5

Velocity Analysis

One of the primary purposes of modern GPR surveys is to accurately map stratigraphy and buried archaeological features in three dimensions. In the past, many GPR studies, especially those conducted in archaeological investigations, had the limited objective of defining buried anomalies that could potentially represent archaeological features, which could be excavated later. The actual depth and orientation of any features discovered, and the nature of surrounding stratigraphy that may have been related to those features, were usually of secondary interest.

In contrast to most of these early "anomaly hunting" GPR studies, most recent work has been conducted for the purpose of noninvasively mapping buried features in detail, sometimes without ever having to excavate. Many times when excavations are planned as a follow-up to geophysical mapping, GPR maps can very accurately delineate specific areas (that are hopefully the areas of importance related to certain research questions) to concentrate on without the need for extensive digging. To accomplish these goals, precise subsurface mapping in true depth is necessary.

Archaeologists with a geological background have also learned that GPR data yield excellent stratigraphic information about sediments and soils that surround archaeological features of interest (Conyers 1995; Conyers et al. 2002; Imai et al. 1987), which are usually areas of sites that are rarely studied in detail by standard archaeological methods. This kind of stratigraphic information, unobtainable in any other way except with long trenches or dense coring, can be of great value when reconstructing buried topography, studying anthropogenic disturbance, analyzing postdepositional processes, or mapping buried soil zones or other ancient landscape features.

The changing focus of GPR exploration in archaeology has necessitated accurate subsurface mapping in real depth. Specific reflections visible in GPR data, which are always measured in two-way travel time, must usually be tied to known stratigraphy or archaeological features at measurable depths. This conversion of two-way travel time to depth can be conducted as part of the preacquisition equipment calibration procedure and at the very least must be done before any realistic data interpretation can begin once returning from the field. Conversion of radar travel times to depth can only be conducted if the velocity of the material through which the radar energy is traveling can be calculated. This chapter describes a number of field and laboratory tests that can be performed to arrive at those velocity measurements.

Radar wave travel time is the only direct measurement obtained using GPR equipment in the field. Depth (or distance) to buried interfaces or features of interest can be directly measured only using a measuring tape or other distance measuring device in an open excavation or outcrop or by probing or coring. If both time and distance are known from these two direct measurements, average velocity of wave propagation in the ground can be calculated. There are two general field techniques for determining velocity: the *reflected* (or possibly *refracted*) *wave* method and the *direct-wave* method. Reflected wave methods require that radar energy be reflected from objects or stratigraphic interfaces at depths that can be directly measured (Conyers and Lucius 1996; Sternberg and McGill 1995). Direct-wave methods transmit radar waves directly through the ground, from one antenna to another, also along a measured distance. Other methods of obtaining velocity are a direct measurement of the relative dielectric permittivity of samples in the laboratory (which rarely mimic field conditions) or an analysis of the geometry of reflection hyperbolas generated from buried point sources using various computer programs.

If possible, multiple velocity tests should be conducted at different locations of a study area because it is common for the velocity of soils and sediments in a test area to change both laterally and with depth. Lateral velocity variations are most commonly caused by changes in water saturation and lithology across a site. Water content is usually the single most significant variable that affects radar wave velocity (Conyers 2004). Dry quartz sand has a RDP of about 4 (table 3.1), which calculates to a radar wave velocity of 14.99 centimeters per nanosecond (equation 3.1). In contrast, the RDP of water is about 80, which yields a radar velocity of 3.35 centimeters per nanosecond. Therefore, if only a small amount of water is contained in the pore spaces of dry sand, the velocity of radar energy traveling in it will decrease significantly because of that additional moisture. In most settings, the water content of soil and sediment will naturally increase with depth, and therefore the average radar wave velocity of the material will correspondingly decrease.

The degree of residual water content in sediment and soils located above the water table, as well as the depth to the water table, can often fluctuate dramatically across an area due to changes in surface topography, stratigraphy, and the location of drainage features. In archaeological contexts, buried anthropogenic features can also create layers of different composition that affect water saturation and create dramatic velocity changes across a site. Velocity is therefore influenced by water saturation differences as they are controlled by changes in the composition of sediment and soils. Many times it is difficult to determine the causes of velocity differences across an area because they can be related to both water saturation changes and material differences, or, usually, both.

It is important to recognize that velocity measurements at a site are often valid only for GPR data that are collected within a few days (or sometimes a few hours) of when the tests are performed. Changes in velocity can vary dramatically with time as sediment and soil moisture fluctuate seasonally and can sometimes change rapidly, even during the time a survey is being carried out, due to torrential rainfall, snowmelt, or flooding. For example, velocity tests performed at a site in Central America, consisting of mostly volcanic ash, during the rainy season yielded a RDP of 12 (average velocity of 8.7 centimeters per nanosecond) (Doolittle and Miller 1992), while similar tests performed in the same area at the end of a 6-month dry season measured a RDP of about 5, or an average velocity of 13.4 centimeters per nanosecond (Conyers 1995; Conyers and Lucius 1996). In this case, if the velocity tests performed during one season were used to process and interpret GPR data acquired just a few months later, the velocity adjusted depths of radar reflections would be extremely inaccurate. The same kind of dramatic changes have also been seen overnight. In the American Southwest, good radar reflections were obtained one day, from depths approaching 2 meters with a 500-megahertz antenna. Overnight 3 inches of rain fell, and the next day, poor reflections from a maximum depth of only 50 centimeters were recorded, with a completely different calculated RDP (Conyers and Cameron 1998). In this case, the addition of water changed not only the velocity of radar propagation but also the depth of radar energy penetration in the ground.

REFLECTED WAVE METHODS

The most accurate and straightforward method to measure velocity is to identify reflections in GPR profiles that are produced from objects, artifacts, or zones of interest, which occur at known depths. These methods allow for a direct determination of the average velocity of radar waves from the surface antenna to a measured depth. In the past, these types of velocity tests have been conducted at archaeological sites on objects as diverse as buried whale bones (Vaughan 1986), copper wire (Kenyon 1977), and empty paint cans (Doolittle and Miller 1992). Because metal is a near-perfect radar energy reflector, the reflections generated in a profile crossing a metal object are easily identifiable on most GPR profiles as distinct hyperbolas. Other tests of a similar sort can be performed when a buried wall or some other point source reflection feature is partially exposed in an excavation and can be identified in GPR profiles (Conyers and Lucius 1996). In a similar way, identifying a distinctive reflection generated from a noticeable material change in the ground, and then coring or excavating a test trench to expose it, will serve the same purpose as long as the exact reflection surface can be positively identified. This was done where a stream channel, with a distinctive base, was seen in reflection profiles and this surface could be easily distinguished in an auger probe as a change from coarse sand and gravel to clay at the base of the channel (figure 5.1). The depth of the channel bottom was then measured in the auger hole and velocity could be easily calculated.

In all cases, velocities measured in this way are an average from the ground surface to the depth of the object or interface measured. Multiple tests of this type from many depths in the ground can determine if there is a large change in

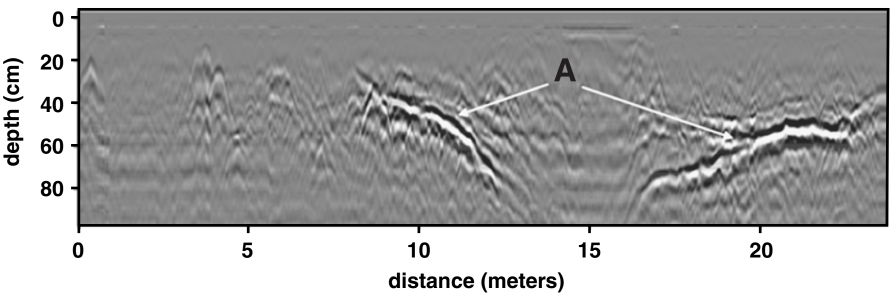

FIGURE 5.1
Stratigraphy Identification for Velocity Determination. The base of a sandy river channel (A) was visible in profiles collected near Lompoc in coastal California with a 500-MHz antenna. The depth to the base of the channel was tested with an auger, and velocity was calculated.

velocity with depth and also laterally across a site. Without accurate velocity measurements, all interpretations of GPR profiles that require any three-dimensional resolution will be speculative.

The easiest and most accurate method for determining velocity is to excavate or find a nearby trench or outcrop and place an iron bar horizontally in a vertical face. Antennas are then slowly pulled over the bar while subsurface reflections are recorded in a profile. The metal bar will be apparent as a distinct reflection hyperbola, such as that in figure 3.15. To obtain the maximum amount of reflection from a thin metal bar, the long axis of the surface antennas (from side to side) must be oriented parallel to the length of the horizontal bar. This antenna orientation will create an electric field that is also oriented parallel to the bar, producing the maximum amount of reflection. Also, when doing these types of tests the correct antenna frequency suitable for the depth and object size that needs to be illuminated must be used. If a low-frequency antenna is used, a fairly large target may be necessary in order for it to be visible on standard two-dimensional profiles, because of this antenna's lesser resolution.

When reflection profiles are immediately visible on the computer screen during data collection, and if a time scale is superimposed on the profile, the apex of the hyperbola can be measured in time. Time and depth yield then yield velocity, which can be immediately used to calculate the time window for the depth necessary to resolve features of interest. If the iron bar is not visible, the profile may have to be processed later on to increase the visibility of the target, using the data-filtering and enhancement methods discussed in chapter 6.

When multiple tests are made at different depths at a study area, differing velocities will often be calculated because of changes in water saturation and ground composition with depth. If only one average velocity is used (which is often the case), there could be vertical distortion if a velocity derived from a shallow direct-wave test were used (which would likely have a relatively high velocity) to depth correct all reflections in a profile. Reflections produced from interfaces close to the ground surface would be corrected to about their correct depth, but those from deeper in the ground would likely appear too shallow, as radar travel times from deeper in the ground are probably slower. The alternative would also be true if an average velocity obtained from an object deeper in the ground were used, which would yield a slower average velocity. That slower velocity, when applied to a whole data set, would tend to make shallow reflections appear deeper than they really are.

This is one of the pitfalls encountered using an average RDP (velocity) to correct radar travel times to depth during data processing. If different RDP values were known for specific depths, it is possible for some computer programs to convert profiles measured in time to depth profiles using varying RDPs for different depths. There might still be some distortion in the resulting profiles at the boundaries between units with differing RDP because abrupt velocity changes would be inferred that may not be real. A more accurate approach would be to obtain RDP values at varying depths and then compile a velocity variation curve for the stratigraphic section as a whole. Some GPR data-processing programs allow this type of sophisticated correction to create more accurate depth profiles.

It is quite possible that the imposition of only one velocity (or RDP), derived from a test performed in only one area of the site, to all of the GPR data acquired in surrounding grids could yield spurious depth calculations if subsurface conditions change laterally. For instance, if there were higher water saturations in one area because of a perched water table (yielding slower velocities), actual depth to interfaces of interest might also vary considerably. For the most part, without detailed stratigraphic knowledge of a site, these variations would probably go undetected, and interpretations regarding the depth to certain units would be inaccurate. A more geographically dispersed data set of velocity calibration tests might possibly allow a velocity gradient map to be made in three dimensions and produce more accurate profiles and maps. Without them, these potential velocity problems must be accepted as part of the inherent imprecision of the GPR method.

Another type of mistake that is possible with velocity conversions was made in an area where the only place available for a direct-wave test was an excavation face that had been left exposed to the elements for two years (Conyers et al. 2002). This occurred in a desert area in Jordan where wind blown sand was the matrix material of the site. Numerous direct-wave tests were made on an iron bar at different depths along that exposed face and velocities were found to be consistently very high throughout the section, with an RDP of about 3. All reflections in the grid were then corrected using this average velocity, and the depth to features and stratigraphic interfaces of interest throughout the study area were mapped. When these features were later excavated, it was found that all mapped features were almost three times shallower than predicted in the GPR maps! After evaluating what could have gone wrong, it was concluded that the sand in the exposure where the velocity tests were performed had been allowed to dry out significantly along the excavation face, creating an anomalously dry material that allowed radar waves to travel at a very high velocity. The same type of material that remained buried (where the GPR data were collected) retained its natural moisture. A very erroneous velocity was therefore applied to all the reflection data. This simple, but potentially disastrous, mistake immediately called into question the capability of the geophysical archaeologists conducting the survey, as the features were uncovered while they were still present in the field (Conyers et al. 2002). Fortunately, all involved understood (or were made to understand!) the potential velocity pitfalls in GPR processing and were able to quickly correct the mistakes in processing before additional excavations were conducted. If excavations had taken place days or weeks later, after the geophysicists conducting the survey had long left the field, all the GPR survey results might have been called into question. In this case velocity tests should have been conducted in newly excavated trenches, not the older excavations where the sediment had been allowed to dry out.

DIRECT-WAVE METHODS

Although sometimes not as accurate as reflected wave methods, direct-wave techniques provide an additional way to determine radar wave velocity in the field. In these types of tests, two antennas are separated, with the material to be tested located between the two. One antenna then transmits to the other, and the one-way transmit time between the two can be measured. If the distance between the two antennas is known, velocity can be calculated (Conyers and Lucius 1996). One type of a test of this sort is called *common midpoint* (CMP) (Fisher et al. 1994; Leckebusch 2003; Malagodi et al. 1994; Tillard and Dubois 1995), and a similar test is *wide-angle refraction and reflection* (WARR) (Imai et al. 1987; Milligan and Atkin 1993; Reynolds 1997: 710). *Transillumination* tests are a third type, all of which are based on the same general method where radar waves are transmitted in a one-way direction between two antennas that are separated by the material to be tested.

In all of these types of tests, a GPR system that allows two antennas to be separated is necessary. Many GPR systems commonly used by archaeologists collect data with dual antennas that are permanently attached, recording on only one channel with one antenna cable leading to the control unit, and for this reason these types of velocity tests are not as common as others. Some manufacturers produce dual antennas that are clipped together and can be easily separated, but special connections are usually necessary to allow this separation (or two cables: one connecting each antenna). Otherwise a cable splitter with two separate antennas, or a multichannel GPR system are necessary. If the only two antennas available for a direct-wave test are not the same frequency but are close (e.g., 400- and 500-megahertz antennas), both may be used, as they will both transmit and receive within each other's bandwidth.

CMP and WARR Tests

In both WARR and CMP tests, radar energy is sent from one antenna to the other as they are moved an increasing distance apart. Individual reflection traces are usually collected (and often stacked to improve their quality) in step mode for this type of test. The radar waves moving between the antennas will pass through both the air and near-surface layers of the ground and be received at the other (figure 5.2). If the distance of separation is known and the radar wave travel paths can be deduced, the arriving waves can be measured in time, and a series of velocity measurements of different layers in the ground can potentially be calculated. In the CMP method, both antennas are first placed next to each other on the ground, and one reflection trace is collected. There may be three or more wave arrivals collected at this location: one that travels in air, one along the air–ground interface and possibly more that are reflected and refracted from buried interfaces in the ground. The antennas are then separated a measured distance (10 centimeters, perhaps), and another reflection trace is recorded (figure 5.3). This collection procedure is repeated many times until the antennas are separated by as much as 5 or 10 meters. Energy will continue to travel a number of paths between the two antennas, and if the wave arrivals that have traveled within the ground can be identified, and the distance between the two antennas is known, velocity can be calculated. The same type of recording can also be made in continuous data acquisition with the imposition of fiducial marks to yield distance as measured along a tape measure on the ground.

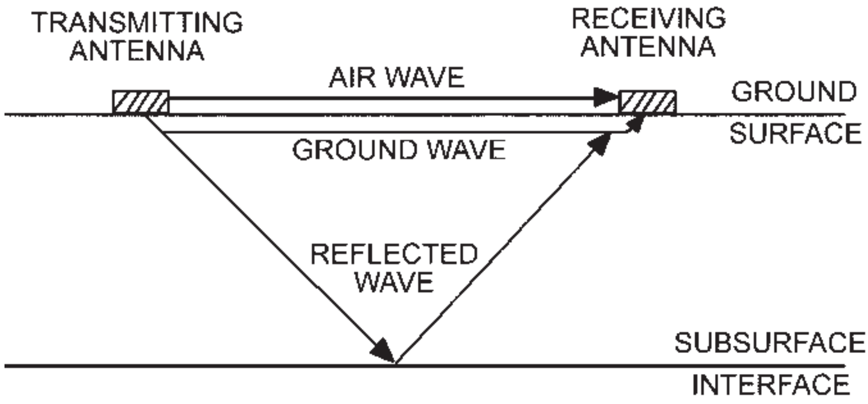

FIGURE 5.2
Travel Paths for a CMP Test. At least three waves are recorded in CMP and WARR tests: the air wave that travels in air from transmitting to receiving antennas, the ground wave that moves along the interface between the ground and the air, and one or more reflected (and sometimes refracted) waves that move within the ground.

FIGURE 5.3
Conducting a CMP Test. Antennas are separated and the transmitter and receiver are moved apart in steps (pin flags denote the antenna offset distances). Reflection traces are recorded at each location.

Reflection traces are collected in the same way in the WARR method, except only one antenna is moved while the other remains stable. Sometimes WARR tests must be performed instead of CMP tests if there are not enough people in the field at the time of the test to move both the antennas simultaneously.

In WARR tests, there should be subsurface layers to reflect energy that are either horizontal or not dipping greatly (Reynolds 1997: 711). This is because energy must move in a predictable way between the two antennas, which is rarely the case. For this reason, CMP tests are the preferable method, as the midpoint between the antennas remains the same, allowing the points where energy are reflected on each subsurface reflector to be determined at each offset location and thus aerial consistency at depth is not a requirement. Also, for the result of WARR tests to be accurate, it must be assumed that the velocity of the individual layers does not change dramatically laterally, which is also rarely the case.

Common midpoint and WARR data are typically displayed in a standard GPR reflection profile, with the antenna separation distance on the horizontal axis and time on the vertical axis (figure 5.4). As the antennas are moved apart, the first wave received is the air wave. Ideally it is recorded at time zero when the distance of antenna separation is zero, or the zero offset can be later taken into account during data processing. The second wave arrival is usually the ground wave that travels along the ground–air interface and is recorded soon after the air wave. The third, and any subsequent arrivals, are usually reflected or refracted waves generated at subsurface interfaces. In areas with shallow water tables, it may be possible to distinguish between what are referred to as "dry" ground waves and those that are "wet" and that may be traveling within saturated ground near the surface (Fisher et al. 1994). The ground wave should also intersect the air wave at time zero on the portion of the radar profile where the two antennas were touching (figure 5.4). Other radar waves that traveled deeper within the ground can be refracted within soil and stratigraphic units and sometimes reflected between subsurface layers before arriving at the receiving antenna, creating what can potentially be a confusing series of recorded wave arrivals. These subsequent arrivals can usually be differentiated from ground or air waves because they do not intersect at time zero when the two antennas were touching.

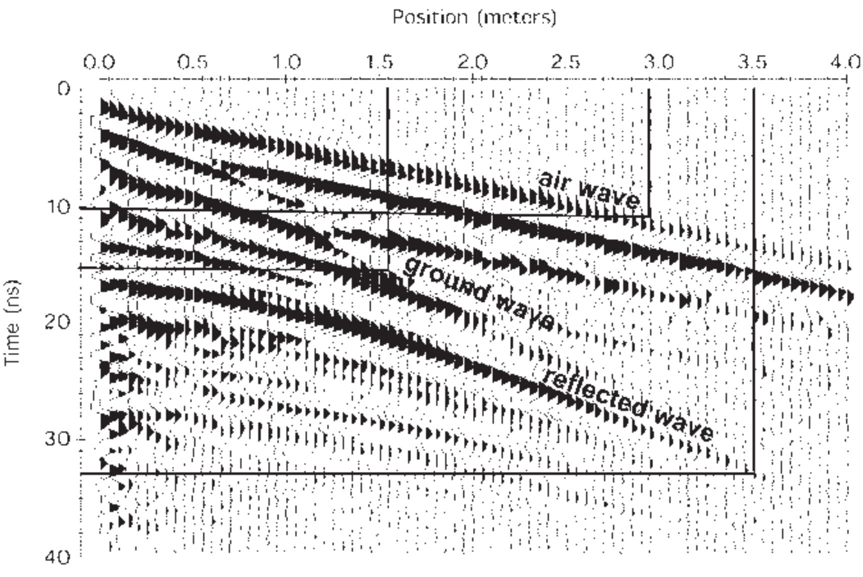

FIGURE 5.4
A CMP Test. This series of reflection traces when stacked and then viewed in a profile show the air wave, ground wave, and reflected wave from within the ground, arriving at different one-way travel times. Using these measurements both time and depth can be determined in order to arrive at velocity.

When time is measured and distance (between the antennas) is known, and the reflections from certain distances in the ground can be identified, velocity can be calculated. In figure 5.4, the air wave can be identified at any point along the wave diagram by taking a time and distance reading and calculating velocity. In this example, the air wave arrival at an antenna separation of about 3 meters occurred at 10 nanoseconds, which is a velocity of 0.3 meters per nanosecond (exactly the speed of light in air). The ground wave arrived at 15 nanoseconds when the antennas were separated 1.6 meters, which is a velocity of about 0.1 meters per nanosecond (a decrease from the air wave velocity of about a third). The reflected wave from some unknown horizon in the ground arrived at 33 nanoseconds when the antennas were separated 3.5 meters, also giving a velocity of about 0.1 meters per nanosecond.

In most cases, CMP and WARR tests usually only measure velocities of surface soils or other material that is located very near the ground surface. They should not be viewed as a way of determining velocity at any great depth unless it is somehow possible to identify actual paths of radar waves that traveled to deeper within the ground. For deeper velocity determinations, direct-wave methods should be used. Many GPR processing programs have software routines available to quickly process data collected in this way and average velocity at a number of depths in the ground can be estimated for later data processing.

A modified CMP data collection method was used as a way to collect a very precise three-dimensional reflection data set in a small area where accurate volumes of reflection data in real depth were needed (Pipan et al. 1996; Pipan et al. 1999). Using the CMP method within an 8-by-8–meter grid, many hundreds of CMP tests were performed, collecting thousands of traces that were then stacked and processed into a three-dimensional cube. This innovative approach, although difficult to conduct and time-consuming to process, produced superior three-dimensional images of the ground not available in any other way.

Transillumination Tests

The transillumination method is another direct-wave velocity test that is applicable to archaeological settings because it can be conducted in two nearby excavations where the section of material to be tested is preserved between them. It was originally developed as a method for evaluating the integrity of intact structures for both engineering and archaeological applications (Bernabini et al. 1994). To conduct transillumination tests, the faces of excavations should be as close to parallel as possible. It is also best if tests are performed soon after the material is exposed in the excavations so that any evaporation or seepage of water along the faces does not significantly change the water saturation characteristics of the material to be tested.

Two antennas, one to send and the other to receive, are then placed on the walls of the two excavations, pointing toward one another (figure 5.5). It is important that the two excavations be separated by at least one wavelength or so of the center frequency of the antenna being used to transmit so the receiving antenna is beyond the near-field zone of the transmitting antenna.

A series of transillumination tests are then made starting at the base of the excavations and moving upward. The two antennas can be moved upward either in steps, collecting one or many stacked reflection traces at each step, or continuously as radar energy is transmitted between the two. Care must be taken to keep the antennas separated a known distance and a known height from the base of the excavation as they are moved. If the antennas are moved in steps it is important that each antenna be moved the same distance from the top or bottom of the exposed faces so that the distance between the two is always known. If the walls of the excavation are sloping, then a series of distance measurements must be made in order to arrive at the antenna separations for each of the steps where data are collected.

When the material to be tested in this way is highly stratified, it is important that the electric field generated by the dipole antenna be oriented parallel to the bedding planes. To do this, the long axes (from side to side) of the antennas must be placed parallel to the bedding planes. In this way the majority of the electrical portion of the electromagnetic field will vibrate parallel to the bedding layers and there will be maximum isolation of the radar beam within each stratigraphic unit (Conyers and Lucius 1996). The cone of illumination of the radar antenna may, however, still transmit radar energy into adjacent layers regardless of the orientation of the antennas, and, as always, energy travel paths in the ground are difficult to predict or define after the fact. In all cases, the transmitting and receiving antennas must be oriented in the same direction so that there is maximum "communication" between the two.

In one transillumination test of this sort, two excavations exposed a thick section of volcanic ash (Conyers and Lucius 1996). Eight different ash units were identified on the faces of the excavations, and reflection traces were collected at each bed in seven steps, from the base of the excavation upward. A 300-megahertz antenna was put on one side of the exposure to receive and a 500-megahertz antenna on the other to transmit. An analysis of the travel times at each step showed that velocity increased from about 6 centimeters per nanosecond at the base (RDP of 23.2) to 28 centimeters per nanosecond (an RDP of 1.1) at the top (figure 5.6). The two velocity measurements at the top were probably

FIGURE 5.5
Conducting a Transillumination Test. When conducting this test, two antennas were held on parallel vertical faces, pointing toward each other and separated by the material to be tested.

not measuring radar wave travel in the ground, as radar energy probably "leaked" over the top of the excavation and traveled in the air between the two antennas, producing the RDP of 1.1, which is almost that of the velocity of radar transmission in air.

The identification of the "leaked" air waves that traveled between the two excavations illustrates the importance of using fairly deep excavations when conducting transillumination tests. If tests are conducted too close to the surface, radar waves will travel over the top or around the material to be tested, and the first arrivals may be only air waves. It is also critical that accurate distances between antennas at all positions be obtained so that air wave calculations can be made and their arrival times calculated in advance and then identified.

Knowing the horizontal separation of the antennas and the one-way travel time of the radar energy between the two antennas at each step, velocities can be calculated and RDP determined, using equation 3.1. When the velocity measurements at each of the seven steps as shown in figure 5.6 were plotted against the depth of the antennas, a velocity gradient graph was constructed. Velocity information derived from transillumination tests can be of great importance because it identifies velocity changes as a function of depth, which is not usually possible in direct-wave methods. In the graph in figure 5.6, the velocity increases at a fairly constant rate with greater depth, probably indicating gradually increasing residual water saturation, which was also visible as minor color changes in the exposed section of volcanic ash tested. The minor change in the velocity gradient at 100 centimeters may indicate a change in velocity between layers of very different composition and therefore differing water saturations.

If changes in velocity can be correlated with lithology or other compositional or water saturation changes in the material, they can yield important information for interpreting nearby reflection profiles, as it is always important to understand the origins of reflections when attempting to understand GPR data from any site. Because all reflections are generated at buried interfaces where there are distinct velocity changes, transillumination tests can be one of the best methods with which to understand these variations and possibly correlate reflections to known stratigraphic units in the subsurface.

Data from transillumination tests should still be used with caution because radar wave travel paths within the material being tested can never be known for sure, just as with CMP and WARR tests. In all these types of direct-wave tests, radar energy will tend to travel preferentially within the highest-velocity material, and the time of the first arrival that is being used to calculate the velocity may be from the waves that traveled in the "fastest" material, not necessarily those within the material from the depth at which the antennas are placed. Any wave arrivals that may have traveled through the lower-velocity layer would then be overwhelmed, obscured, or otherwise unrecognizable in the resulting traces.

Transillumination, CMP, and WARR tests should always be performed in conjunction with direct-wave tests of objects at known depths. The combination of both types of velocity test methods will yield both average vertical velocity measurements as well as a velocity gradient with depth.

LABORATORY MEASUREMENTS OF RDP

At most archaeological sites, samples of subsurface units can usually be collected for later processing in the laboratory to determine relative dielectric permittivity, electrical conductivity, and magnetic permeability. These measurements can

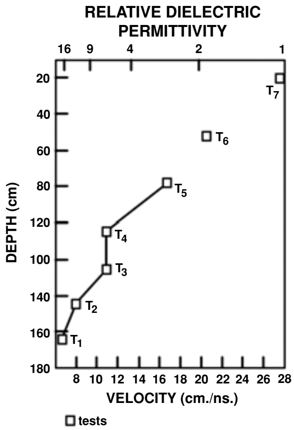

FIGURE 5.6
Transillumination Test Results. Velocity measurements can be determined as a function of depth. In this test there is a gradual decrease in velocity with depth, because of higher water saturation in the material being tested. Tests 6 and 7 measured energy that traveled in air over the top of the excavation.

then be used to estimate velocity and energy attenuation for materials at a site. They are also valuable when constructing two-dimensional computer models, discussed in chapter 7. If soil and sediment samples are collected and immediately stored in watertight containers, they can be considered as approximating field conditions. In reality, however, samples that are stored and transported in plastic bags or bottles will never replicate field conditions as their porosity, grain packing, and water saturation will all change somewhat in the process of gathering and transporting them.

Unfortunately, only a few devices can make these types of laboratory measurements, none of which are readily available to most archaeologists. One way of determining the magnetic and electrical properties in the lab is by using techniques described by Olhoeft and Capron (1993) and Saarenketo (1998). In these tests, samples are first dried and crushed and then subjected to differing frequencies of electromagnetic energy in a device called a network analyzer (Conyers 2004). Measurements of RDP, conductivity, and magnetic permeability can be made when the samples are totally dry and at differing water saturations. Water saturation changes that might be found in the field can be simulated by progressively wetting the samples with water from a dropper between tests, allowing time for the water to adequately penetrate the material.

There is a danger when using data from these types of laboratory tests because changes in the material that affect grain packing and porosity always occur during the testing procedure (Olhoeft 1986). Also, when water is artificially placed back into a sample after it has been artificially desiccated in the laboratory, conditions unlike those in the field are created. Devices that measure the electromagnetic properties of samples also tend to transmit more energy into a sample than would usually occur in the field, where attenuation and wave dispersal with depth always occur.

A laboratory test of this sort was conducted on what appeared to be a clay soil from central Illinois (Conyers 2004). It was later determined to be a silty clay, and the clay was determined to be not mineralogic clay but wind-blown clay-size rock fragments. The sample was first totally desiccated in an oven overnight to remove all residual water. Its relative dielectric permittivity was then measured at many frequencies ranging from 10 to 1,200 megahertz (figure 5.7). An analysis of those readings indicated that these types of measurements are somewhat frequency-dependent with variations at the high and low end of the range, but RDP was fairly stable within the frequency range of most GPR antennas (200 to 1,000 megahertz). These types of laboratory measurements are always frequency-dependent. At high frequencies, some electromagnetic energy is lost in the atomic structure of the materials due to displacement currents, caused by small perturbations within the orbits of electrons. At low frequencies, ions in the material cannot respond fast enough to the imposed electromagnetic field, and there is greater ionic conductivity, and therefore higher RDP values are measured.

Those frequency variations aside, what is most remarkable about the test shown in figure 5.7 is how sensitive the samples were to the addition of water. When only 0.5 cubic centimeters of distilled water was added to the total sediment sample of 13 cubic centimeters, the RDP increased from 3 to about 8. And with an additional 0.5 cubic centimeters of water it increased even more, to about 17. This test dramatically illustrates how important the addition of a small amount of water is to the velocity of radar travel (and therefore RDP of the material in the ground). This same phenomena is also visible in the transillumination test in figure 5.6 where ash beds of identical composition have greatly varying RDP values with greater depth in the ground (and therefore greater water saturation), as well as with porosity changes between different stratigraphic units (that also changes the amount of water held in any one stratum).

An interesting approach to laboratory measurements was taken by Sternberg and McGill (1995) in Arizona. At their sites, samples were taken of subsurface sediment units, which were analyzed for their particle size, mineralogical constituents, and water saturation. Without having to rely on laboratory measurements of RDP and electrical conductivity, they compared their mixtures consisting of sand, clay, and water to published tables of RDP and other measurements for those materials (Olhoeft 1986) in a fairly simplistic but effective way. Relative dielectric permittivity and velocity were then estimated for their unique field conditions, and radar times were converted to approximate depth, with good results.

ANALYSIS OF POINT SOURCE REFLECTION HYPERBOLAS

When GPR transects cross subsurface features that generate point sources, such as pipes, walls, rocks, or small void spaces, hyperbolic reflections are generated (figure 3.15). The geometry of the generated hyperbola (in general how steeply the arms of the hyperbola dip) is a function of the average velocity of the material

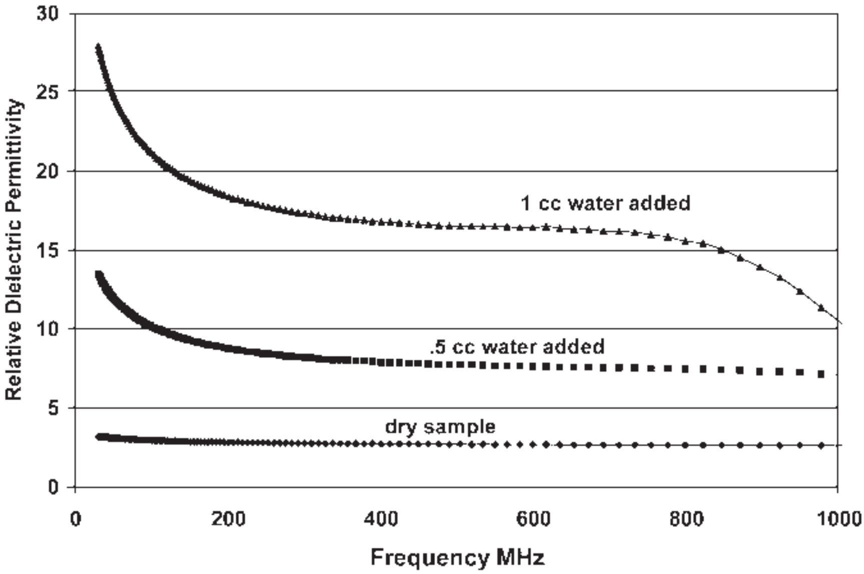

FIGURE 5.7
Laboratory Tests of RDP. The sample of clay when dry had an RDP of 3, which increased rapidly as small amounts of distilled water were added, illustrating how important water is to the transmission and reflection of radar energy in the ground.

through which the radar energy passes (Leckebusch 2000; Lucius and Powers 2002; Martinaud et al. 2004; Paniague et al. 2004; Tillard and Dubois 1995) and the size of the point source that generated the hyperbola. When a profile is collected with equally spaced surface fiducial marks (or with a survey wheel where reflection traces are equally spaced along a transect), distance is known in one dimension, and the velocities of many wave travel paths to and from the point source in the ground are measured when the antenna is at different surface locations. A computer-generated hyperbola is then "fit" to the hyperbola generated in the ground, and its dimensions are calculated (figure 5.8). Velocity and distance can then be measured, and average velocity from the ground surface to the point source can be calculated using computer programs that apply trigonometric functions to these measurements. The simplest version of this type of processing program is called Fieldview (Lucius and Powers 2002), but there are many other commercially available programs that perform the same calculations.

A GPR survey that generates many hyperbolas in reflection profiles can be readily used to evaluate velocity with both depth and throughout a grid without having to resort to any of the above field velocity test methods. In this method, hyperbolas can be tested in many reflection profiles at different depths in the ground (assuming there are hyperbolas present) and variations in velocity can be determined both with depth and spatially across a grid. Often this is more information than is needed, or even wanted, and usually an average velocity for the data set as a whole is sufficient to correct radar travel times to approximate depth.

VELOCITY ANALYSES CONCLUSIONS

The most accurate velocity tests are those performed in the field that directly measure the radar travel times of objects at known depths. The object to be resolved should be metal in order to maximize radar reflections. If possible, one or more velocity tests should be made within or near a proposed GPR grid to test the velocity of all materials that will potentially be studied. At depths greater than a few meters, iron bars or other relatively small objects may not be visible, and larger objects, such as a buried structure wall, can be used as a target. Without these types of tests, the correlation of important stratigraphic units or buried cultural materials to reflections measured in radar travel times will always be suspect unless the stratigraphy is so simple and the archaeological features are so dramatic that the origin of resulting reflections is not in doubt. This is rarely the case.

If two or more excavations are available in close proximity, transillumination tests can be performed. The velocity data gathered from these types of tests can

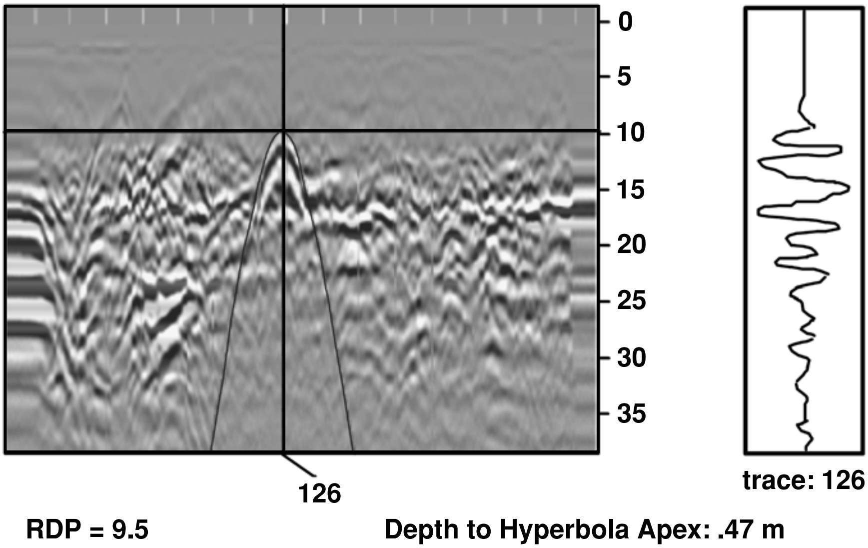

FIGURE 5.8
Hyperbola-Fitting Velocity Tests. Computer programs can be used to fit hyperbolas of a known geometry to reflection hyperbolas in radar profiles in order to arrive at velocity.

yield velocity gradient curves and also delineate interfaces in the subsurface most likely to reflect radar energy. These types of data can be especially valuable in correlating reflections to known stratigraphy and other subsurface features.

If excavations are not available at a site, velocity of near-surface zones can be estimated using common midpoint or wide-angle reflection and refraction tests. These tests can be used to estimate near-surface velocities, but are usually not as valuable in obtaining velocity information from any great depth.

It is important to understand that any data derived from field velocity tests of any sort must be applied only to GPR reflection profiles that were acquired at about the same time. Ground conditions can change with the season or due to other factors such as heavy rainfall or snowmelt and subsurface radar velocity can change accordingly.

Lacking field velocity tests of any sort, samples of overburden material collected in the field can be analyzed in the laboratory or compared to standardized tables in order to obtain electrical and magnetic properties. These data can be used to arrive at an approximate relative dielectric permittivity, from which velocity can be calculated, if no other information is available.

A GPR grid that contains an abundance of reflection hyperbolas generated from buried point sources can also yield important velocity information by using computer programs that fit the geometry of hyperbolas. These analyses can be performed without the need for excavations and are often quite accurate and an easy way to obtain average velocity estimates.

All or some of the velocity tests described in this chapter should be performed as a matter of course during GPR surveys. For the most part, they are not difficult or time-consuming and will yield valuable time–depth information that is necessary in order to process raw GPR reflection data. Reflections that are recorded and interpreted only in time can only be used as a crude estimate of depth without accurate time–depth conversions.