowing layer in profile B produced a lower-amplitude reflection along its crest (A) because some energy was scattered away from the surface antenna and was not received back at the surface antenna.

face Resolution with resolution decreasing with greater spacing (Jol and Bristow 2003).

Radar energy that is reflected off a buried interface that slopes away from a transmitting antenna will probably not travel back to the paired receiving antenna on the ground surface. In this case, all reflected energy would be lost, and the sloping interface will go unnoticed in reflection profiles. A buried surface with this orientation would only be visible if an additional antenna traverse were located in an orientation where that same buried interface is sloping toward the receiving antenna. This is one reason why it is important to always acquire transects of data within a closely spaced surface grid, and sometimes in traverses perpendicular to each other, in order for all buried features, no matter what their orientation, to be visible. This is the same concept exploited in the "stealth" technology for airplane construction. Wings and the fuselage of stealth aircraft are built in a geometry that reflects energy in any direction but back to the receiving antenna, making them essentially invisible to radar.

In most geological and archaeological settings, the materials through which radar waves pass may contain many small point targets that generate good reflections very small in size (e.g., the small ceramic artifacts in figure 3.16), which can only be described as *clutter* (if they are not the target of the survey). The amount of clutter visible in a reflection profile is totally dependent on the wavelength of the radar energy being propagated. If both the features to be resolved and the discontinuities producing the clutter are on the order of 25 percent of one wavelength, or a little less in maximum dimension, and about the same size, then reflection profiles may 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 that produces a long wavelength is used.

There will always be radar energy that propagates in many complex orientations depending on frequency changes and the complexities of materials in the ground. To minimize the amount of reflection data derived from the sides of a survey line (called *side scatter*), the long axes of the antennas are usually aligned perpendicular to the survey transect. This allows the cone of transmission to be elongated in an in-line direction (figure 3.18). If there are narrow elongated features in the subsurface that are parallel to the direction of antenna travel (and therefore parallel to the electrical field generated by the antenna), only a small portion of the radar energy will be reflected back to the surface. In this case, if the antennas were not traversing almost directly on top of the buried linear feature, it might not be visible. Elongated buried features of this sort would usually have to be oriented perpendicular to direction of antenna travel in order to be visible on GPR profiles, and they would be visible as distinct "point sources" with noticeable reflection hyperbolas when crossed in this orientation (figure 3.15). Electrical engineers have developed a number of different antenna designs that produce other types of radiation patterns, most of which are not used in standard GPR surveys for archaeology (Annan and Cosway 1992). Some have also experimented with many different antenna radiation patterns and orientations along transects, which necessitate very different data processing and interpretation methods that are not discussed here (Jol and Bristow 2003).

RADAR PROPAGATION AND REFLECTION COMPLICATIONS

Ground Coupling

When a dipole antenna is placed on the ground, a major change in the radiation pattern occurs, owing to *ground coupling* (Engheta et al. 1982). This coupling occurs as the electromagnetic waves move from transmission in the air to transmission within the ground. During this process, refraction occurs as the radar energy passes through surface units, creating a change in the geometry of the propagating radar beam, with most of the energy channeled downward in a more focused cone from the transmitting antenna (Annan et al. 1975). The higher the RDP of the surface material through which the energy passes, the lower the velocity of the transmitted radar energy, and the more focused (less broad) the conical transmission pattern becomes (Goodman 1994). This focusing effect continues to occur as radar waves travel into the ground and materials of higher and higher RDP are encountered (figure 3.22). The amount of energy refraction that occurs with depth, and therefore the amount of focusing of the conical beam, is a function of Snell's Law (Sheriff 1984). According to Snell's Law, the amount of reflection or refraction that will occur at a boundary between two media depends on the angle of incidence and the velocity changes that occur at the interface. In general, the greater the increase in RDP with depth (which is the case in most ground conditions), the more focused the cone of transmission becomes (figure 3.22). This is because soil and sediment layers deeper in the ground are usually more compact and also have higher water saturations, both of which lead to higher RDP values. Radar beams could theoretically broaden the deeper energy

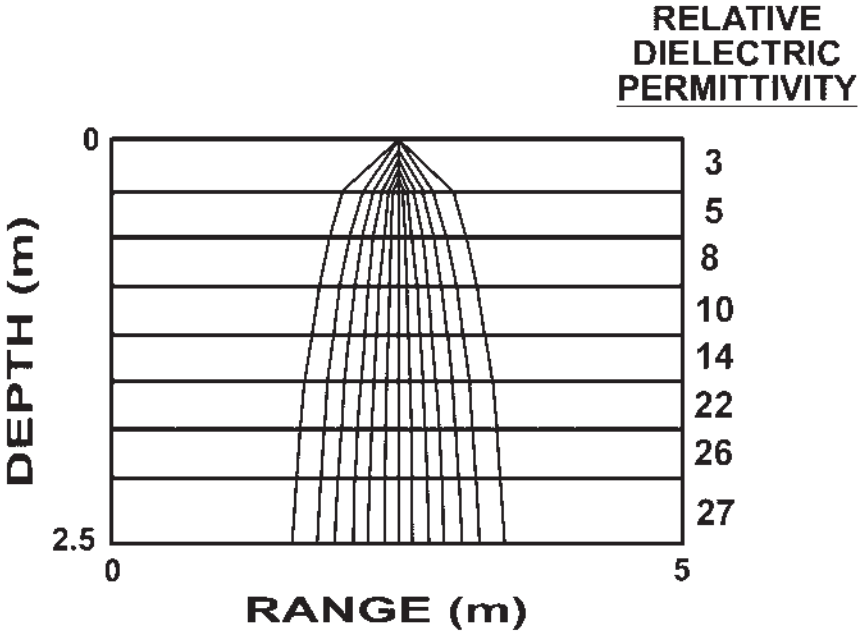


FIGURE 3.22
Energy Focusing with Depth. The radar energy cone of transmission will often become focused as energy travels in successive layers in the ground of increasing RDP, which is common for most field conditions.

moves in the ground if units of lower RDP were encountered, but this would be a rare phenomenon.

The type of surface materials within which the radar energy is coupled will also greatly affect the amplitude of the reflected waves below it. In figure 3.23, good radar reflections were recorded to about 40 nanoseconds through a surface material of limestone cobbles, but when the antennas crossed asphalt, the amount of energy coupled with the ground greatly increased. Reflections along the same transect were recorded at greater than 100 nanoseconds when the ground surface consisted of a good coupling material, illustrating how surface coupling can dramatically affect energy penetration depth and the resulting reflection amplitudes.

Radar energy coupling variations are also important because these changes in propagation depth and reflection amplitudes can be confused with “real” variations in reflectivity of materials in the ground when viewed in profiles.

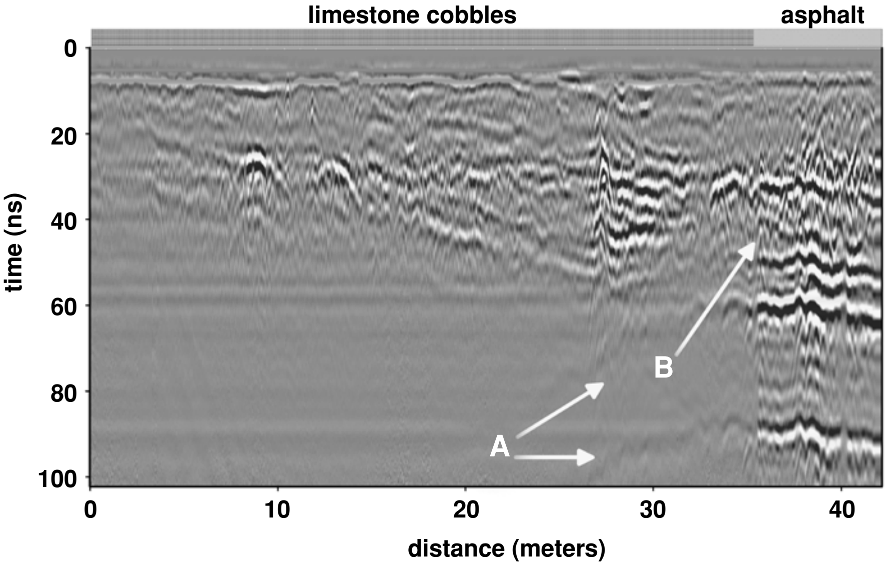


FIGURE 3.23
Coupling Changes Due to Differences in Surface Materials. Energy coupling with the ground can be variable, depending on the type of surface materials present. In this profile, collected along a street in southern Portugal, limestone cobbles had poor coupling properties, and energy propagated to only about 40 to 50 nanoseconds. Reflections that are visible at 60 and 90 nanoseconds on the right side of the reflection profile are barely visible (A) under the limestone cobble pavement. When the antennas crossed onto asphalt (B), coupling improved dramatically.

As antennas move over different surface materials (figure 3.24) or are moved over surface obstructions such as rocks or tufts of grass, coupling will also change, sometimes drastically and in a very short distance along a transect. This can create many strange and difficult-to-interpret reflection profiles with differing amplitudes of waves, none of which are reflecting "red" subsurface conditions. Uniform coupling, with little variation in the transmitted waveform along radar transects, occurs on paved surfaces and flat ground or areas with mowed grass. In uneven ground conditions, great care must be taken to keep the antennas close to the ground and at about the same orientation with the surface.

Frozen ground, especially with a thin layer of snow, can often be an excellent energy coupling surface producing little variation in transmitted waveform. In fact, some of the highest-quality GPR data have been acquired in frozen ground conditions, with excellent depth penetration and the recording of high-

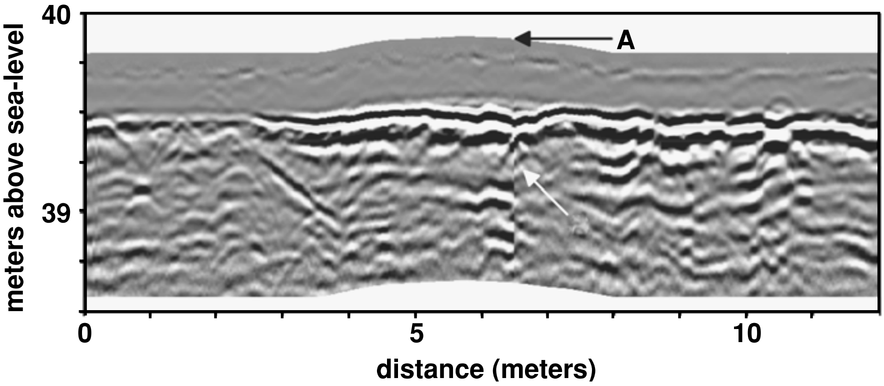


FIGURE 3.24
Coupling Changes Producing Anomalous Reflections. When antennas move over uneven ground and clumps of vegetation (A), antenna coupling changes the nature of waves traveling through the ground, producing anomalous amplitude changes (B), which can be misinterpreted as geological or archaeological changes.

amplitude waves. Data collected over the same ground after the ground thaws can often yield disappointing results, because of a drastic difference in energy coupling. One survey in particular that was conducted in Colorado is notable because the ground was frozen when data collection started in the early morning, producing high-quality reflection data. As the day progressed, and the sun slowly melted the ground surface, a noticeable decrease in the penetration depth of the energy was evident along with a decrease in amplitude of the reflected waves. This change was totally the result of differences in energy coupling and not differing constituents of materials in the ground.

Background Noise

An additional complication that affects resolution of reflections in the ground is *background noise*, which is almost always recorded during GPR surveys. Ground-penetrating radar antennas employ electromagnetic energy of frequencies that are similar to those used in television, FM radio, and other radio communication bands, so there are almost always nearby noise generators of some kind (figure 3.2). If there is an active radio transmitter in the vicinity of the survey, then there may be more interference than usual, but even when far away from the city, there will usually be background noise of some kind. Most radio transmitters have a very narrow bandwidth; if its frequency is known, it can be determined in advance, and an antenna frequency can be selected that is as far away as possible from any frequency that might generate spurious reflections in the data. With the wide bandwidth of most GPR antennas, however, it is usually difficult to completely avoid such external transmitter effects, and any major adjustments in antenna frequency may affect survey objectives.

External electromagnetic noise usually only becomes a significant problem if a study site is located in a city, near a military base, airport, or radio transmission antennas. One survey conducted near a U.S. military research site was occasionally disrupted by radar noise from unknown sources. This noise was visible during collection as periodic very high-amplitude reflection traces that totally overwhelmed any reflections derived from within the ground (figure 3.25). Many different frequency-filtering schemes were attempted, to no avail.

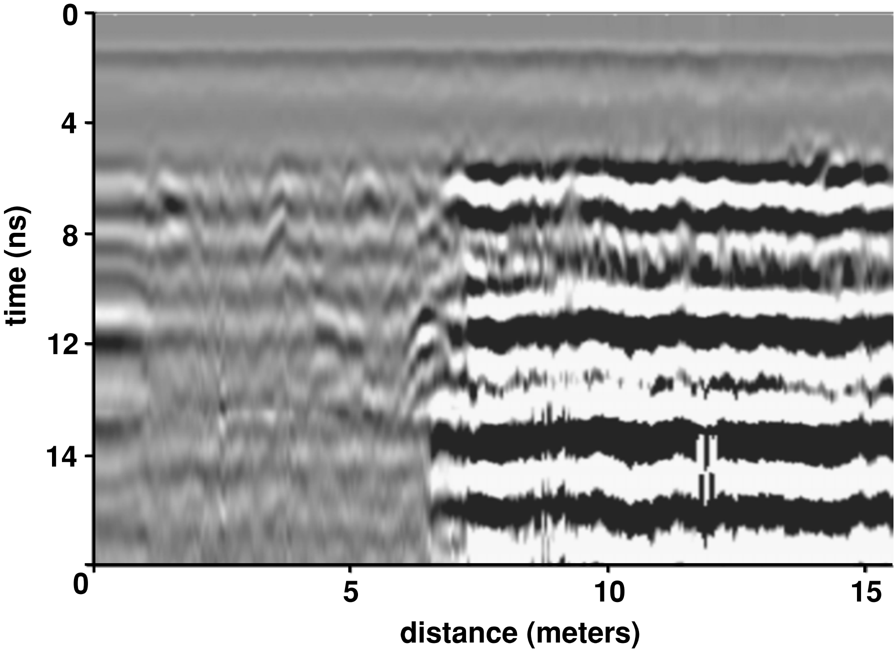


FIGURE 3.25
Extreme Electromagnetic Noise in a Reflection Profile. Sometimes electromagnetic energy noise generated from a source nearby will totally overwhelm energy recorded at a surface antenna from within the ground. This reflection profile shows the onset of a "blast" of noise producing very high-amplitude reflections from 7 to 16 meters along the transect. The source of this noise, near the Los Alamos National Laboratory, in New Mexico, was never discovered and lasted about 15 minutes.

Finally, in about an hour, the noise completely disappeared, and data collection could continue. The source of the interfering electromagnetic energy was never discovered.

The recent proliferation of cellular telephones that can be in use nearby during data acquisition has also become a problem, as they produce FM radio noise in the same frequencies as some GPR antennas. This type of noise has been observed when collecting GPR data near a busy road where interference generated by passing motorists using cellular phones periodically disrupted recorded reflections.

Focusing and Scattering Effects

Reflection off a buried surface that contains ridges or troughs, or any other irregular features, can either focus or scatter radar energy, depending on the surface's orientation and the location of the antenna on the ground surface. If a reflective subsurface plane is slanted away from the surface antenna's location or is shaped so that the surface is convex upward, most energy will be reflected away from the antenna, and no returning energy, or a very low-amplitude reflection, will be recorded (figures 3.21 and 3.26). This is termed radar *scatter*. The opposite is true when the buried surface is tipping toward the antenna or the surface is concave upward (figure 3.26). Reflected energy in this case will be focused, and a very high-amplitude reflection derived from a portion of the buried surface would be recorded.

Figure 3.26 illustrates an archaeological example of the focusing and scattering effects when a narrow buried moat is bounded on one side by a trough and the other side by a mound. When the radar antenna is located to the left of the deep moat, some of the reflections are directed back to the surface antenna, but there is some minor scattering, generating a weaker reflection than usual from the buried surface. When the antennas are located directly over the deep feature, there will be a high degree of scattering, and much of the radar energy, especially that which is reflected off the sides of the moat, will be directed away from the surface antenna and not be recorded. This scattering effect would make the narrow moat almost invisible in reflection profiles. When the antenna is located directly over the wider depression to the right of the moat, there will be focusing of the radar energy, creating a higher-amplitude reflection from this portion of the subsurface interface.

This focusing and scattering condition is quite common, and it can occur

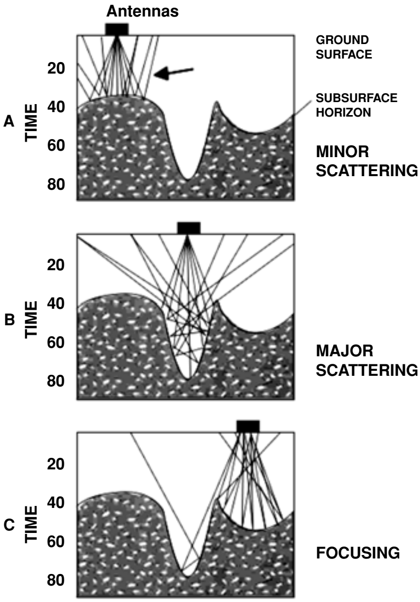


FIGURE 3.26
Energy Scattering and Focusing. Radar energy transmitted from a surface antenna will be scattered from a convex upward interface (A). Deep trenches or other near-vertical features (B) will produce a great deal of scattering, and little energy will reach the surface antenna to be recorded, making features of this sort almost invisible in reflection profiles. Concave upward features (C) will focus radar energy, producing high-amplitude reflections.

often repeatedly along one buried planar surface. It was noticed when mapping the surface of a buried prehistoric agricultural field, consisting of uniform ridges and furrows (figure 3.27). The furrows on this buried interface focused the radar energy, creating higher-amplitude reflections while the ridges scattered it, producing only weak reflections or none at all. The undulating surface itself was not discernible in reflection profiles, as a 300-megahertz antenna was used, which tended to blur somewhat the reflection from the buried interface. It was the periodic changes in the wave amplitudes that were a hint that these types of buried features were present. The layer was later excavated, and the

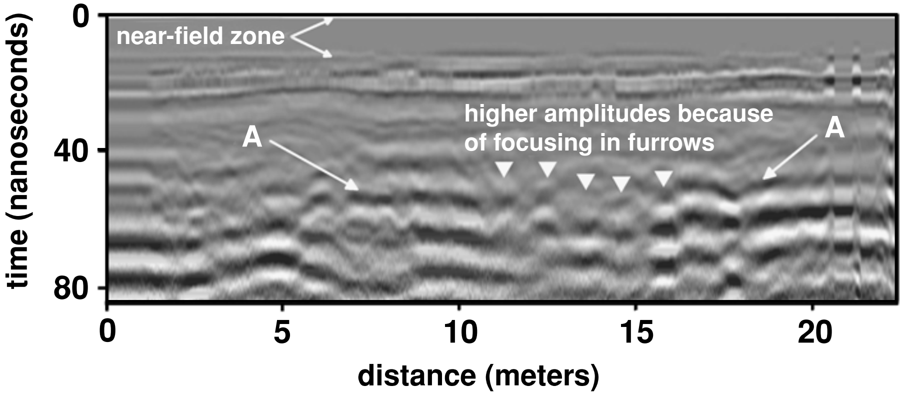


FIGURE 3.27
Scattering and Focusing on a Horizontal Reflection Surface. Varying high and low amplitude reflections along reflection surface (A) were found to be small ridges and furrows in a buried agricultural field at the Ceren site in El Salvador.

geometry of the bedding plane was confirmed to be a buried ancient agricultural field (figure 3.28).

The Near-Field Effect

Energy radiated from a surface antenna generates a strong electromagnetic field around the antenna within a radius of about 1.5 wavelengths of the center frequency (Balanis 1989; Engheta et al. 1982; Kraus 1950; Sheriff 1984). Within this zone, coupling of the radar energy is occurring with the ground, generating an advancing wave front of propagating waves in the standard conical transmission pattern. It can be said that the ground within about 1.5

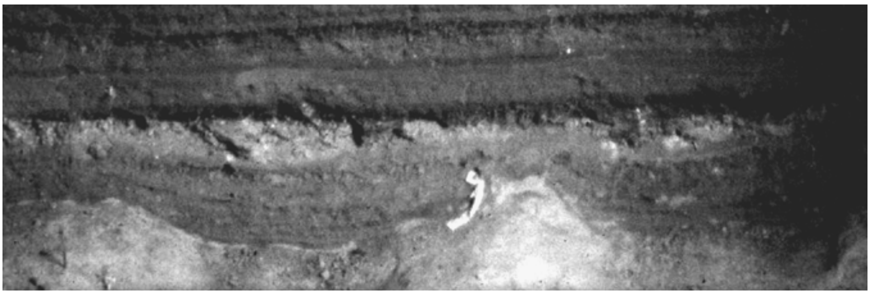


FIGURE 3.28
Buried Agricultural Field That Causes Focusing and Scattering. Excavation of the reflecting surface A, shown in figure 3.27, shows the ridges and furrows of a prehistoric agricultural field, which alternately focused and scattered reflected radar waves.

wavelengths of a standard dipole antenna is technically "part of the antenna" in that no radiation is occurring within this zone and therefore technically no wave propagation. This *near-field zone* is usually visible in GPR profiles as a region of little or few reflections beginning at the ground surface and continuing to some depth (figure 3.21). In the GPR literature, this zone is sometimes incorrectly called the near-surface zone of interference. For the 10-, 100-, and 1,000-megahertz antennas, the near-field zones are approximately 30 meters, 3 meters, and 30 centimeters, respectively, but vary depending on the downloaded frequency.

If low-frequency antennas are used, the near-field zone where few significant reflections are generated can sometimes be between 2.5 and 5 meters of the ground surface. If the target features are located within the near-field zone, it is unlikely that they will be visible in GPR profiles, and a higher-frequency antenna should be used. There can, however, sometimes be important reflection data recorded within the near-field zone, even if reflections are not immediately visible on standard two-dimensional reflection profiles. Due to the wide bandwidth of radar transmission, some high-frequency (shorter-wavelength) energy will still be generated even from a lower-frequency antenna, which will couple with the ground at a much shallower depth, and some shallow reflections can still be generated and visible in profiles within what is broadly defined as the near-field zone. If these reflections are high enough in amplitude, they will still appear as weak reflections within the otherwise reflection-free near-surface layer. Some subtle reflections in the near-field may never be noticeable in standard two-dimensional profiles but can become visible after the data are computer processed to produce amplitude slice maps, which are discussed in chapter 7. Other very weak, but important, reflections in the near-field can also be enhanced in profiles by increasing amplitudes in the shallowest portion of the profiles with the aid of computer software. This technique, called *range gaining*, is usually performed during equipment setup prior to collecting data (chapter 4), but it can also be applied after returning from the field, which is discussed in chapter 6.

Air Waves and Near-Surface Obstructions

The wide field of energy transmission from most GPR antennas can produce unwanted reflections that occur from features that may not be in the ground, especially with lower-frequency antennas that are not well shielded.

When using unshielded antennas in areas of high-tension power lines or nearby buildings, reflections are likely to be produced from these features, creating what are called *air waves* in reflection profiles (figure 3.29). These reflections are often high in amplitude and can obscure meaningful reflections from within the ground. They are called air waves because the radar energy that produces them travels to and from the unshielded GPR antennas in the air. As the velocity of radar transmission in air does not change like it does in the ground, air waves produce very straight reflections that occur at one time in the profiles when antennas are moved parallel to the reflecting surface. When antennas are moved toward or away from a surface reflecting source, the energy traveling in air will be recorded as a straight reflection that gradually increases or decreases in time (figure 3.29). A GPR survey was once attempted with poorly shielded 300-megahertz antennas in a parking lot, bounded on three sides by tall buildings, and there were many more air wave reflections recorded from the buildings than from within the ground, making the survey results essentially unusable.

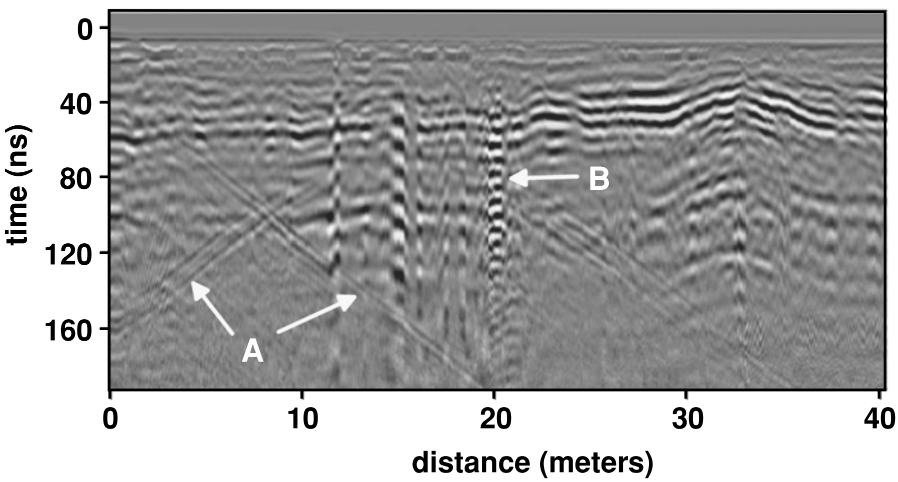


FIGURE 3.29
Air Waves. Radar energy that travels in air from the antenna, to an object on the surface, and back to the antenna is recorded as air waves (A), visible as sloping, almost straight reflections. This reflection profile was collected with unshielded 300-MHz antennas along the edge of a road in El Salvador where nearby trucks reflected energy. Three pieces of buried metal can also be seen as multiple horizontal reflections, one of which is noted as (B).

The air wave problem was encountered to a large extent within a deep excavation whose sides had been supported by metal barriers to keep them from collapsing (Carrozzo et al. 2003). The high-amplitude air waves generated from the metal barriers either overwhelmed or interfered with reflections from within the ground, necessitating a complex series of processing steps to remove them. This was done by first producing a mean profile of the air wave reflections generated

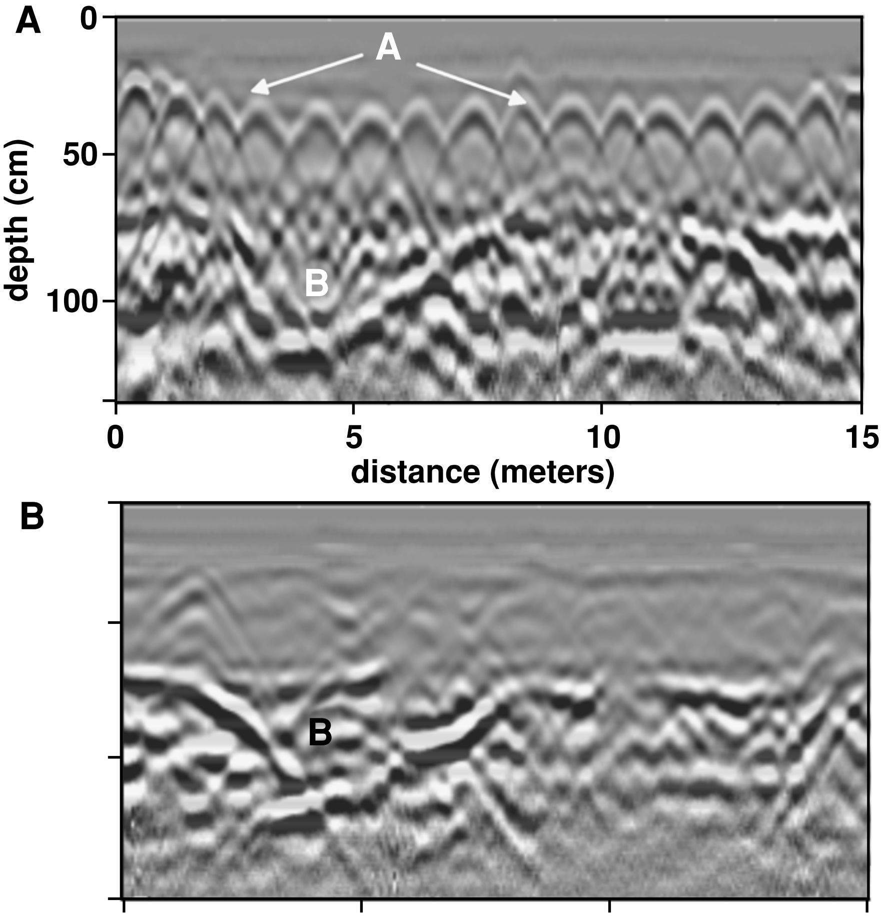


FIGURE 3.30
Near-Surface Metal Interference. Metal reinforcing bars buried in surface concrete produce evenly spaced hyperbolic reflections (A) in profile A collected over a buried trench (B). Enough energy is transmitted through the metal obstructions to produce a useful image of the buried features below. In profile B, located 50 centimeters away and parallel to profile A, the surface pavement contained no metal, and the trench (B) is much better defined. These profiles were collected in downtown Reno, Nevada.

from the metal walls, which was possible because the walls were a known distance away from the antennas, and the velocity of the air waves was known (the speed of light) and their arrivals were calculated. The mean reflection profiles of the predicted air waves were then subtracted from the actual reflection profiles to produce residual reflection profiles, which were then processed to increase the remaining amplitudes generated from within the ground. Good results were achieved, but only after significant and lengthy data-processing steps.

Surface or near-surface metal objects can often create multiple reflections that "ring down" through a profile or create a number of shallow reflection hyperbolas, obstructing some or all features below them (figure 3.30). This is very common when conducting GPR surveys on road surfaces where metal reinforcing bars are used to stabilize concrete or where there are an abundance of buried pipes. Buried metal wire or bars used for reinforcing in roadways and sidewalks will often produce many equally spaced hyperbolic reflections, which are very distinct in reflection profiles (figure 3.30). Even with this kind of near-surface energy obstruction, some radar energy will still travel between the metal, reflecting from other materials buried deeper in the ground, and usable data can still sometimes be obtained.