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**Subject:** Investigation of tree roots with ground-penetrating radar (GPR)

**Date:** 8 February 2000

**To:** John Butnor  
Southern Research Station  
USDA Forest Service  
Raleigh, North Carolina

**Purpose:** The purpose of this investigation was to evaluate the suitability of using ground-penetrating radar to locate tree roots and buried woody coarse debris.

**Participants:**

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**Activities:**

All activities were completed during the period of 10 to 13 January 2000. On 10 January, tree root studies were conducted on upland soils at the Westvaco Birch Fiber Farm near Olar, South Carolina. On 11 January, studies were conducted at two flatwood sites in Berkley County, South Carolina. Studies were conducted on upland soils at the Southeast Tree Research and Educational Site in Scotland County, North Carolina, on 12 January. On 13 January, studies were conducted on upland soils at the Duke Forest near Durham, North Carolina.

**Background:**

In recent years, increased attention has been focused on the detection and characterization of features buried within the shallow subsurface (0.25 to 1.5 m). For many applications, ground-penetrating radar (GPR) has proven to be a most appropriate geophysical tool. This rapid and noninvasive technique has been used to locate buried artifacts (Conyers and Goodman, 1997), drain tiles (Chow and Rees, 1989), anti-personnel mines (Bruschini et al., 1998; Daniels 1998), and pipes and cables (Ulriksen, 1982; Daniels, 1996).

Though commonly observed on soil profiles (Bevan, 1984; Truman et al., 1988; Farrish et al, 1990;) and often considered a source of unwanted noise that complicates radar interpretations (Doolittle and Miller, 1991; Barker and Doolittle, 1992), roots have seldom been the focus of a GPR study. Recently, GPR was used to map the coarse (greater than 3 cm diameter) rooting system of 50-year old oak (*Quercus petraea*) trees (Hruska et al., 1999). Typically, coarse tree roots have been measured by excavating the system. However, This method of observation is destructive. Because of its noninvasiveness, suitable depth range and resolution, Hruska and others (1999) consider GPR an appropriate tool for the measurement of coarse root systems. The objectives of this study were to expand upon the works of Hruska and others (1999), and to assess the feasibility of using GPR for similar research in southeastern United States.

### Ground-Penetrating Radar:

Ground-penetrating radar is an impulse radar system designed for shallow, subsurface investigations. This system operates by transmitting short pulses of electromagnetic energy into the ground from an antenna. Each pulse consists of a spectrum of frequencies distributed around the center frequency of the transmitting antenna. Whenever a pulse contacts an interface separating layers of differing electromagnetic properties, a portion of the energy is reflected back to a receiving antenna. The receiving unit amplifies and samples the reflected energy and converts it into a similarly shaped waveform in a lower frequency range. The processed reflected waveforms are displayed on a video screen or stored on a disk for latter playback, processing, or printing.

The radar unit used in this study was the Subsurface Interface Radar (SIR) System-2000, manufactured by Geophysical Survey Systems, Inc.<sup>1</sup> The SIR System-2000 consists of a digital control unit (DC-2000) with keypad, VGA video screen, and connector panel. A 12-volt battery powered the system. This system is backpack portable and, with an antenna, typically requires two people to operate. Daniels (1996) discusses radar systems and principals of operation.

The radar profiles included in this report have been processed through the WINRAD software package.<sup>1</sup> In general, processing was limited to signal stacking, horizontal scaling, color transforms and table customizing. Color transformation and table customization were used to reduce background noise. In addition, high pass horizontal filtration and range gain were used on the radar profile shown in Figure 4.

The models 5100 (1.5 GHz) and 5103 (400 MHz) antennas were used in this study. These antennas have a bowtie dipole configuration. The lower frequency 400 MHz antenna has greater powers of radiation, longer pulse widths, and emits signals that are less rapidly attenuated by earthen materials than signals emitted from the higher frequency, 1.5 GHz antenna. The 1.5 GHz antenna is smaller, provides better resolution of subsurface features, but in most medium and fine textured soils, its performance and depth of observation are severely restricted.

Resolution is the ability to discriminate two closely spaced features. Resolution improves with frequency. Resolution increases with decreasing wavelength (time to complete signal waveform). High frequency antennas have shorter wavelengths and provide higher resolution than low frequency antennas. Two or more closely spaced roots may appear as one reflection on a radar profile and be interpreted as one root with a lower frequency antenna. However, these same roots may be resolved and correctly interpreted with a higher frequency antenna.

The system radiates energy in an elliptical cone of divergence and scans a footprint area beneath the antenna. Because of the antenna's radiation pattern forms an elliptical cone of divergence, small features are sensed before and after the antenna is moved directly over them. Because of the initially decreasing and then increasing travel time to a subsurface reflector, small subsurface features, such as roots, often produce hyperbolic patterns. These hyperbolas are readily observable on most radar profiles and can aid interpretations. The apex of a hyperbola occurs when the antenna is directly over the root. Other linear features, such as a buried pipe and drainage tiles, have been observed to produce visible hyperbolas only when crossed at a traverse line angle greater than 45 degrees (Chow and Rees, 1989; Roberts and Daniels, 1993). However, when crossed at angles of less than 45°, these features produced images that were elongated, obscured and more difficult to distinguish. These observations apply to roots as well.

The footprint area "illuminated" by the radar is considered an elliptical cone (Conyers and Goodman, 1997). The footprint area illuminated by a radar can be approximated by the formula (Conyers and Goodman, 1997):

$$A = \lambda/4 + D/\sqrt{e+1} \quad [1]$$

where A is the radius of the footprint area at depth D,  $\lambda$  is the center frequency wavelength of the antenna, and e is the dielectric permittivity of the scanned materials. According to equation [1], the foot print area varies directly with the wavelength of the antenna. Higher frequency antennas have shorter wavelengths and will provide a smaller or more focused footprint area than lower frequency antennas. Also, the higher the dielectric permittivity of the profiled material, the smaller the illuminated footprint area. Therefore, wetter soil conditions should result in a more contracted cone of radiation.

Because of the antennas comparatively broad beam, objects that are located at some distance on either side of the antenna track can be sensed. Typically these objects will have lower amplitudes than similar objects that occur directly beneath the path of the

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<sup>1</sup> Trade names have been used in this report to provide specific information. Their use does not constitute endorsement.

antenna. In addition, because of longer pulse travel times to these offset reflectors, they will appear on radar profiles at deeper than actual depths.

#### **Soil Factors:**

Compared with other geophysical techniques, GPR provides the highest resolution of subsurface features. However, results of radar surveys are site specific. In some areas, conductive soil conditions limit the profiling depth and the applicability of GPR. Ground-penetrating radar is best suited for shallow (3 to 10 meters) investigations in electrically resistive mediums (i.e. dry, sandy soils).

The maximum depth of observation is, to a large degree, determined by the conductivity of the soil. Soils having a high electrical conductivity rapidly dissipate the radar's energy and restrict observation depths. The principal factors influencing the conductivity of soils to electromagnetic radiation are: degree of water saturation, amount and type of salts in solution, and the amount and type of clay.

Generally, soils have lower signal attenuation when dry than when wet. As the water-filled porosity is increased, the rate of signal attenuation is increased and the observation depth of the radar is reduced. Even in arid and semi-arid environments, small amounts of moisture in the soil can significantly increase the rate of signal attenuation (Dolphin and Yetter, 1985).

Electrical conductivity is directly related to the concentration of dissolved salts in the soil solution. The concentration of ions in the soil solution is dependent upon the clay minerals present, the pH of the soil solution, the degree of water filled porosity, the nature of the ions in solution, and the relative proportion of ions on exchange sites. In general, soluble salts are more thoroughly leached from soils in humid than in arid or semi-arid areas. In semi-arid and arid areas, soluble salts are more likely to accumulate in the upper parts of soil profiles and increase signal attenuation.

The observation depth of GPR increases as the clay content decreases or the proportion of low activity clays increases. Daniels and others (1988) noted a reduction in observation depths from about 5 meters (with a 1 GHz antenna) in sandy soils to less than 2 meters (with a 100 MHz antenna) in clayey soils. Ions absorbed on clay particles undergo exchange reactions with ions in the soil solution and contribute to the electrical conductivity of the soil. Smectite and vermiculite clays have higher cation-exchange capacities than kaolinite, gibbsite and goethite clays, and under similar soil moisture conditions, are more conductive. Kaolinite, gibbsite and goethite are considered low activity clays.

Under unfavorable conditions (wet, calcareous, clayey soils), the maximum observation depth of the GPR is less than 0.5 meters. In addition, as low frequency antennas are required to achieve these observation depths, resolution of subsurface features is often poor. However, under electrically resistive conditions (dry, coarse-textured soils), observation depths of 5 to 35 meters have been achieved with lower frequency antennas, and 3 to 6 meters with the higher frequency antennas.

When assessing the appropriateness of using GPR, a major consideration is signal attenuation at the desired antenna operating frequency (Daniels et al., 1988). As signal attenuation increases with frequency, low frequency antennas must be used in high-loss mediums to increase observation depths. The maximum depth of observation decreases rapidly with increasing antenna frequency. High frequency antennas (>400 MHz) can provide well-resolved images of shallow features in soils having low conductivity. In soil having high conductivity, levels of signal attenuation become prohibitive to GPR systems (Daniels et al., 1988). In these soils, low frequency antenna can be used to improve the depth of observation. However, as lower frequency antennas are used to achieve the desired depth of observation, resolution is diminished and smaller features, such as roots, are not detected and are more likely to be overlooked. Generally, in most radar surveys, resolution is sacrificed to achieve greater observation depths.

#### **Soils at the Study Sites:**

Study sites were selected in the Atlantic Coast Flatwoods, Georgia and Carolina Sandhills, and Southern Piedmont Major Land Resource Areas (MLRA) (Austin, 1965). The Atlantic Coast Flatwoods MLRA consist primarily of very poorly drained to excessively drained soils formed in eolian and marine sediments. Relief is typically less than a few feet, but as much as 20 feet along stream valleys (Austin, 1965). Sites with contrasting soils were selected within the Atlantic Coast Flatwoods MLRA. Root studies were conducted in an area of Lakeland sand at the Westvaco Fiber Research Farm located near Olar, South Carolina. The very deep, excessively drained, rapidly permeable Lakeland soil formed in thick beds of eolian or marine sands. Lakeland soil is a member of the thermic, coated Typic Quartzipsamments family. Lakeland soil has limited profile development. All horizons are

sand or fine sand with less than 10 percent silt and clay. Unless limed, the soil is very strongly acid to moderately acid. As this soil has low clay, moisture, and soluble salt contents it is well suited to GPR.

Additional sites were selected in Berkley County, South Carolina, within the Atlantic Coast Flatwoods MLRA. These sites were located in areas of Lynchburg soil. The very deep, somewhat poorly drained Lynchburg soil formed in loamy marine sediments. Lynchburg soil is a member of the fine-loamy, siliceous, semiactive, thermic Aeric Paleaquults family. Lynchburg soil is wetter, has more clay, and greater profile development than Lakeland soil. Lynchburg soil has an argillic horizon with as much as 30 percent silt and clay. It is somewhat poorly drained with a water table that is seasonally within depths of 60 cm. Content of coarse fragments range from 0 to 7 percent. Unless limed, the soil is extremely acid to strongly acid. Because of its high moisture content and moderate silt and clay content, Lynchburg soil is considered moderately suited to GPR.

The Southeast Tree Research and Educational Site (SETRES) in Scotland County, North Carolina, is located within the Georgia and Carolina Sandhills MLRA. The Georgia and Carolina Sandhills MLRA consist principally of dissected rolling to hilly uplands (Austin, 1965). Within this MLRA, soils formed in marine, eolian, and fluvial Coastal Plain sediments. Study sites within the SETRES were located in areas of Wakulla soil. This very deep, excessively drained, rapidly permeable soil formed in sandy Coastal Plain sediments on uplands. The Wakulla soil is a member of the sandy, siliceous, thermic Psammentic Hapludults family. In a typifying profile, Wakulla soil contains about 85 to 92 percent sand and 8 to 15 percent silt and clay. Unless limed, the soil is very strongly acid to moderately acid. As Wakulla soil has low clay, moisture, and soluble salt contents, it is considered well suited to GPR.

Two sites were selected in the Duke University Forest near Durham, North Carolina. These sites were located within the Southern Piedmont MLRA and in areas of Appling and Georgeville soils. The Southern Piedmont MLRA consists principally of gently rolling to hilly uplands (Austin, 1965). Many of the soils of the Southern Piedmont MLRA formed in residuum weathered from the underlying schists, gneisses, granites, sandstones, and slates (Austin, 1965). The very deep, well drained, moderately permeable Appling soil formed in residuum weathered from felsic igneous and metamorphic rocks on uplands. Appling soil is a member of the fine, kaolinitic, thermic Typic Kanhapludults family. Appling soil has an argillic horizon with 35 to 60 percent clay that extends to depths of 76 to 152 cm. These clays have a low cation exchange capacity. Coarse fragments range from 0 to 35 percent by volume in the A horizon and 0 to 10 percent in the argillic horizon. Unless limed, the soil is very strongly acid to strongly acid.

The very deep, well drained, moderately permeable Georgeville soil formed in residuum weathered from Carolina slate or phyllites on uplands. Georgeville soil is a member of the fine, kaolinitic, thermic Typic Kanhapludults family. The typifying Georgeville profile has a thin (5 to 23 cm) surface layers that is underlain by an argillic horizon with 35 to 65 percent clay that extends to depths of 66 to 157 cm. The clays have a low cation exchange capacity. Coarse fragments range from 0 to 20 percent by volume in the surface layers and 0 to 10 percent in the argillic horizon. Unless limed, the soil is very strongly acid to strongly acid. Although the clays are predominantly low activity, because of their moderate moisture and high clay contents, Georgeville and Appling soils are considered poorly suited to GPR.

#### **Other Factors that Affect the Detection of Roots:**

Even with favorable soil conditions (i.e. dry, coarse-textured soils) the detection of a buried roots with the GPR cannot be guaranteed. The detection of roots is affected by (i) the electromagnetic gradient existing between a root and the soil, (ii) the size, shape, and orientation of a root, and (iii) the presence of scattering bodies within the soil.

The amount of energy reflected back to an antenna by an interface separating two materials is a function of the dielectric gradient existing between the two materials. The greater or more abrupt the difference in dielectric properties, the greater the amount of energy reflected back to the antenna, and the more intense will be the amplitude of the image recorded on the radar profile. The reflection of energy from an interface is dependent upon its reflection coefficient. The reflection coefficient is expressed in the following equation (Daniels, 1996):

$$R = \frac{\sqrt{\epsilon_1} - \sqrt{\epsilon_2}}{\sqrt{\epsilon_1} + \sqrt{\epsilon_2}} \quad [2]$$

Where  $\epsilon_1$  and  $\epsilon_2$  are the dielectric permittivities of the two materials. Though dependent upon bulk density, porosity, structure, composition, and temperature, the dielectric permittivity is largely dependent upon moisture content (Conyers and Goodman, 1997). Therefore, the reflection coefficient is largely dependent on contrast in moisture contents across an interface.

As very little research has been carried out using GPR to investigate roots, the contrast in dielectric properties between a root and the surrounding soil matrix is largely unknown. Assuming that roots have a high moisture content, the contrast between a root and the surrounding soil matrix is assumed to be greater under drier soil conditions. Increases in soil moisture will decrease or dilute the electromagnetic gradient between roots and soil.

The ability of GPR to detect individual roots will depend on the root's size, depth and spacing. Hruska and others (1999) found an error of 1 to 2 cm between radar interpreted and excavated measurements of coarse tree roots. By using higher frequency (greater than 450 MHz) antennas, these authors were able to resolve roots that were less than 1 cm in diameter. Large roots reflect more energy and are easier to detect than small roots. Most small roots (< 0.5 cm) are not directly detectable with GPR. Small, shallowly buried roots will be overlooked, unless located directly beneath the aperture of the radar antenna. In addition, the reflective power of any object buried in the soil will decrease at a rate proportional to the fourth power of the distance to the object (Bevan and Kenyon, 1975). Therefore, small, deeply buried roots are not directly discernable with GPR.

Clutter is introduced by reflections from undesired objects in the soil. In soils, reflections from roots are difficult to distinguish from those produced by rock fragments, concretions, animal burrows, modern cultural debris and features, or some stratified or segmented soil layers. These scattering bodies can produce undesired subsurface reflections that complicate radar imagery and mask the presence of roots. These features produce hyperbolic reflections that can cause destructive interference among several closely spaced features. In soils that contain a large amount of scattering bodies, reflections from roots are indistinguishable and interpretations are ambiguous. High levels of clutter are also introduced from rough surfaces such as rocky ground or forest sites littered with underbrush and fallen tree limbs. In addition, roots located near the surface are often difficult to discern because of interference from the strong surface reflection.

#### **Calibration:**

Ground-penetrating radar is a time scaled system. This system measures the time that it takes electromagnetic energy to travel from the antenna to an interface (e.g., soil horizon, stratigraphic layer, bedrock surface) and back. To convert the travel time into a depth scale, either the velocity of pulse propagation or the depth to a reflector must be known. The relationships among depth (d), two-way, pulse travel time (t), and velocity of propagation (v) are described in the following equation (Morey, 1974):

$$v = 2d/t \quad [3]$$

For most mediums, the affects of magnetic permeability on propagation velocity can be ignored. Consequentially, the velocity of propagation is principally affected by the relative permittivity ( $\epsilon$ ) of the profiled material(s) according to the equation:

$$\epsilon = (c/v)^2 \quad [4]$$

where c is the velocity of propagation in a vacuum (0.3 m/nanosecond). Velocity is expressed in meters per nanosecond (ns). The amount and physical state of water (temperature dependent) have the greatest effect on the dielectric permittivity of a material.

The radar was calibrated at each site. To determine a depth scale, a metallic plate was buried in the ground at each site, at depths ranging from about 40 to 50 cm. Because of the large contrast in dielectric properties that exists between the metal plate and the surrounding soil matrix, detection was easy and straightforward. At each site, the plate was clearly visible on radar profiles. The depth and two-way pulse travel time to this interface were used to estimate the velocity of propagation and to scale (depth) the radar imagery.

Using equation [3], the averaged velocity of propagation was estimated to be 0.1072 m/ns for the 1.5 GHz antenna in an area of Lakeland soil at the Westvaco Birch Fiber Farm near Olar, South Carolina. The associated dielectric permittivity was estimated to be 7.8. The averaged velocity of propagation was estimated to be 0.0665 m/ns and 0.0738 m/ns for the 400 MHz and 1.5 GHz antennas, respectively, in two areas of Lynchburg soil on Westvaco Corporation properties in Berkley County, South Carolina. The associated dielectric permittivity was estimated to be 20.3 and 16.5. The higher dielectric permittivity and slower velocity of propagation in areas of Lynchburg soil reflect the shallower depth to the water table and the higher moisture content of this soil. In areas of Wakulla soil at the Southeast Tree Research and Educational Site in Scotland County, North Carolina, the averaged velocity of propagation was estimated to be 0.1070 m/ns and 0.1320 m/ for the 400 MHz and 1.5 GHz antennas, respectfully. The associated dielectric permittivity was estimated to be 7.9 and 5.2. At the Duke Forest, in an area of Appling soil, the averaged velocity of propagation was estimated to be 0.1176 m/ns for the 1.5 GHz antennas, respectfully. The associated dielectric constant was estimated to be 6.5.

A basic assumption of this survey was that soil materials were rather uniform and that large differences in the velocity of propagation did not exist within sites. Although each site was nearly level and considered uniform, slight variations in the velocity of propagation resulted in slight discrepancies in depth measurements.

#### Westvaco Fiber Research Farm, Olar, South Carolina

The study site was located within an eastern cottonwood (*Populus deltoides* Bartr.) plantation. The area has been mapped as Lakeland sand, moderately shallow, 0 to 2 percent slopes (Crow et al., 1966). A random transects were conducted with both the 400 MHz and 1.5 GHz antenna. The ground surface was relatively free of debris and litter. While the 400 MHz antenna provided superior depth of observation, it was unable to detect and resolve roots from two-year old cottonwood trees. The 1.5 GHz antenna provided improved resolution and detected more tree roots within the upper 45 cm of the soil profile. However, below a depth of 45 cm, the signal from the 1.5 GHz antenna was too severely attenuated to sense roots. At this site, the 1.5 GHz antenna provided the best balance of resolution and observation depth for the investigation of tree roots.

Figure 1 is a representative profile obtained with the 1.5 GHz antenna from an area of Lakeland sand. The white, vertical lines at the top of this radar profile represent event markers and are spaced about 60 cm apart. Based on a scanning time of 16 ns, a propagation velocity of 0.1072 m/ns, and equation [3]; the maximum profiling depth was about 86 cm. A depth scale is provided along the left-hand margin of this figure. Depths are expressed in cm. Although this antenna detected the metallic reflector buried at a depth of 50 cm, no roots were detected below a depth of 45 cm.

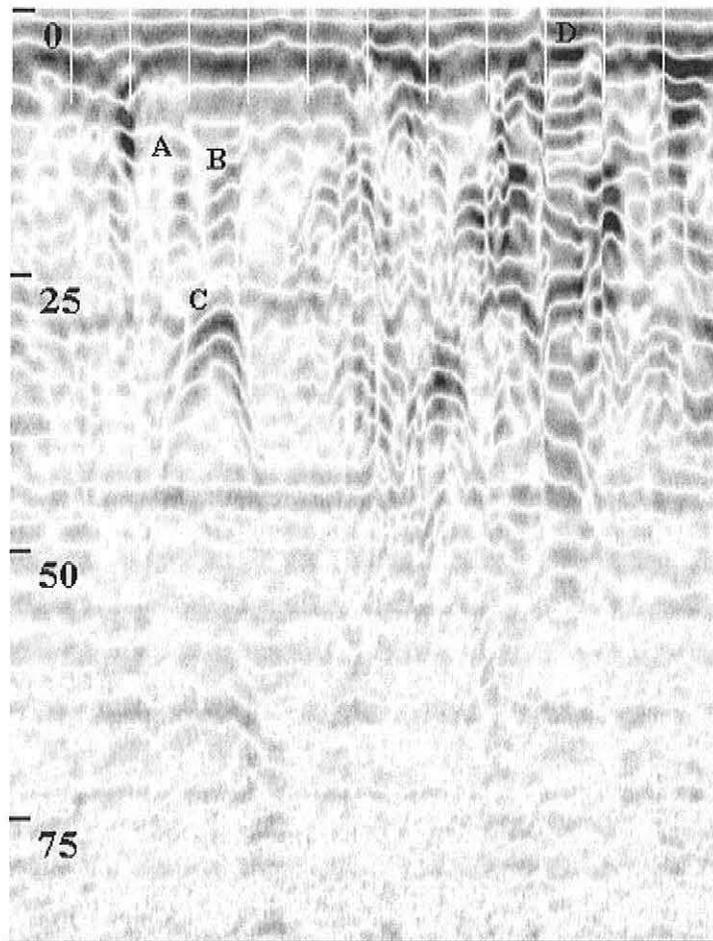


Figure 1. Representative radar profile obtained with the 1.5 GHz antenna from an area of Lakeland sand. Vertical Scale is a depth scale and is expressed in cm.

Interpretations were verified at three observation points (in Figure 1, see A, B, and C). The difference between interpreted and measured depths to these reflectors averaged 1.23 cm with a range of 0.7 to 2.0 cm. The radar identified and satisfactorily depth scaled a 0.6 cm root at 11 cm (A), and a 1.7 cm root at 14 cm (B). However, three very closely spaced roots with diameters of 1.5, 0.7, and 0.7 cm produce a strong subsurface reflection that was misinterpreted as only one root at a depth of 27 cm (C). At “D,” an exposed root was passed over by the antenna and produced reverberated signals.

Latter, a 244 by 244 cm grid was established around a two-year old eastern cottonwood stump. The diameter of the stump was 14.7 cm at the root collar. The grid interval was about 30 cm. The 1.5 GHz antenna was pulled along nine north-south grid lines. The scanning time was 16 ns. Radar profiles were reviewed in the field and reflections from suspected tree roots were identified. Based on radar interpretations and confirmed with knowledge of the site, roots were more concentrated along the tree rows than in the more opened inter-row areas. The tree rows were covered with landscape mulch and irrigated from drip chemagation tubing.

Following this GPR survey, the tree root was extracted with the aid of a tractor. A total of twenty-four roots were observed extending outward from the extracted stump. These roots averaged 2.79 cm in diameter, with a range of 1.5 to 6.3 cm. One half of the roots had diameters between 1.85 and 3.4 cm. As predicted by GPR, a majority of the roots had been concentrated along the mulched and irrigated tree row line. Seventeen of twenty-four roots (71 percent) had extended laterally outward from the stump along the mulched centerline of the tree row. Along this row, roots from adjoining trees had been closely intertwined with roots from the extracted stump.

The grid was resurveyed with the 1.5 GHz antenna following the removal of the tree stump. Once again, the 1.5 GHz antenna was pulled along nine north-south grid lines. The scanning time was 16 ns.

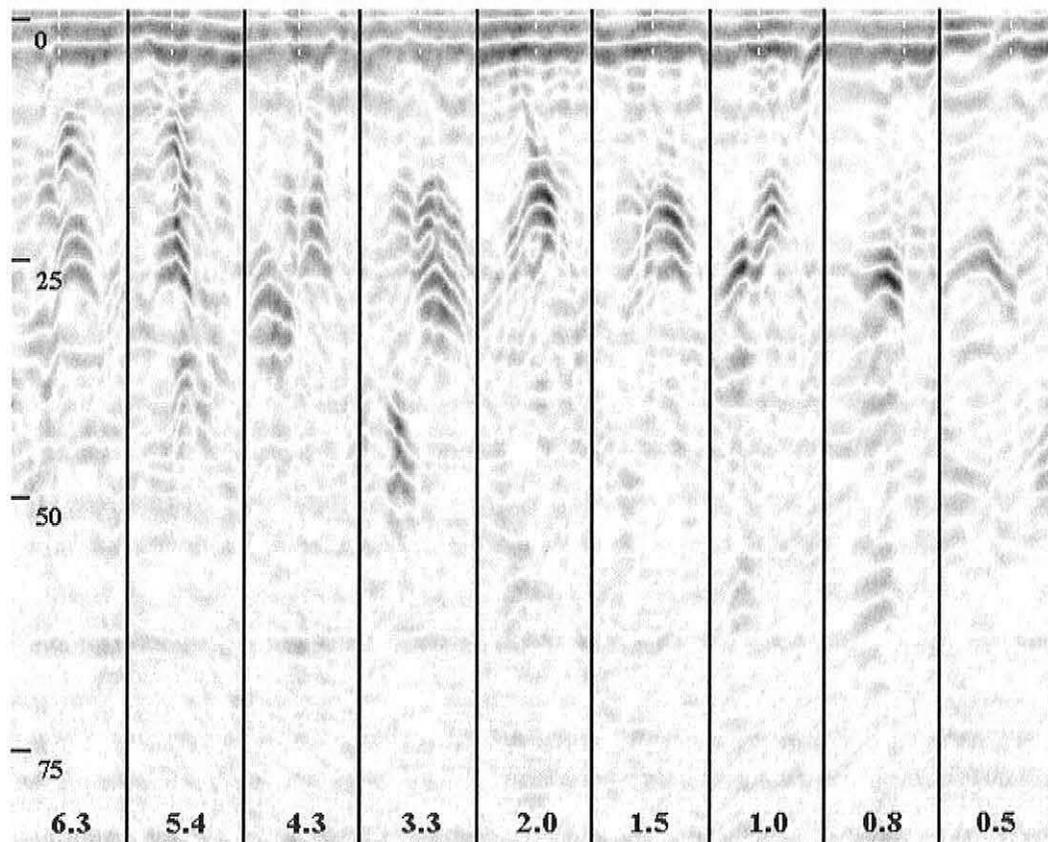


Figure 2. A composite radar profile obtained with the 1.5 GHz antenna showing reflections from different diameter roots. The depth scale is in cm. The numbers appearing at the bottom of the figure represent the diameter (cm) of the detected root.

A complete set of radar files (files 3 to 20) from the grid site has been forwarded to Dan Delea at Geophysical Survey Systems, Inc.,

for advanced processing and the construction of three-dimensional grids. Dan will attempt to construct “before and after” block diagrams of the grid site.

To evaluate reflections from different segments (different sizes) of one root, a section was buried in a small trench at a depth of about 20 cm. The trench was located in a relatively open area away from trees. Because of variations in the size and bends in the root, the measured depth to the root varied along the trench. The root was orthogonally traversed with the 1.5 GHz antenna at nine points. The diameter of the root at these points ranged from 0.5 to 6.3 cm. Figure 2 is a composite of the 9 radar traverses. The numbers appearing at the bottom of the figure represent the diameter (cm) of the root along each traverse.

Although the radar detected the root on each of the 9 traverses, reflection patterns were similar, amplitudes were variable, and no clear measure was provided as to the diameter or size of the root. Diffraction hyperbolas from the smallest diameter (0.5 cm) root appeared larger than those from the largest diameter (6.3 cm) root. The similarity was attributed to geometry of the reflective surface, slight variations in speed of advance, and the angle at which the antenna crossed the root. The relative size and definition of these root patterns can be slightly improved through post-processing (i.e., signal stacking and normalizing the horizontal scale). However, processing would add additional time and expense to projects and may not be practical or result in significant improvements.

In Figure 2, the trench wall and soil inhomogeneities were sources of unwanted clutter. Clutter introduced some ambiguity into the identification of roots. For larger root diameters (greater than 3.3 cm), two sets (each consisting of three multiples) of hyperbolas are evident in Figure 2. This suggests that with a diameter greater than 3.3 cm, the 1.5 GHz antenna can resolve both sides of a root.

#### **Westvaco Property, Berkley County, South Carolina**

Two study sites were selected. The first site was in an area that had been harvested four years ago. It had been replanted in loblolly pines (*Pinus taeda*) two years ago. The site was bedded. The second site was in a twenty-five years old plantation that had been recently burned of undergrowth. Both sites are in areas that had been mapped as phases of Lynchburg soils. Slopes are less than 2 percent.

Radar traverses were difficult to conduct at these sites because of plants, fallen tree limbs, and irregular soil surfaces. Each traverse line required clearing before the radar survey was begun. After clearing and site preparation, it was still difficult to maintain ground contact and uniform speeds of antenna advance.

The performance of GPR at both sites was poor. Interpretations were ambiguous and roots were difficult to distinguish on radar profiles. Although several roots were detected, random borings revealed that more roots had been overlooked with GPR. The sites were somewhat poorly drained with a water table at a depth of about 45 to 50 cm. Water can dilute electromagnetic gradients. As a consequence, reflected signals are weakened making the detection of subsurface interfaces and features more difficult. Compared with the Lakeland site (see Figure 1), signals from the 400 MHz and the 1.5 GHz antennas were more rapidly attenuated at the Lynchburg site. The higher rates of signal attenuation and more restricted observation depths were attributed to the higher clay and moisture contents of Lynchburg soil. The signals from the 1.5 GHz antenna were severely attenuated and observation depths were less than about 35 cm. With the 400 MHz antenna, observation depths of about 1.3 meters were obtained. Although several stumps were passed over with these antennas, these features provided little to no evidence of their occurrence on the radar profiles.

Figure 3 is a representative radar profile obtained with the 1.5 GHz antenna from an area of Lynchburg soil. The white, vertical lines at the top of this radar profile represent event markers and are spaced about 150 cm apart. Based on a scanning time of 16 ns, a propagation velocity of 0.0738 m/ns, and equation [3]; the maximum profiling depth was about 59 cm. A depth scale is provided along the left-hand margin of this figure. Depths are expressed in cm. A metallic reflector (see “A”) was buried at a depth of 47 cm. This reflector is visible in the lower left-hand corner of this figure. Although the 1.5 GHz antenna detected the buried metallic reflector, roots were less apparent and were not distinguishable below a depth of about 35 cm. Though partially obscured by the surface reflection and bands of low frequency noise, several high amplitude reflections are evident within the upper 25 cm. These reflectors represent roots, soil horizons and features, and system noise. Compared with data collected in the drier area of Lakeland sand (see Figure 1), the radar data from the wetter area of Lynchburg soil is more complex and interpretations of roots less straightforward and more ambiguous. Under wet soil conditions, because of higher gain settings needed to obtain desired observation depths, background noise is often high and the amplitude of reflected signals is reduced.

In Figure 3, the quality of the radar profile is considered poor. This profile is extremely noisy with parallel bands of low frequency

noise. While some point reflectors (roots) are apparent within the upper 35 cm of the soil profile, many are indiscernible.

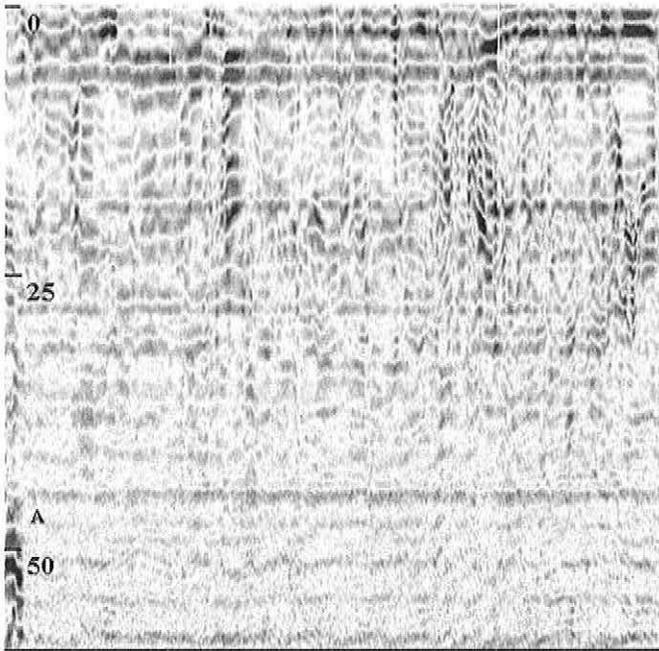


Figure 3. Representative radar profile obtained with the 1.5 GHz antenna from an area of Lynchburg soil. Vertical scale is in cm. Horizontal scale is about 6 m.

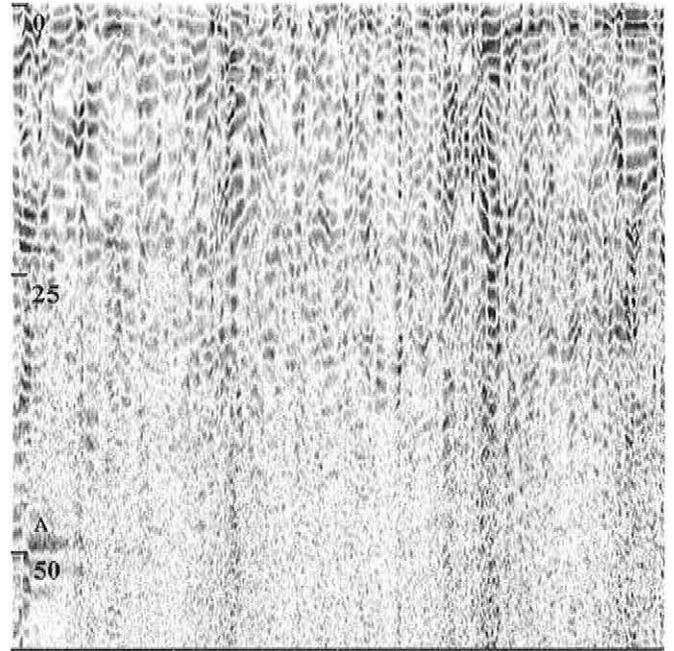


Figure 4. A processed version of the radar profile shown in Figure 3.

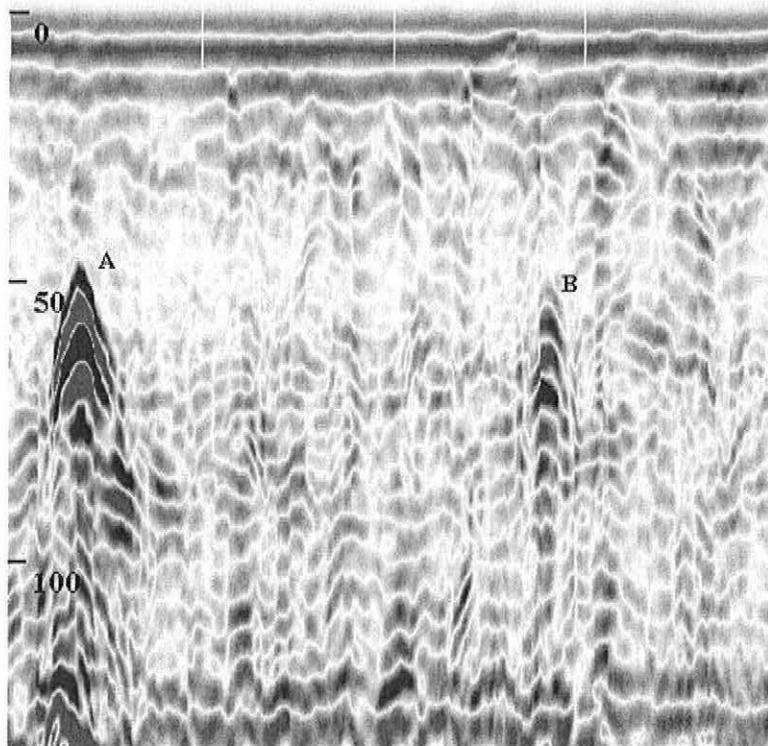


Figure 5. Representative radar profile obtained with the 400 MHz antenna from an area of Lynchburg soil. Vertical scale is expressed in cm. Horizontal scale is about 6 m.

In Figure 4, high frequency horizontal filters and gains have been applied to remove these bands of noise from the data. Compared with Figure 3, point reflectors (assumed to be roots) are more apparent in Figure 4. However, the large number, variable amplitude and overlapping patterns of these reflectors produce a highly complex profile that is difficult to interpret.

In Figure 4, while the integrity of many point anomalies remains, some are obscured (see A, the buried metallic reflector) by filtration and range gain. As soil horizons with smooth boundaries are parallel with the soil surface and the unwanted bands of background noise, they are often removed from the data by processing. Soil horizons with irregular boundaries are more likely to persist following horizontal filtration processes. Because of lateral changes in dielectric properties, some planar reflectors (i.e., soil horizons) produce segmented spatial patterns of varying signal amplitudes that are similar to the hyperbolas produced by roots. These similarities often result in greater uncertainty and misinterpretations. Unless aided by automated interpretation programs, the identification of roots under similar soil conditions will be highly subjective, flawed, and labor intensive.

Figure 5 is a representative radar profile obtained with the 400 MHz antenna from an area of Lynchburg soil. The white, vertical lines at the top of this radar profile represent event markers and are spaced about 150 cm apart. Based on a scanning time of 40 ns, a propagation velocity of 0.0665 m/ns, and equation [3]; the maximum profiling depth was about 133 cm. The metallic reflector (see "A"), buried at a depth of 47 cm, is clearly visible near the central left-hand margin of this figure. In Figure 5, a dead root that was impregnated with resins (see B) provides a very conspicuous reflector at a depth of 50 cm. Lower amplitude reflections are evident in upper part of Figure 5. These reflections are presumed to represent larger roots. The 400 MHz antenna provided superior depths of observation and higher quality radar profiles. However, compared with the 1.5 GHz antenna, fewer roots were distinguishable with the 400 MHz antenna. Even with a more restricted observation depth, smaller roots were less distinguishable on the profiles obtained with the 400 MHz antenna.

#### **Southeast Tree Research and Educational Site (SETRES) in Scotland County, North Carolina.**

The SETRES is located in the Georgia and Carolina Sandhills MLRA. The site contains replicated irrigation and fertilization factorial study plots. Fertilized and non-fertilized plots of longleaf pine (*Pinus palustris* Mill.) are known to have a very different root mass and root density. These plots are located in an area of Wakulla soils. This coarse-textured soil has a very low organic matter content and low water-holding capacity.

The performance of the GPR was exceptional at this site. Figure 6 and 7 are representative radar profile obtained with the 400 MHz and 1.5 GHz antennas, respectively. The dashed, vertical white lines appearing at the top of each radar profile are event markers spaced at an interval of about 30 cm. A metallic point reflector, buried at a depth of about 48 cm, is evident to the immediate right of "A" in each profile. In Figure 6 the maximum profiling depth is about 107 cm. This scale is based on a propagation velocity of 0.1070 m/ns, a scanning time of 20 ns and equation [3]. The propagation velocity of the 1.5 GHz antenna was slightly faster (0.1320 m/ns). In Figure 7 the maximum profiling depth is about 66 cm. This scale is based on a propagation velocity of 0.1320 m/ns, a scanning time of 10 ns and equation [3].

Compared with the 400 MHz antenna, the 1.5 GHz antenna provided more highly resolve data of the upper 50 cm of the Wakulla soil profile. With the 1.5 GHz antenna, a greater number of point reflectors (roots) were distinguishable in the upper 50 cm of the soil profile (compare figures 6 and 7). In Figure 7, reflectors are concentrated within the upper part of the soil profile and above a depth of about 30 cm. Spatially, these reflectors are more numerous in the right-hand portion of both figures 6 and 7. In this portion of the radar traverse, the antenna passed several trees. Radar interpretations were confirmed by excavating several small soil pits. In these excavations, where interpreted, roots were encountered at anticipated depths. Unfortunately, these records were lost.

Sixteen, 1 by 1 m grids were established to the northwest of the base of loblolly pines in 8 plots. The grid interval was about 25 cm. The 1.5 GHz antenna was pulled along the five south north and the five east-west grid lines. The scanning time was 10 ns. The data were printed showing only the high amplitude signals (Color transform 4). Radar profiles were reviewed and the high amplitude reflections from suspected tree roots were identified. Table 1 lists by plot and tree the number of suspected roots distinguished in each south to north (1 to 5) and each east to west (1 to 5) grid lines. The summation of all suspected tree roots counted in each plot is listed under the column labeled "density." Many tree roots were repeatedly recorded and counted in parallel and orthogonal traverses.

Radar files from two-grid site have been forwarded to Dan Delea at Geophysical Survey Systems, Inc., for advanced processing and the construction of three-dimensional grids. Kim Ludovici has been given a complete set of the radar files from this site. She will

attempt image analysis of this data.

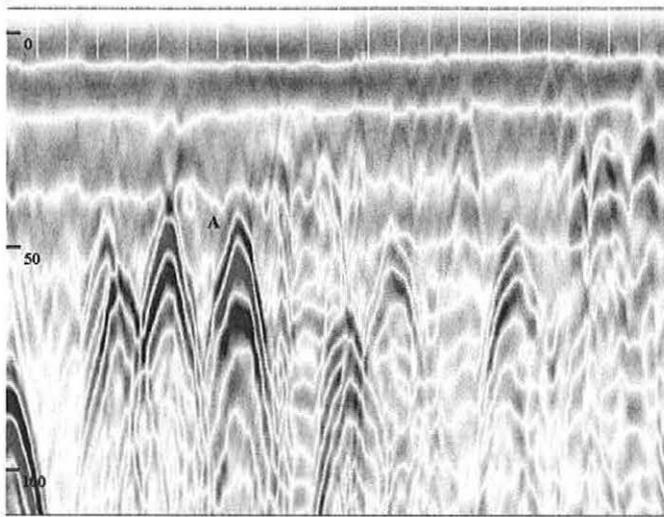


Figure 6. Representative radar profile obtained with the 400 mHz antenna from an area of Wakulla soil. Vertical scale is expressed in cm. Horizontal scale is about 13.4 m.

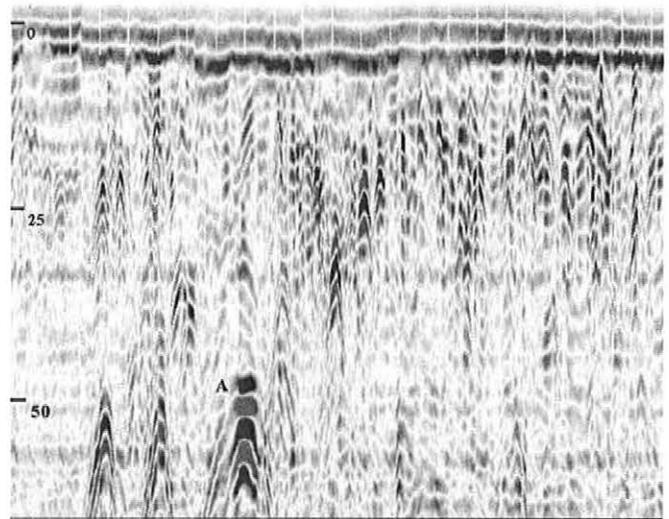


Figure 7. Representative radar profile obtained with the gHz antenna from the same area of Wakulla soil shown in Figure 6. Vertical scale is expressed in cm. Horizontal scale is about 13.4 m.

**Table 1**  
**Number of High Amplitude Point Reflectors**  
**Observed Along GPR Traverse Lines**

Plot	Tree	South to North Lines					East to West Lines					Density
		1	2	3	4	5	1	2	3	4	5	
1-1	69B	8	8	5	5	6	6	5	5	6	4	58
1-1	40B	7	7	4	5	5	4	5	5	4	5	51
1-3	13B	2	4	3	2	3	3	5	4	4	1	31
1-3	145BX	3	5	4	5	4	3	5	3	3	5	40
2-3	84B	4	3	4	3	2	5	3	4	3	3	34
2-3	51B	7	6	7	4	6	5	3	4	5	6	53
2-1	39B	3	3	2	2	4	1	1	2	1	1	20
2-1	169BX	4	4	3	4	3	3	4	3	2	5	35
4-1	40B	1	1	0	3	4	2	1	0	1	2	15
4-1	122B	3	4	3	3	3	3	0	1	2	3	25
4-3	18B	6	6	5	3	5	8	6	7	4	6	56
4-3	35B	5	4	3	4	3	5	6	4	3	4	41
3-1	105BX	5	5	3	3	3	2	4	3	3	3	34
3-1	10B	3	3	2	3	2	2	3	3	3	2	26
3-3	81B	5	7	4	7	6	5	5	6	8	9	62

**Duke Forest, Orange County, North Carolina.**

Two sites were selected for this study. One site was in an area of Appling soil the other in an area of Georgeville soil. Radar signals were attenuated by the high clay contents of both the Appling and Georgeville soils and observation depths were restricted.

In areas of Appling soils, with the 1.5 GHz antenna, high levels of background noise were observed. Parallel bands of noise caused by high gain settings obscured some reflectors. Numerous point reflectors were detected within the upper 30 cm of the soil profile. These point reflectors represented rock fragments and roots.

Figure 8 is a representative radar profile obtained with the 1.5 GHz antenna from an area of Appling soil. In this figure the vertical scale is a depth scale and is expressed in cm. The dashed, white vertical lines at the top of the radar profile are event markers that are spaced at distance of about 2 m. Based on a scanning time of 10 ns, a propagation velocity of 0.1176 m/ns, and equation [3]; the maximum profiling depth was about 59 cm. In Figure 8, a metallic reflector (A) was buried at a depth of about 48 cm and is evident in the lower central portion of this figure.

The radar profile shown in Figure 8 is considered of modest interpretative value. High levels of low frequency background noise have produced horizontal bands that partially mask reflections from point anomalies, many of which are assumed to be roots. This profile requires high-pass horizontal filtration to remove this noise. However, even after processing, this profile was considered difficult to interpret and summarize. The large number of reflectors produces a highly complex profile that is difficult to interpret. Unless aided by automated interpretation programs, the identification of roots under similar soil conditions will be highly subjective, flawed, and labor intensive.

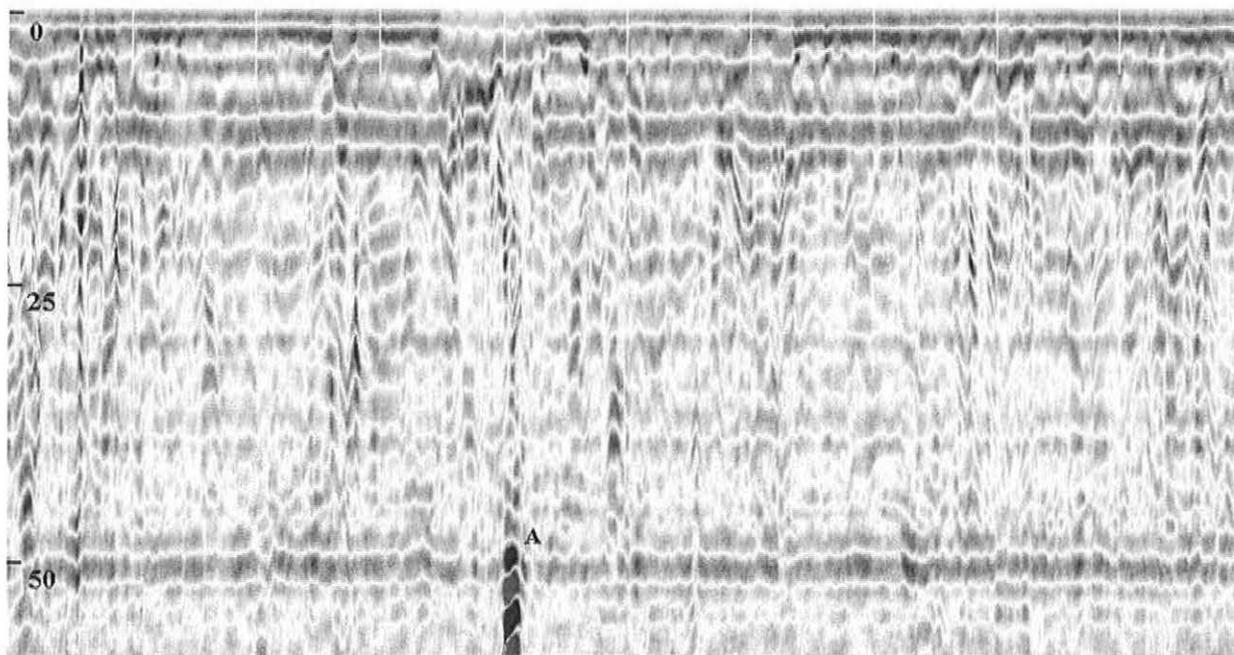


Figure 8. Representative radar profile obtained with the 1.5 GHz antenna from an area of Appling soil. Vertical scale is expressed in cm. Horizontal scale is about 20 m.

*velocity 0.1176 m/ns  
with  
900 MHz*

The 400 MHz antenna was calibrated to provide a profiling depth of about 1 m. Figure 9 is a representative radar profile from an area of Appling soil. In this figure the vertical scale is a depth scale and is expressed in cm. The dashed, white vertical lines at the top of the radar profile are event markers that are spaced at distance of about 2 m. In Figure 9, a metallic reflector buried at a depth of about 48 cm is evident at "A." Based on radar interpretations, six soil pits were excavated to verify radar interpretations. Large roots were observed in four (in Figure 9, see B, C, D, and E) of the six pits at the interpreted depths. Roots with diameters of 10 (B), 7.4 (C), 7.0 (D), and 3.7 (E) cm were distinguished. However, in the other two pits, coarse rock fragments were observed at the interpreted depths. Coarse fragments are common in these soils. Their reflections were similar and easily confused with those of roots. Although some larger roots (3.7 to 10 cm in diameter) were detected with the 400 MHz antenna, smaller roots were not detected.

In areas of Appling and Georgeville soils, small roots are difficult to distinguish with either the 400 MHz or 1.5 GHz antennas. The 400 MHz antenna provided more contrasting and less ambiguous images of the large (>3.5 cm diameter) roots. The use of a 900

mHz antenna may provide a better balance of observation depth and resolution. In areas of Appling and Georgeville soils, the 900 mHz antenna may be a more suitable tool for the detection of roots.

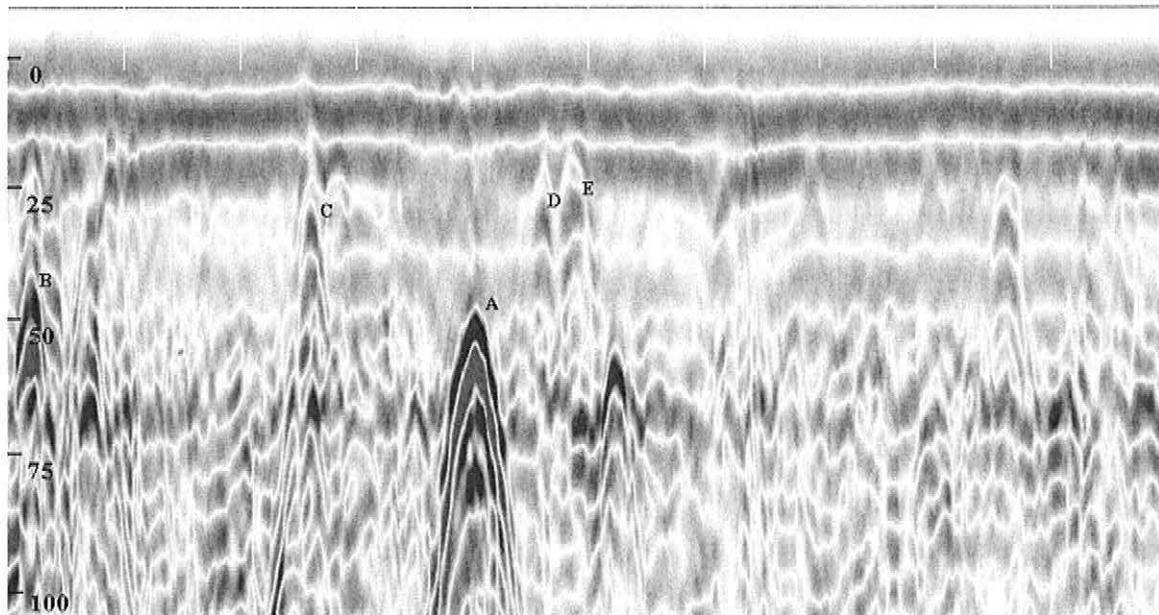


Figure 9. Representative radar profile obtained with the 400 mHz antenna from an area of Appling soil. Vertical scale is expressed in cm. Horizontal scale is about 20 m.

Latter, a long leaf pine root was buried at a depth of about 15 cm in an area of Georgeville soil. The trench wall provided an interfering reflection that masked reflections from the root.

#### Conclusions:

1. Roots are detectable with GPR. This technique works best in well drained, coarse-textured soils that have minimal soil development and few or no scattering bodies such as rock fragments. In these mediums, the 1.5 GHz antenna provides superior resolution of roots within the upper 50 cm of the soil profiles. Roots as small as 0.5 cm in diameter are distinguishable with this antenna.
2. Depths are restricted and roots are more difficult to distinguish in soils that have high clay and moisture contents. Clays attenuate the radar signal and reduce observation depths. Moisture dilutes electromagnetic gradients and weakens the amplitudes of reflective signals. Roots are more difficult to distinguish in wet soils than they are in dry soils.
3. Interpretations are based on pattern recognition. When crossed at angles greater than  $45^\circ$ , roots produce hyperbolic reflections. Reflections from roots are similar and difficult to distinguish from those produced by scattering bodies such as: rock fragments, concretions, animal burrows, modern cultural debris and features, or some stratified or segmented soil layers. These scattering bodies can produce undesired subsurface reflections that complicate radar imagery and mask the presence of roots. In soils that contain a large amount of scattering bodies, reflections from roots are indistinguishable and interpretations are ambiguous.
4. Sizing of roots is difficult. In this study it was observed that diffraction hyperbolas from a root with a 0.5 cm diameter appeared larger than those root with a 6.3 cm diameter. The similarity was attributed to geometry of the reflective surface, slight variations in speed of advance, and the angle at which the antenna crossed the root. The relative size and definition of these root patterns can be slightly improved through post-processing (i.e., signal stacking and normalizing the horizontal scale). However, processing would add additional time and expense to projects and may not be practical or result in significant improvements.

5. In many high-loss mediums, high levels of low frequency background noise can mask reflections from roots. In these mediums, post-processing of the radar data may be required. However, while processing add additional time and expense to projects it may not be practical or result in significant improvements in interpretations.
6. While only two antennas were used in this study, others are available from manufacturers. A 900 MHz antenna may provide a better balance of observation depth and resolution for root studies.
7. In soils that contain a large number of roots, radar profiles are often highly complex and difficult to interpret. Unless aided by automated interpretation programs, the identification of roots will be highly subjective, flawed, and labor intensive.
8. Dan Delea of Geophysical Survey Systems, Inc, is preparing three dimensional block diagrams showing the rooting patterns within three small grid areas. Results from Dan's work will help to clarify the possibilities of using GPR to map root system.
9. Without the assistance of Geophysical Survey Systems, Inc., results from this study would be less complete. Geophysical Survey Systems, Inc., loaned a 1.5 GHz antenna to this study. The participants and their respective agencies are indebted to Geophysical Survey Systems, Inc.

With kind regards,

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