FINAL REPORT

DETECTION OF ABANDONED UNDERGROUND STORAGE TANKS IN RIGHTS-OF-WAY WITH GROUND-PENETRATING RADAR

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Detection of Underground Storage Tanks in Rights-of-Way with Ground-Penetrating Radar

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Abstract

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ABSTRACT

Highway agencies need a simple, effective, nondestructive way to inspect certain properties in rights-of-way for the possible presence of abandoned underground storage tanks, without disturbing the ground, before actual construction begins. Overall, ground-penetrating radar (GPR) fills this need better than other nondestructive methods. This report explains why GPR was chosen over the other nondestructive methods available, discusses the principle of GPR, describes the basic radar equipment needed and the general procedures involved in conducting such inspections, and provides examples of the type of radar data such inspections produce.

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INTRODUCTION

The absence of adequate records on properties acquired for right-of-way can lead to the unexpected bulldozing of abandoned underground fuel storage tanks (UST) during the construction or widening of roadways. If the tanks are corroded and residual fuel has leaked into the surrounding soil, a costly disruption of construction usually results, because of the nature of the environmental remediation procedures that have to be followed. Such situations can be avoided if suspected areas in prospective rights-of-way can be inspected for such objects during the preliminary engineering phase without disturbing the ground. UST's could then be avoided, if possible, or the necessary remediation could be adequately planned for.

Unfortunately, the Virginia Department of Transportation (VDOT) does not have an established procedure for detecting abandoned storage tanks, and many other states are in the same situation. This project was undertaken to find a relatively simple, inexpensive, and rapid method that VDOT and other DOT's can use for detecting UST's.

A literature survey indicated that, among the various available geophysical techniques, only infrared (IR) sensing[1] and subsurface interface or ground-penetrating radar (GPR)[2] have been investigated for applications like the one addressed here. Infrared sensing, a passive remote-sensing technique, is usually done with an IR scanner mounted on an airborne platform. The technique relies on the differential effects of underground objects on the ground surface temperature. Unfortunately, IR sensing frequently requires sophisticated image analysis to resolve the interpretation problem that arises from the masking effects of the IR emissivity of the ground surface.

Ground-penetrating radar (GPR), an active technique, uses microwave pulses radiated from an antenna to explore the underlying soil strata. The microwave pulses are reflected differently by each boundary between strata of differing dielectric properties. The presence of any storage tank would result in an additional reflection exhibiting a characteristic signature typical of all cylindrical objects. No complex data analysis beyond recognizing this characteristic radar signature on a recording chart would be required for detecting UST's. In fact, this is probably the simplest possible application of GPR.

Since GPR is simpler to use than IR, the overall cost of using GPR is likely to be lower than the cost of IR even though the equipment costs for these techniques are comparable. Consequently, GPR was tested on UST's in some VDOT area headquarters. A brief discussion of the underlying principle is presented below, followed by a general description of the recommended methodology for such inspections and some typical radar signatures for UST's.

Principle of Ground-Penetrating Radar

When a radar transducer or antenna emitting microwave pulses is passed over the ground, the composite waveform that results from pulses reflecting back to the antenna from various subsurface features (Figure 1) is influenced by three parameters or properties. These are: (1) the propagation velocity (V) of the microwave pulses through each subsurface layer or medium; (2) the attenuation (A) of the energy in the microwave pulses by each material; (3) the reflectivity (r), the ability of a boundary between two different materials to reflect the pulses.[3]

Microwave pulses transmitted into the ground travel through the first layer of soil or rocks at a velocity (V_1) dependent on the relative dielectric constant of that layer of soil (ε_{r1}):

$$V_1 = \frac{C}{\sqrt{\varepsilon_{r1}}} \qquad (1)$$

where C is the propagation velocity of electromagnetic waves, such as microwaves, through air. This is equivalent to the speed of light, 0.3 m/ns (1 ft/ns). If the depth of this first layer of material is D_1, then the two-way transit time (t_1) required for the pulses to travel through this layer, reach a boundary or interface, and reflect back to the antenna is given by:

$$t_1 = \frac{2D_1}{V_1} = \frac{2D_1\sqrt{\varepsilon_{r1}}}{C} \qquad (2)$$

As Figure 1 illustrates, the difference in transit time (y-axis) between the reflection of the signal from the ground surface and the reflection of the signal from the first subsurface interface should be t_1.

As the microwave pulses traverse through the first layer of material, their energy is attenuated as follows:

$$A_1 = 12.86\times10^{-8} f\sqrt{\varepsilon_1}\left[\sqrt{1+\left(\frac{1.80\times10^{10}\sigma_1}{f\varepsilon_{r1}}\right)^2}-1\right]^{\frac{1}{2}} \qquad (3)$$

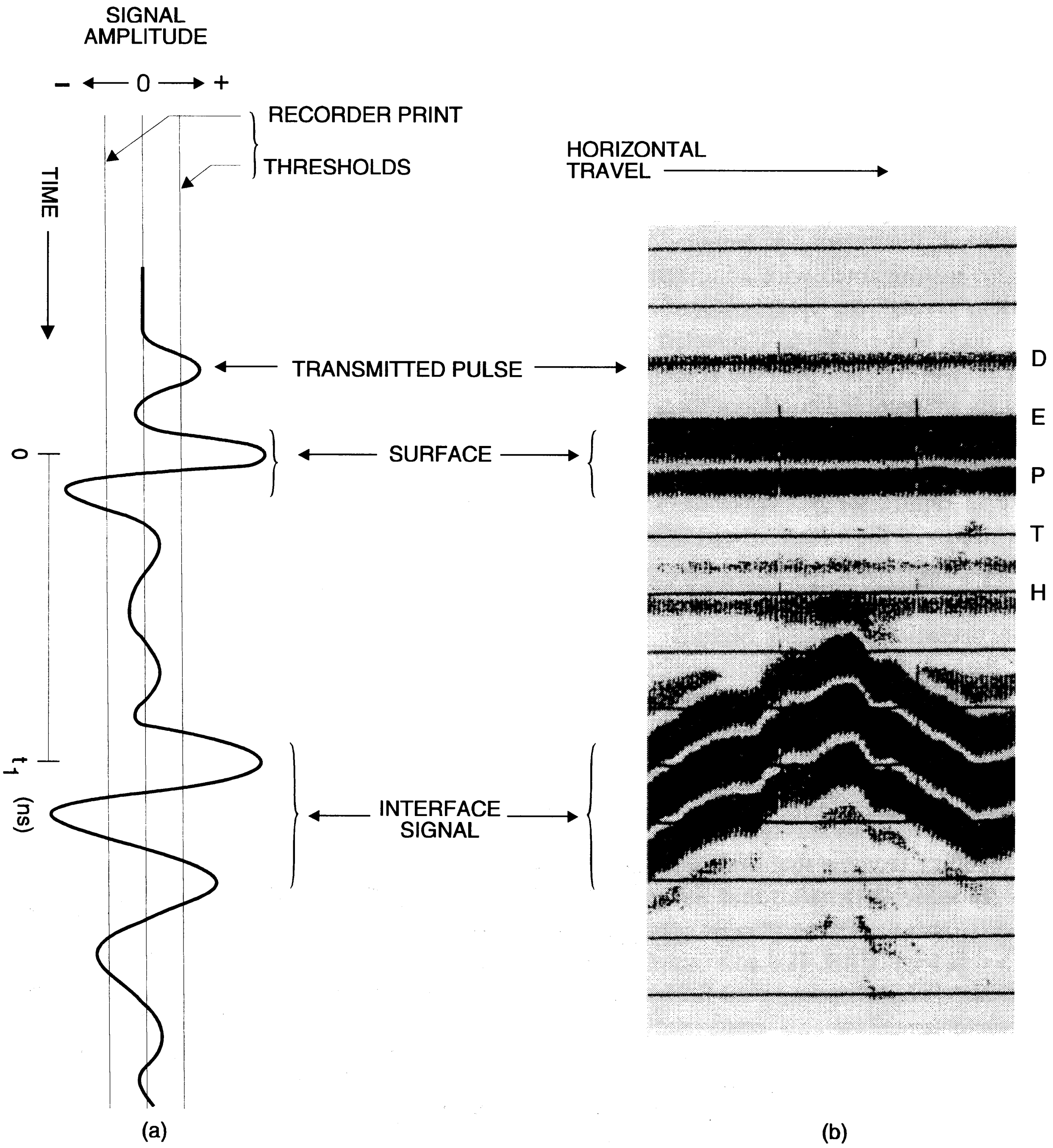

Figure 1. (a) A single composite waveform resulting from reflections received by the antenna, and (b) a display of cascading waveforms by a facsimile graphic recorder as the antenna is towed horizontally over an area.

where A_1 is the attenuation in dB/m, f is microwave frequency in Hz, and σ_1 is the electrical conductivity of the material in mho/m. Due to this attenuation, only a portion of the original energy that penetrates through the surface reaches the bottom of the first layer and strikes the interface between that layer and the second layer. Then, reflection of a portion of the net energy striking the interface occurs, and the extent of reflection is depended on the reflectivity (ρ_{12}) of this interface, which is given by

$$\rho_{12} = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} = \frac{\sqrt{\varepsilon_{r1}} - \sqrt{\varepsilon_{r2}}}{\sqrt{\varepsilon_{r1}} + \sqrt{\varepsilon_{r2}}} \tag{4}$$

where η_1 and η_2 are the wave impedances of soil layers 1 and 2, respectively, and ε_{r2} is the relative dielectric constant of layer 2.

As indicated in Eq. 4, if layer 2 has a larger relative dielectric constant than layer 1, the resulting reflectivity at their interface is a negative value. This means that the polarity of the reflected energy is the opposite of that arbitrarily assigned to the incident energy. If the incident pulses are positive, the dominant peak of the reflected pulses would be negative -- in contrast to the positive reflected pulse or signal shown in Figure 1, where the dominant peak is positive.

Finally, the portion of energy that penetrates this interface will continue its propagation through layer 2, and repeat the attenuation and reflection processes in layer 3, and so on, until all the initial energy radiated by the antenna is completely dissipated.

The total depth of penetration of the microwave pulses into the ground is determined not only by the extent of the reflection at each of the subsurface interfaces, but also by the extent of attenuation of the pulses during travel through each layer. As indicated by Eq. 3 and 4, these parameters are influenced by the relative dielectric constants of the various layers of subsurface materials. The dielectric constants of various types of soil, sand, and rock have been reported to vary between 4 and 12.[4] Depending on the moisture content of the various layers of soil at the time of survey, the actual relative dielectric constants of these different layers of materials can be higher, because of the high relative dielectric constant of water, which is 81.

In addition, when water is present, it usually carries with it various amount of salts in solution, which contribute significantly to the conductivity of wet soil. In accordance with Eq. 3, radar penetration should be considerably less in wet soil than in dry soil. In practice, it is quite difficult to predict a radar system's penetration depth accurately at a site before a survey or inspection is actually conducted.

Equation 3 also shows an important factor in the selection of an appropriate probing radar antenna -- the microwave frequency. In general, attenuation increases and, therefore, penetration decreases with the frequency of the microwave pulses. Clearly, the best combination of power rating and frequency of the radar system has to be selected for each type of application.

To summarize, when electromagnetic pulses radiate into the ground, a series of reflections of decreasing intensities and different polarities returns from the different underlying soil interfaces. Each reflection arrives at a time determined by the thickness and relative dielectric constant of the corresponding layer. A buried object will produce an additional reflection, if the size of the object is not too small in comparison to the microwave wavelength. The interpretation of reflection data is discussed in a later section.

PURPOSE AND SCOPE

The purpose of this study was to demonstrate that GPR is a simple, effective tool for inspecting suspected areas in rights-of-way for abandoned UST's without disturbing the ground. A relatively basic GPR system was used to probe selected VDOT area headquarters for UST's, obtaining radar reflections which were then used to show how to identify UST's.

METHODOLOGY

Ground-Penetrating Radar System

Detection of UST's with GPR basically involves scanning a suspected area with an appropriate antenna/radar system. The antenna/radar system used to test this application of GPR was the SIR System 8, manufactured by Geophysical Survey Systems, Inc., of North Salem, New Hampshire (Figure 2). This basic 10-year-old system is suitable for this type of application, easy to use, and most importantly, readily available. The components are:

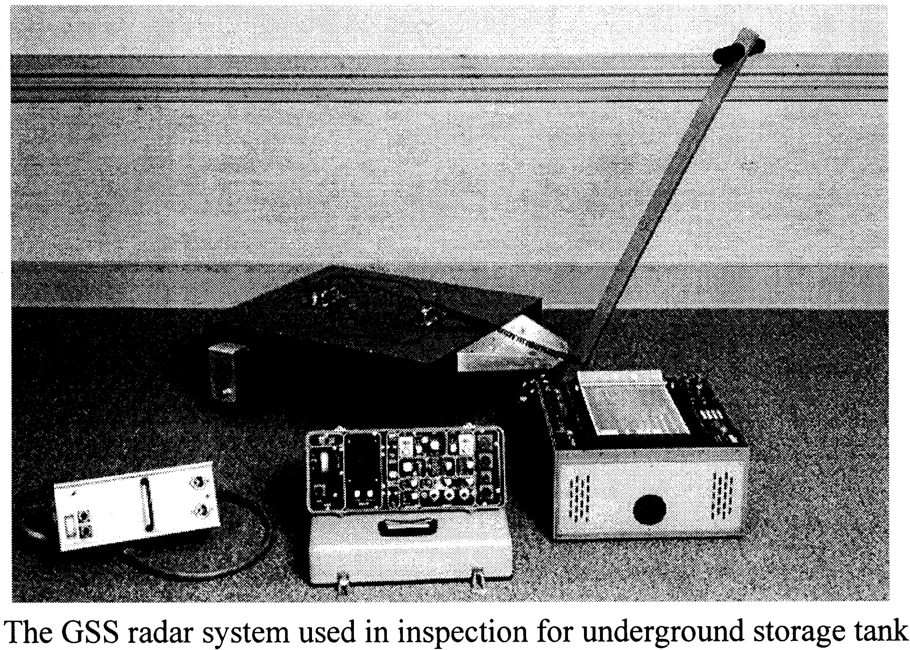

Figure 2. The GSS radar system used in inspection for underground storage tanks. Clockwise from the top: radar antenna, graphic recorder, control unit, and power distribution unit.

1. Antenna (Model 3105AP)
2. Control unit (Model 4800)
3. DC power distribution unit (Model 07)
4. Graphic Recorder (Model SR-8000)
5. Digital cassette tape recorder (Model DT-6000).

The system was designed to be powered by a 12-volt battery or, if a proper adaptor is available, by a vehicle battery.

As Figure 3 illustrates, the control unit controls the operation of the antenna and the recorders. It provides a synchronizing signal to a pulse generator in the antenna, which produces microwave pulses by electrically discharging pulses of electromagnetic energy. The 3105AP antenna emits microwave pulses with a center frequency of 300 Mhz, and a pulse width of 3 nanoseconds. This provides sufficient depth penetration, at least 6 to 9 m (20 to 30 ft), and adequate resolution. It is relatively lightweight and equipped with wheels and a towing bar, and can be easily towed over practically any terrain.

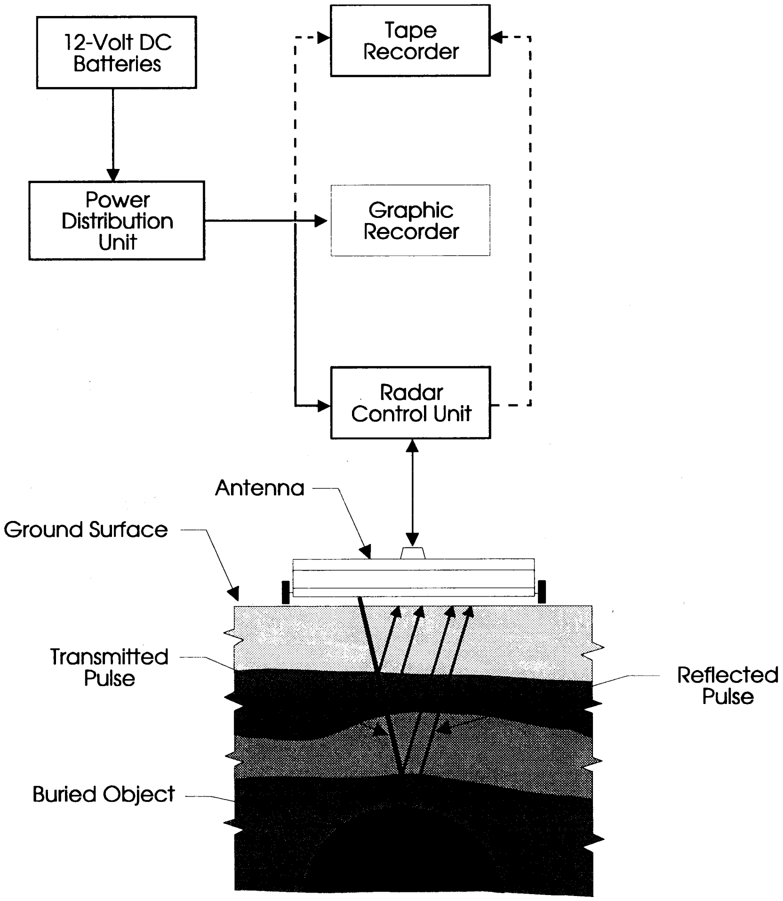

Figure 3. Setup of the simple GPR system used.

When the antenna detects a reflected radar pulse, the signal is transmitted to the receiver. The receiver converts the analog signal from an initial duration of nanoseconds to tens of milliseconds before transmitting it to the control unit. The control unit then processes the signal further before sending it to the recorders.

For this application, the graphic recorder alone would be adequate to record the radar data. A tape recorder is not absolutely necessary. However, a tape of the digitized radar data can be replayed through the graphic recorder and, if necessary, processed by computer to eliminate unwanted radar signals.

Inspection Procedure

The inspection procedure consisted of setting up the radar system and then scanning a suspected area by manually towing the antenna over it (Figure 4). Two people were needed; one to operate and monitor the radar control unit and recorder, and the other to tow the transducer. The operation of the control unit and the recorders involved adjusting various parameters (range, signal threshold, amplifier gain, sensitivity, scan rate, etc.) on these instruments, following guidelines provided in the operational manuals by the manufacturer.

Figure 4. Scanning a location by towing the antenna over it.

Before scanning, suspected areas were inspected for outward signs typically associated with buried fuel storage tanks, such as pump islands, vents, etc., to define or narrow down the area(s) where buried tanks were likely to be. Once these locations were roughly defined, each location was scanned by towing the antenna over it in different parallel passes (transect lines) separated by 1.5 m (5.0 ft) intervals. If the depth of a UST was desired, equally spaced points at 1.5 m (5.0 ft) intervals were placed on each transect line to create a grid over the location. Existing landmarks, such as fence lines, utility poles, signs, monitor wells, etc., were used as much as possible to supplement grid points as reference points for noting the exact position of the antenna during any moment in a scan. Such reference points were noted as tick marks on the chart recording, using electronic event markers supplied with the GPR system.

RESULTS AND DISCUSSION

Interpretation of Radar Data

Qualitative interpretation of radar reflection data is relatively simple. The beam of energy radiating from the antenna into the ground is fairly broad and conical in shape, with an included angle of about 90° and an apex at the center of the antenna. When the ground consists of relatively flat soil interfaces, the antenna receives the center portion of this beam, which is directed straight down and then reflected at a right angle (90°) from an interface. The other portion of the beam, which is transmitted and reflected to the sides, is not received. Therefore, as the antenna is being towed over the ground along a transect line, the graphic recorder displays the soil strata at different depths, much as these strata would appear to an observer standing in a trench and looking at the vertical wall.

The situation is different for cylindrical objects such as pipes and tanks, since these round objects offer many normal or perpendicular surfaces to the radar beam as the antenna approaches and passes, at right angles to their axes. As illustrated in Figure 5, a portion of the beam fanning out ahead or behind the radar strikes the side of the tank at a right angle, and that part of the beam returns to the antenna. Therefore, the antenna begins to "see" a cylindrical tank before it actually passes over it, and continues to see the tank until it is some distance beyond it.

As Figure 5 illustrates, the resulting composite reflection pattern shown on the recorder for a buried cylindrical tank appears as a hyperbola, with the locus situated directly above the tank. If the horizontal scale, which indicates the distance travelled by the antenna, is compressed more than the vertical (time or depth) scale, the hyperbola appears more like a vertical comet on the chart. This parabola or vertical comet is the signature by which buried tanks can be readily identified. In addition, old tanks are made of metal, which is practically a perfect reflector. Their unique signature is particularly strong or intense.

If the antenna approaches and passes over a tank at an oblique angle, the resulting reflection pattern from the tank does not resemble a vertical comet. Instead, it appears as a broad strong reflection, with a width dependent on the angle at which the antenna passes over the tank.

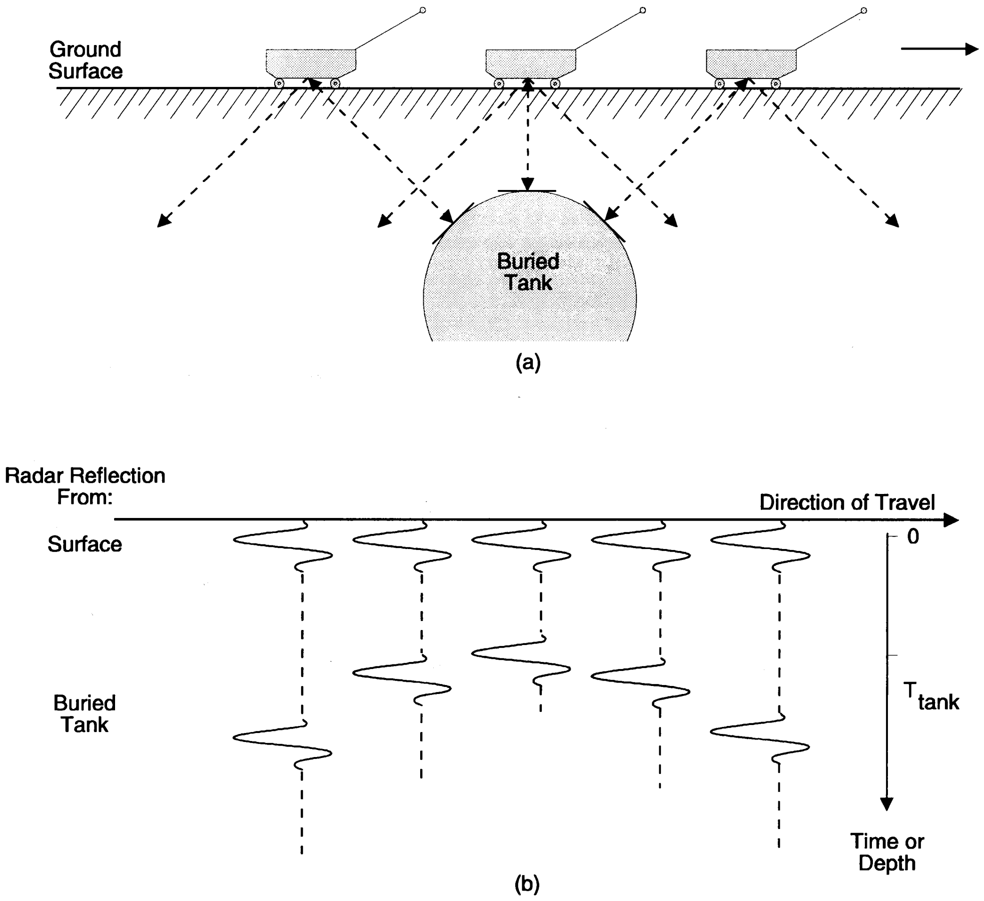

Figure 5. (a) Radar antenna being towed over an underground storage tank, and (b) the resulting idealized reflection pattern or signature for the tank.

Examples of UST Radar Signatures

The following radar reflection data were recorded during tests at three VDOT area headquarters. These provide examples of the unique vertical-comet signature of UST's.

Yancey Mill Area Headquarters

The ground on the north side of the fuel service building at this area headquarter was scanned along four transect lines (A, B, C, and D) (Figure 6). Figures 7-10 show the radar recordings of these four scans.

In scan A, the radar detected a tank between tick marks 2 and 3, as manifested by the vertical-comet signature shown in Figure 7. In addition, the radar detected but could not yet identify another strong reflector, apparently a metallic object, between marks 4 and 5.

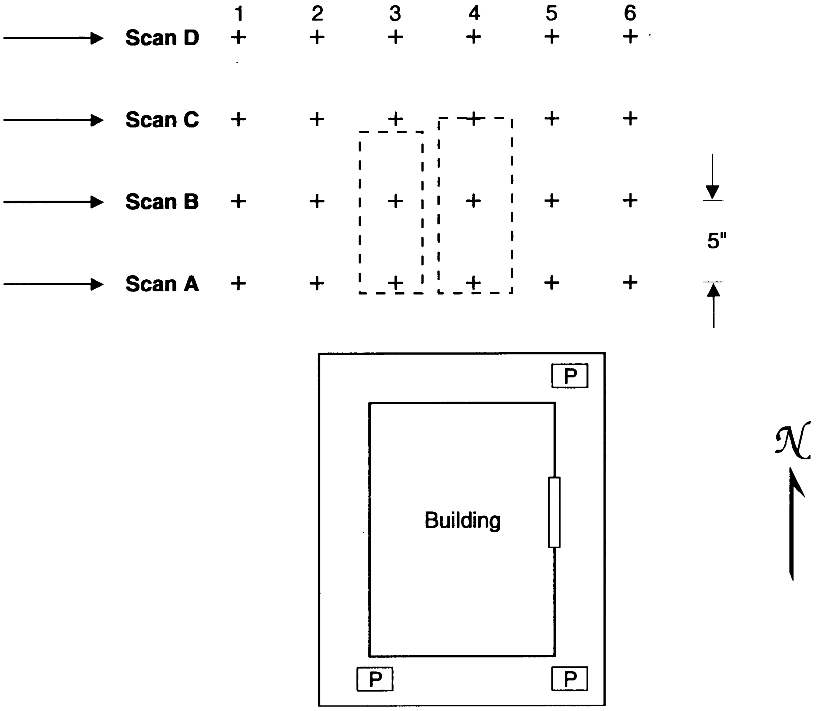

Figure 6. Four different radar scans made on the ground at the north side of the fuel service building at the Yancey Mill Area Headquarters. Tick marks were placed on the ground to form a grid of 5 ft x 5 ft squares. Areas outlined by dashed lines represent the general locations of buried tanks.

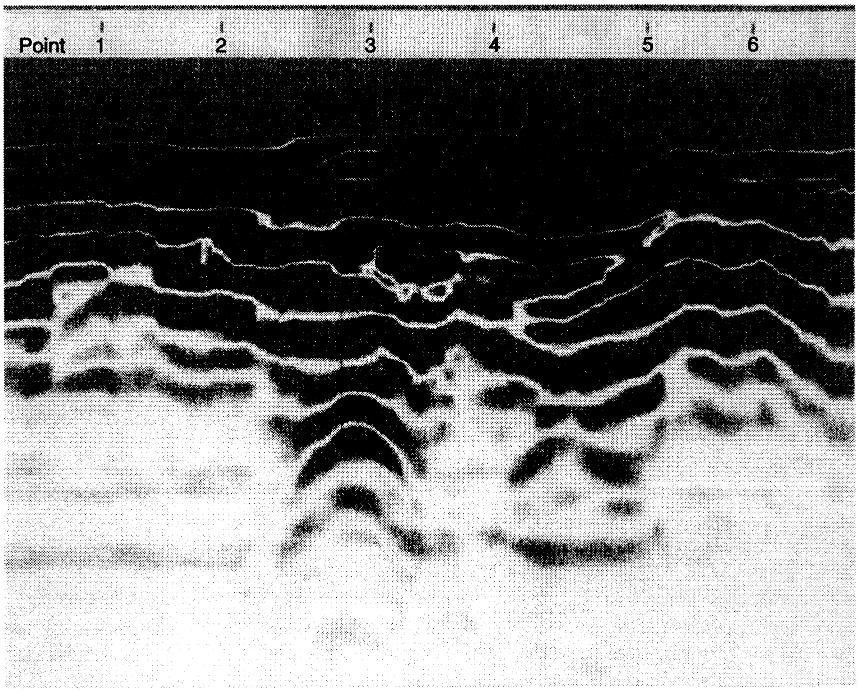

Figure 7. Radar scan A made over north side of the fuel service building at Yancey Mill Area Headquarters.

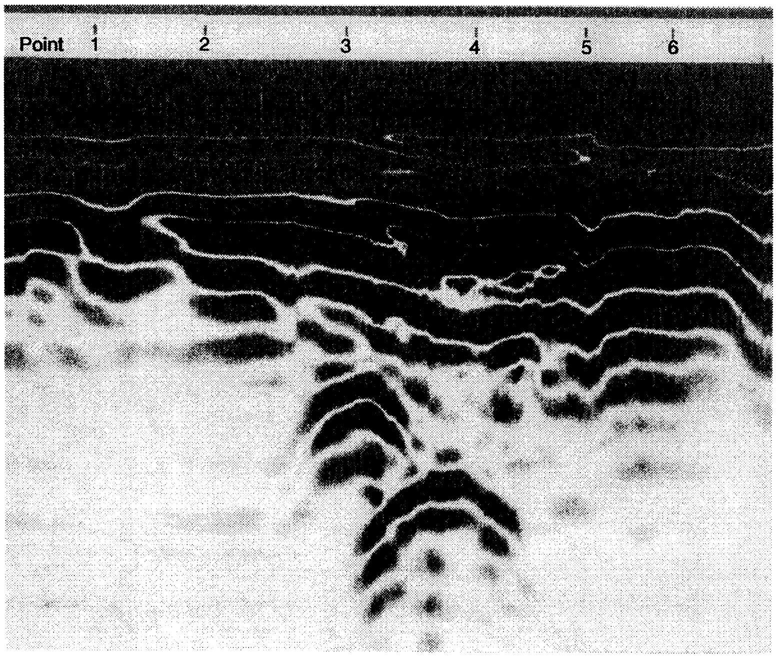

Figure 8. Radar scan B made over north side of the fuel service building at Yancey Mill Area Headquarters.

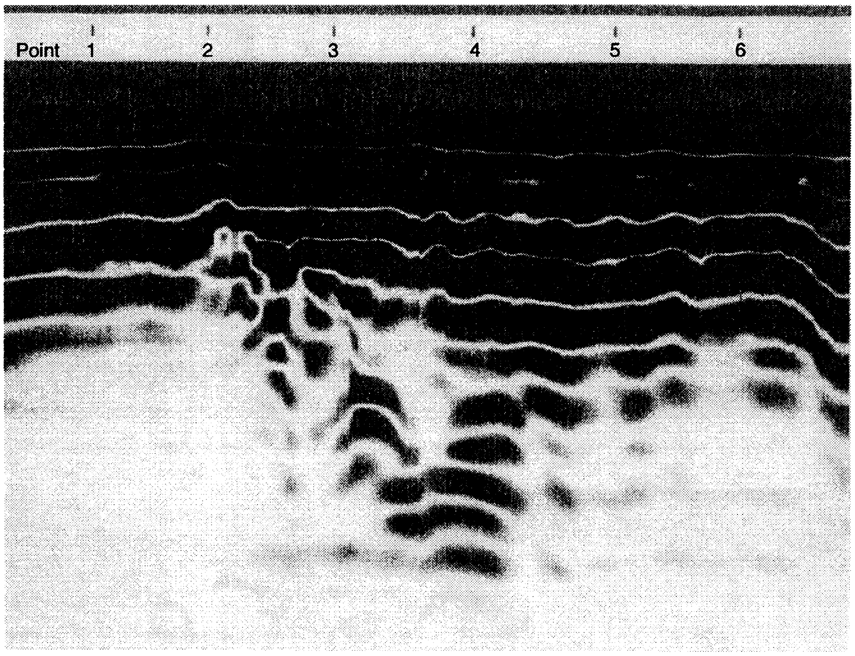

Figure 9. Radar scan C made over north side of the fuel service building at Yancey Mill Area Headquarters.

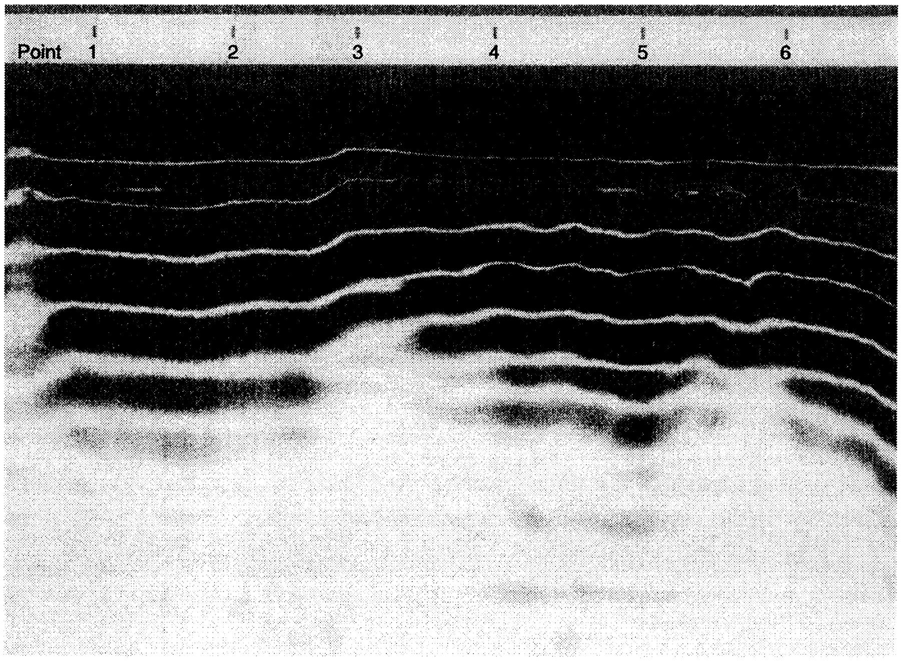

Figure 10. Radar scan D made over north side of the fuel service building at Yancey Mill Area Headquarters.

Along the transect line 1.5 m (5.0 ft) further north (scan B), the first tank was still "visible" between marks 2 and 3, and the "unknown" second object could be identified clearly as another tank (Figure 8). Apparently there were two buried tanks in this location, north of the building.

Another 1.5 m (5.0 ft) further north (Figure 9), the reflections from these two tanks became intertwined in such a manner that the vertical-comet signatures of the tanks were replaced by similarly strong but broad reflections. Possibly one of the tanks was shorter than the other and ended there. No excavation was conducted to determine the true reason.

Scan D, 1.5 m (5.0 ft) further north, showed that the tanks did not extend that far (Figure 10). These four scans delineated the general locations of the two buried fuel tanks, as outlined in Figure 6.

Free Union Area Headquarters

Figure 11 shows the vicinity of the fuel service building at this area headquarters. Scan A, made north of the building, revealed the presence of a metal pipe, indicated by the relatively small, cylindrical cross section near tick mark F, where a faucet was located (Figure 12).

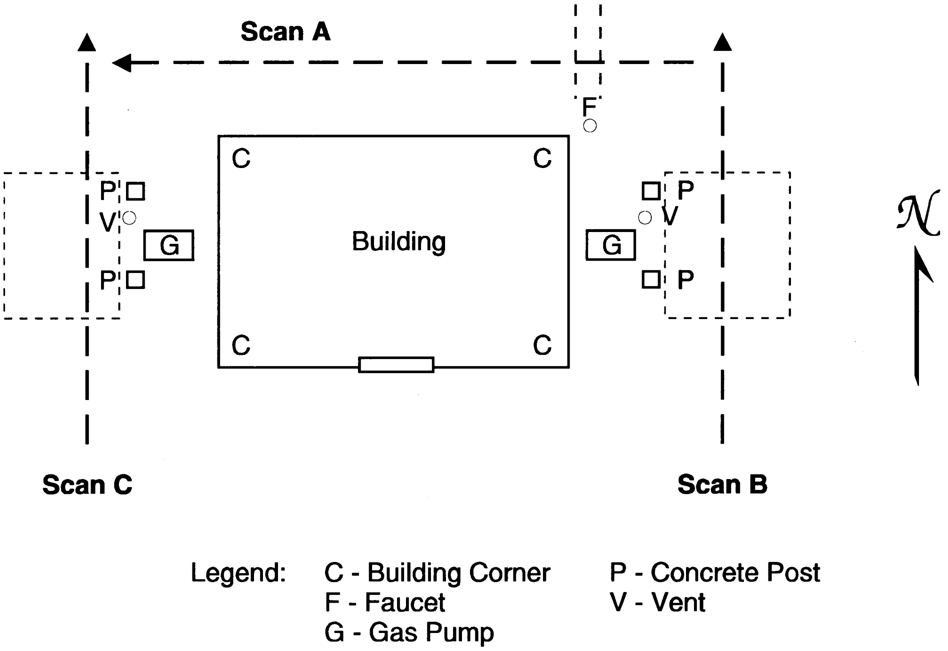

Figure 11. Radar scans made over the ground around the fuel service building at Free Union Area Headquarters. Areas outlined by dashed lines represent the general locations of buried tanks.

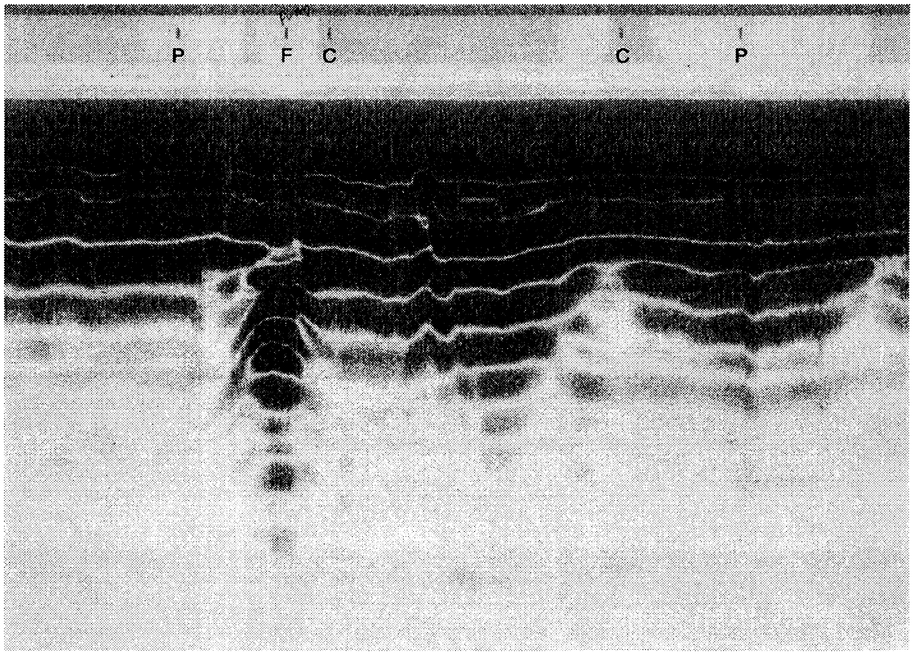

Figure 12. Radar scan A made over north side of the fuel service building at Free Union Area Headquarters.

In scan B, made east of the building, the radar began to detect the tank before the first tick mark P -- the first of the two concrete posts around the gas pump, designated by tick mark G -- and all the way to tick mark C, designating the northeast corner of the building (Figure 13). The absence of the typical vertical-comet shape in this strong metal reflection suggests that the radar scan was made parallel to the axis of the tank. The tank was probably buried with its axis parallel to the side of the building (Figure 11).

Scan C, made west of the building, indicated a second tank (Figure 14). Again, the absence of the distinct vertical-comet radar signature that can be expected when the radar passes over a tank at an angle perpendicular to its axis suggested that this tank was probably also buried with its axis parallel to the side of the building (Figure 11).

Boyd Tavern Area Headquarters

This area headquarters (Figure 15) provided examples of tanks buried at less obvious locations. Scan A, made toward the right side of the fuel service building and over grass and an asphalt walkway (Figure 16), indicated two tanks in the vicinity of two small caps or vents. The larger tank probably extended slightly underneath the asphalt walkway. Apparently the two tanks were buried together in one large excavation of roughly uniform depth, because the top of the smaller tank was buried deeper than the top of the larger one.

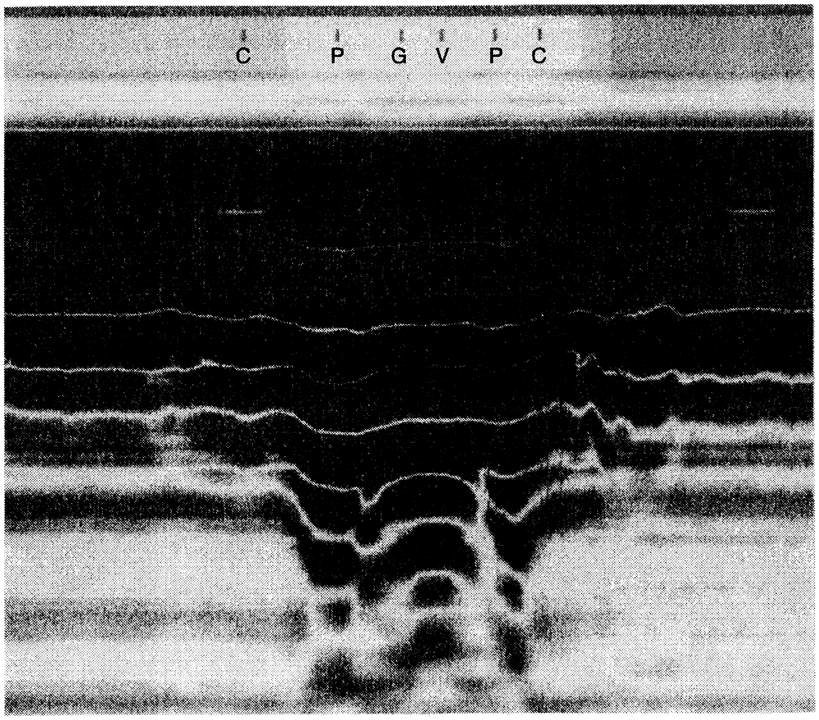

Figure 13. Radar scan B made over north side of the fuel service building at Free Union Area Headquarters.

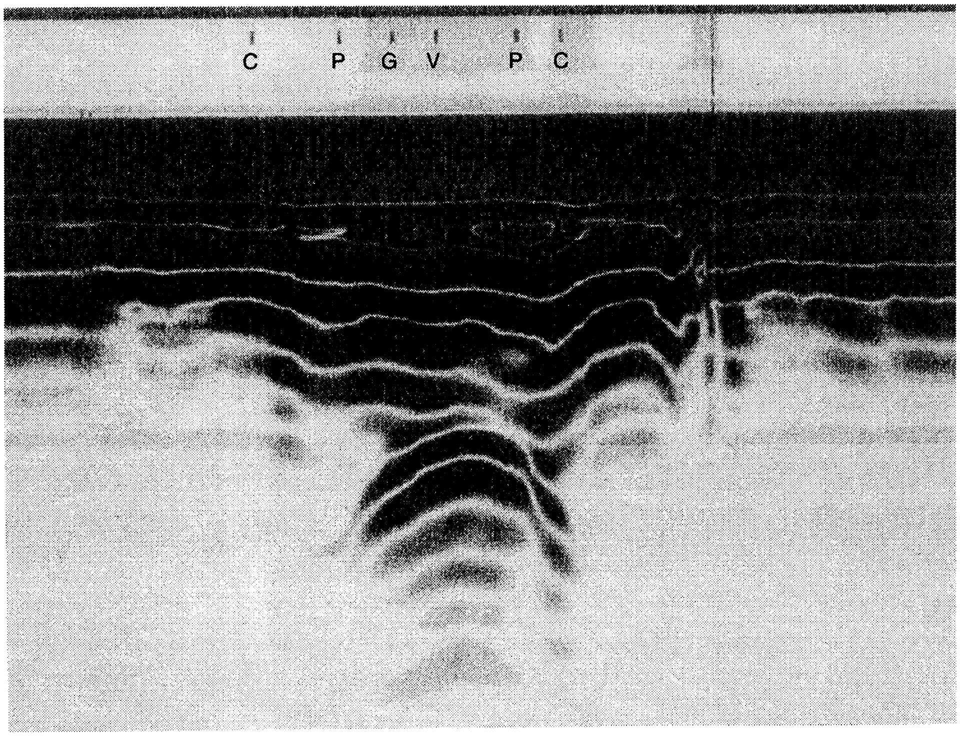

Figure 14. Radar scan C made over north side of the fuel service building at Free Union Area Headquarters.

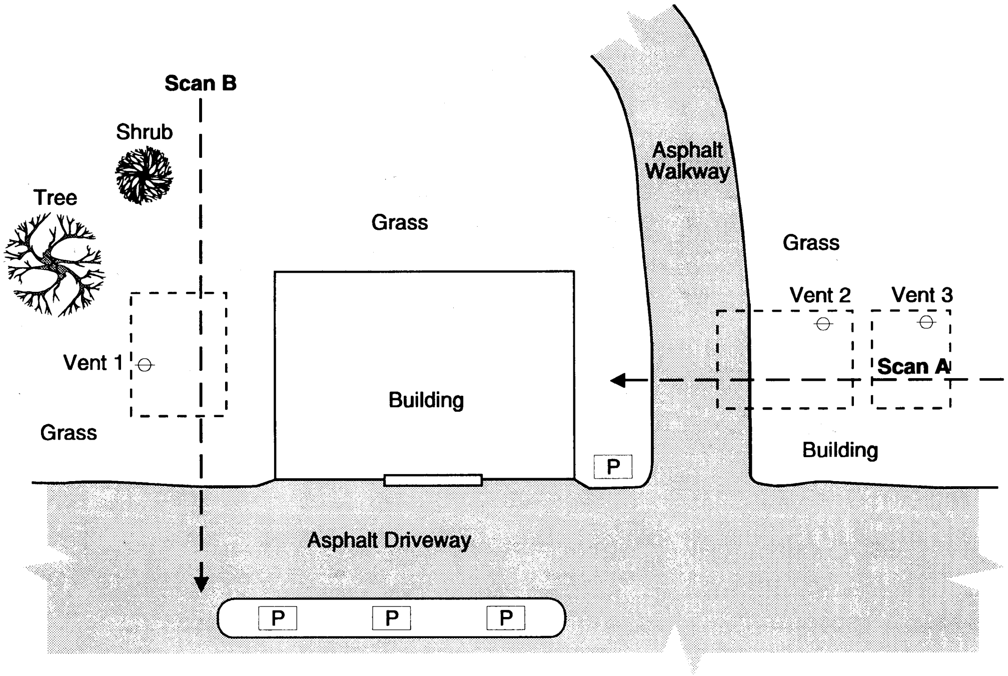

Figure 15. Radar scans made over the ground around the fuel service building at the Boyd Tavern Area Headquarters. Areas outlined by dashed lines represent the general locations of buried tanks.

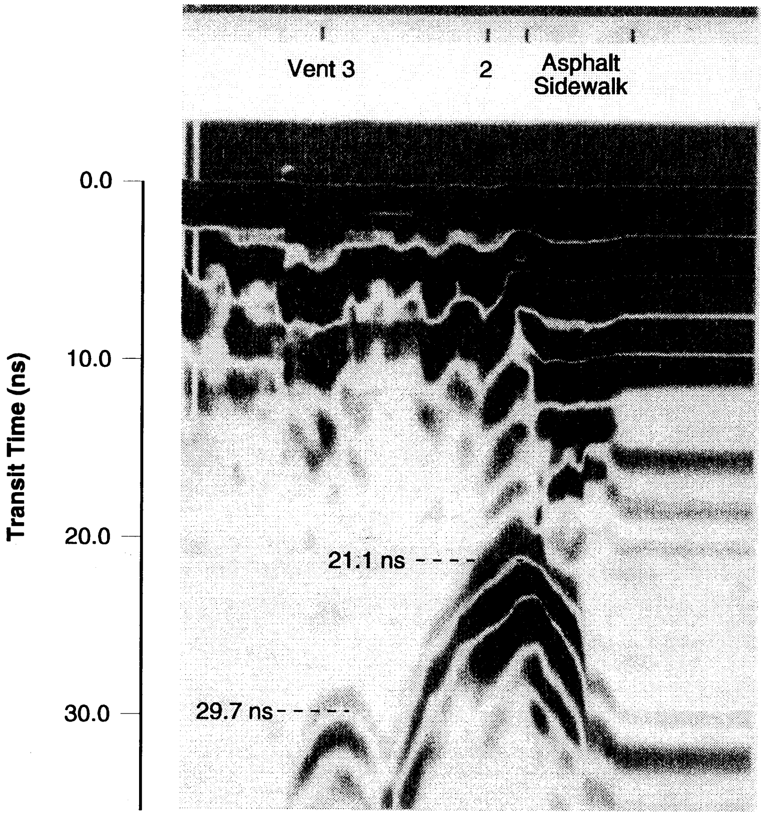

Figure 16. Radar scan A made over the grass and asphalt walkway on the right of the fuel service building at Boyd Tavern Area Headquarters.

By using equation 2, the depths of the tanks could be estimated from the two-way travel times of the microwave pulses striking the top of the tanks and returning to the antenna. This required calibrating the vertical scale or travel time, in nanoseconds (ns), on the chart. The manufacturer's suggested calibration procedure yielded two-way travel times of approximately 21.1 and 29.7 ns for the larger and smaller tanks, respectively (Figure 16). If the dielectric constant of the soil at this location ranged from 6 to 10, a reasonable assumption, a microwave would require 4.9 to 6.3 ns to complete a two-way trip through 30 cm (1 ft) of this soil (Figure 17, derived from equation 2). From this information, the depth of the smaller tank was estimated at 4.7 to 6.1 ft, and that of the large tank 3.4 to 4.3 ft from the surface to the top of the tanks.

Lastly, the radar pass made over grassy ground along the left side of the building, Scan B, indicated a third tank directly underneath a vent (Figure 18).

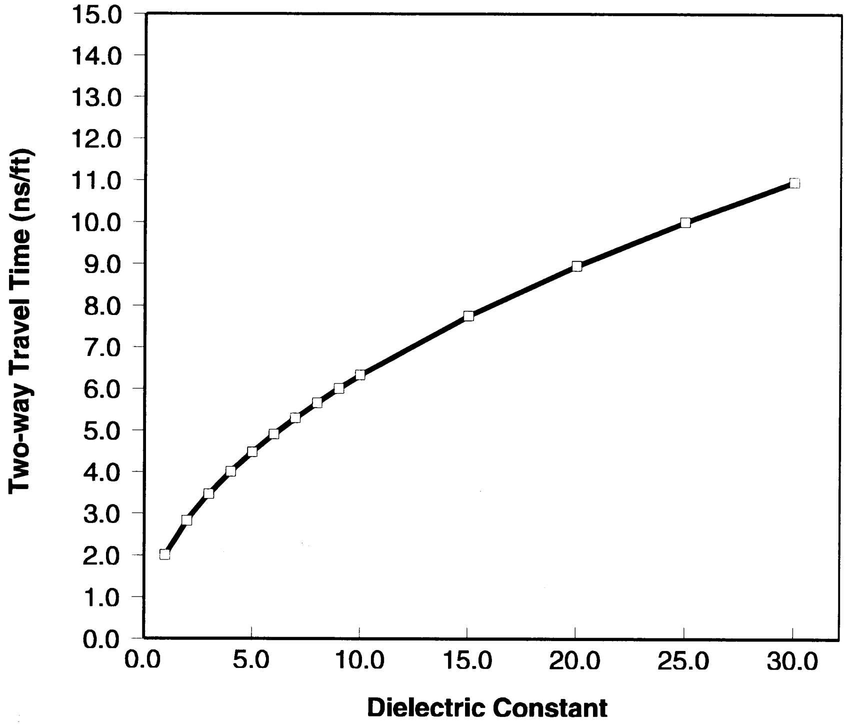

Figure 17. Influence of the dielectric constant of a material on the two-way travel time of a microwave through a unit thickness of the material.

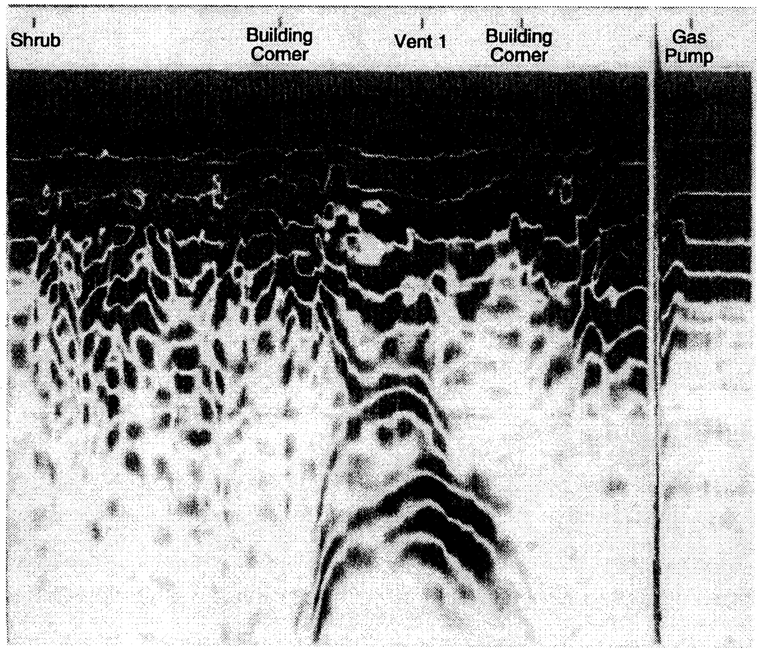

Figure 18. Radar scan B made over the grass along the left side of the fuel service building at Boyd Tavern Area Headquarters.

CONCLUSIONS

Similar trial radar inspections made at other VDOT area headquarters all yielded results generally similar to those presented. Clearly, GPR offers a very simple way to inspect prospective rights-of-way for buried fuel storage tanks abandoned by previous property owners, without disturbing the ground. The radar equipment required for this is minimal, and the inspection procedure and the radar-data interpretation are both relatively simple.

RECOMMENDATION

GPR should be used whenever a prospective property in a right-of-way needs to be inspected for the possible presence of old UST's. VDOT should rely on private geological survey companies for this service, with the assistance of the Research Council in developing specifications.

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