

A Scale Model for Studying Ground Penetrating Radars

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Abstract—A scale model developed for experimentally studying ground penetrating radars is described. The model is one-third full size and is used with transient signals that have significant frequency content within the range 150 MHz to 1.5 GHz. A unique feature is that the earth in the model is represented by an emulsion, which is a mixture of mineral oil, saline solution, and a stabilizing agent. This emulsion is a scale model for red-clay earth; it matches the electrical parameters of the clay, including the dispersion in the conductivity, over a ten-to-one frequency range.

Typical results measured with the model are discussed. These include the measurement of the electric field transmitted by the radar into the earth and the measurement of radar signatures for pipes of various composition buried in the earth.

I. INTRODUCTION

GROUND penetrating radar systems have been proposed for many applications; these include locating buried utilities [1], [2], detecting buried land mines [3], and profiling the subsurface of highway pavement [4]. Both theoretical and experimental evaluations of proposed systems have been undertaken. The experimental tests usually involve a full-size system used out-of-doors to detect a known target, such as a pipe, buried in the earth. Such tests, while providing valuable information, are plagued by several problems. These problems include the continually changing electrical properties of the earth due to changes in the weather (rain), and the lack of specific knowledge of the electrical properties over the complete path for the signal (surface-to-burial depth). Also, it is difficult to change or modify a target once buried without excavation, which generally changes the electrical properties of the earth.

An alternative to tests with the full-size system is the use of an experimental scale model. A reduced-size scale model can be accommodated in the laboratory, thus removing the effects of the weather. In addition, a homogeneous material with prescribed electrical properties can be substituted for the earth in the model. When this material is a liquid, changes and modifications of the target are easily made. In this paper an experimental scale-model

system for use with ground penetrating radars is described, and typical illustrative results obtained with the model are discussed.

II. DESCRIPTION OF THE MODEL

For a scale model to provide accurate information about a full-sized system, the physical parameters for the model and full-sized system must satisfy certain well-known relationships [5]. For the "geometrical" model used in this work, the physical dimensions (\vec{r}) are scaled by the factor k_l , and the frequency (ω) is scaled by the factor $k_\omega = 1/k_l$:

$$\vec{r}_m = k_l \vec{r}_f \quad (1a)$$

$$\omega_m = k_\omega \omega_f = (1/k_l) \omega_f \quad (1b)$$

where the subscripts f and m refer to the full-sized system and the model, respectively. The electrical constitutive parameters for every material in the full-sized system are also scaled. The scale factors are, for the permittivity $k_\epsilon = 1$,

$$\epsilon_m(\omega_m) = k_\epsilon \epsilon_f(\omega_f) = \epsilon_f(\omega_f) \quad (1c)$$

for the permeability $k_\mu = 1$,

$$\mu_m(\omega_m) = k_\mu \mu_f(\omega_f) = \mu_f(\omega_f) \quad (1d)$$

and for the conductivity $k_\sigma = 1/k_l$

$$\sigma_m(\omega_m) = k_\sigma \sigma_f(\omega_f) = (1/k_l) \sigma_f(\omega_f). \quad (1e)$$

From (1c) the permittivities of the materials in the full-sized system and the model must be the same. The condition (1d) for the permeabilities is easily met when all materials in the full-sized system and model are nonmagnetic $\mu = \mu_0$. The conductivities (1e) in the full-sized system must be scaled by the factor $1/k_l$ in the model.

The dimensions of the equipment, such as the antennas, used in the ground penetrating radars of interest are typically less than one meter. Thus, a one-third size ($k_l = 0.333 \dots$) scale model is of convenient size for laboratory use; the components are easily handled, but not so small as to make fabrication difficult. The temporal signals used with the full-sized system generally have significant frequency content within the range $50 \text{ MHz} \leq f_f \leq 500 \text{ MHz}$; thus, from (1b) the frequencies used in the model are $150 \text{ MHz} \leq f_m \leq 1.5 \text{ GHz}$.

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The air in the full-sized system is represented by air in the scale model. With air considered lossless, $\sigma_f = 0$, this choice satisfies both (1c) and (1e).

A red clay, with a density of 2.04 gm/ml and a water content of 20 percent by dry weight, was chosen as the earth in the full-sized system. This clay is typical of the earth in metropolitan Atlanta and northern Georgia. The measured electrical constitutive parameters, ϵ_r and σ , for the clay are shown in Fig. 1 (open dots). Note that the upper and right-hand scales on the graphs apply to the full-sized system. The relative permittivity of the clay is seen to be fairly constant, while the conductivity increases with the frequency. The latter phenomenon, the dispersion in the conductivity, is of great importance, for it makes the attenuation experienced by a wave propagating through the clay increase with increasing frequency—the earth (clay) acts as a low-pass filter. To see this, consider the propagation constants for a plane wave:

$$k = \beta - j\alpha = \omega\sqrt{\mu_0\epsilon}(1 - j\sigma/\omega\epsilon) \quad (2)$$

and the resulting attenuation per unit length (dB/m),

$$A = \text{Attenuation/unit length} = -20 \log_{10}(e^{-\alpha}) \\ = 8.686\alpha \text{ dB/m.} \quad (3)$$

The attenuation for the red clay is shown as a function of frequency in Fig. 2; the low-pass characteristic is evident.

For the scale model to be realistic, the material that represents the earth in the model should have a relative permittivity that is roughly constant (1c),

$$\epsilon_{rm} = \epsilon_{rf} \approx 20.5 \quad (4a)$$

and a conductivity that increases with frequency and is equal to (1e),

$$\sigma_m(f_m) = 3.0\sigma_f(f_m/3.0). \quad (4b)$$

From (3), the attenuation in the model will be

$$A_m(f_m) = 3.0A_f(f_m/3.0). \quad (4c)$$

An oil-in-water emulsion was used to represent the earth in the scale model. This is a mixture of mineral oil, a saline solution, and a stabilizing agent (emulsifier). The ingredients of the emulsion, volume fraction of oil, salinity, etc., were chosen to make the electrical parameters satisfy (4a) and (4b). A systematic procedure developed in [6] was used for this purpose. The ingredients for the emulsion are summarized in Table I.

The electrical constitutive parameters ϵ_r and σ and the attenuation per unit length A for the emulsion are shown in Figs. 1 and 2. Note that the lower and left-hand scales on the graphs apply to the emulsion (scale model). Two sets of curves are shown, the theoretical predictions (solid line) and the measured results (dots). The emulsion is seen to closely match the properly scaled, electrical constitutive parameters of the clay, including the dispersion in the

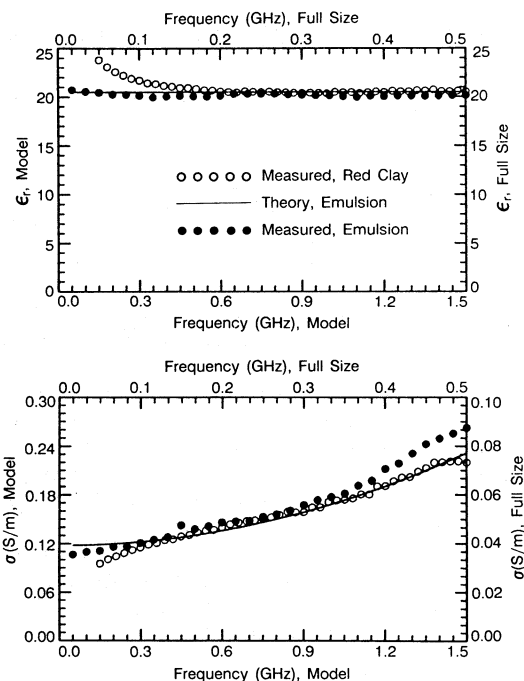


Fig. 1. Measured constitutive parameters for red-clay earth (full-sized system), and theoretical and measured constitutive parameters for emulsion (scale model), $T \approx 23^\circ\text{C}$.

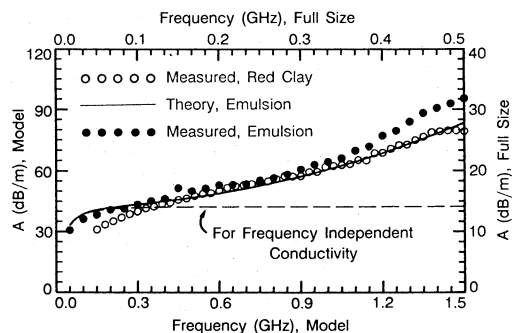


Fig. 2. Attenuation per unit length, dB/m, for red-clay earth (full-sized system) and for emulsion (scale model), $T \approx 23^\circ\text{C}$.

conductivity, over the ten-to-one frequency range for which the clay was measured.¹

The dashed line in Fig. 2 is the attenuation for a frequency independent conductivity equal to the low-frequency value $\sigma_m \approx 0.12 \text{ S/m}$. From this result, it is clear that the dispersion in the conductivity must be included;

¹The dispersion (frequency dependence) in the electrical properties of both the clay and the emulsion is primarily due to the water contained in these materials. The dispersion for water is described by the Debye relation which involves a single relaxation time τ [6]. At frequencies for which $\omega\tau \ll 1$, as in Fig. 1, the relative permittivity and the conductivity of water are

$$\epsilon_r = \epsilon_{r0} - O[(\omega\tau)^2] \\ \sigma = \sigma_0 + \omega\epsilon_0(\epsilon_{r0} - \epsilon_{r\infty})\omega\tau + O[(\omega\tau)^3]$$

where ϵ_{r0} , $\epsilon_{r\infty}$, and σ_0 are frequency-independent constants. When terms of order $(\omega\tau)^2$ or less are ignored, the permittivity is seen to be approximately constant, and the conductivity is seen to contain a constant term plus a term that increases as the square of the frequency. This behavior, the dispersion for the water, is similar to the dispersion observed for both the clay and the emulsion.

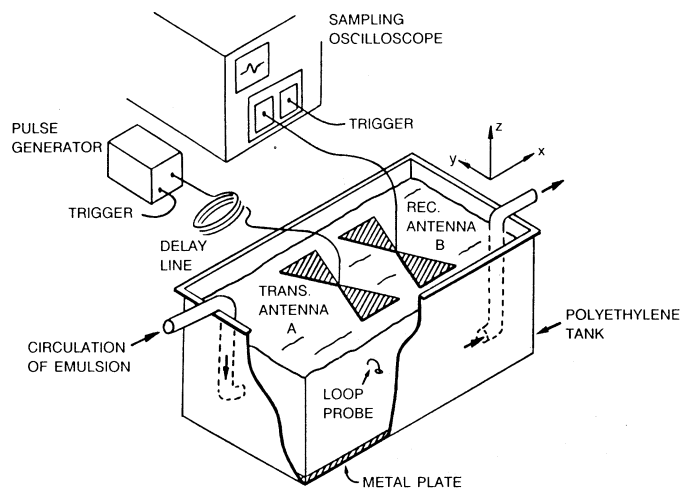


Fig. 3. Scale-model system.

TABLE I
CONSTITUENTS OF EMULSION USED IN SCALE MODEL

Oil	Heavy White Mineral Oil Saybolt Viscosity 335/365, Volume Fraction $\Phi_1 = 0.625$.
Saline Solution	Distilled water with NaCl added to adjust normality to $N = 0.048$.
Emulsifier	Blend of two emulsifiers TWEEN 20 and SPAN 80 with the volume ratio TWEEN 20/SPAN 80 = 4.5/5.5*. Amount of Emulsifier is 10% by volume of amount of oil.

*TWEEN and SPAN are trademarks of ICI Americas, Inc.

otherwise, the attenuation at $f_m = 1.5$ GHz would be underestimated by about 40 dB/m.

Fig. 3 is a sketch of the scale-model system. A polyethylene tank (94 cm \times 51 cm \times 51 cm) containing 242 liters of the emulsion models the earth. The depth of the sion is about 48 cm. The emulsion is periodically mixed by circulating it with a gear pump.

A metal plate covering the bottom of the tank serves as a reference for reflections. An electrically small, insulated half-loop is centered on the plate. This loop is used to measure the transmitted signal at the bottom of the tank.

The transmitting and receiving antennas of the radar are mounted on a rack; their height (z) above the air/emulsion interface and their location (x) along the longitudinal axis can be varied. A pulse generator, Avtech Model AVH-5, is connected to the transmitting antenna, and the signal from the receiving antenna is monitored with a digital processing, sampling oscilloscope, Tektronix Model 7854 with 7S12, S-6 and S-53 plug-in units. The digitized waveforms are sent from the oscilloscope to a microcomputer for signal processing, such as Fourier transformation.

III. EXAMPLES OF MEASURED RESULTS

In the scale-model system described in the previous section, the elements associated with a ground-penetrating radar, such as the antennas, targets, etc., are readily varied. This permits easy experimental comparison of different configurations for the radar, and eventually the optimization of the radar for a particular application. In this section, a few typical measurements made with the scale-model system will be described.

The electrically small half-loop at the bottom of the tank can be used to measure the field pattern of the transmitting antenna of the radar. For this purpose, the transient voltage at the terminals of the loop is measured with the sampling oscilloscope. This voltage is approximately proportional to the temporal derivative of the electric field at the loop. For the orientation shown in Fig. 4, the voltage is

$$V(r, \psi, t) \approx C \frac{dE^i(r, \psi, t)}{dt} \cos \psi \quad (5)$$

where C is a constant of proportionality.

Fig. 5 shows typical results measured with the loop positioned directly below the transmitting antenna, $\psi = 0$. The transmitting antenna for this example is a one-third-size scale model of an antenna used in a commercial utility radar: a "bow tie" formed from sheet metal and terminated with lumped resistors. The output of the pulser, which is connected to the transmitting antenna, is shown in Fig. 5(a), and the voltage received at the terminals of the loop is shown in Fig. 5(b). According to (5), the electric field-radiated by the transmitting antenna is proportional to the integral of the received voltage, which is shown in Fig. 5(c). A comparison of Fig. 5(a) and (c) shows that this particular transmitting antenna roughly differentiates the pulse on radiation.

In the Fourier transform or frequency domain, (5) is equivalent to

$$V(r, \psi, \omega) \approx j\omega C E^i(r, \psi, \omega) \cos \psi. \quad (6)$$

The angle ψ can be varied by changing the position of the transmitting antenna, x in Fig. 4, and a field pattern for the antenna, $E^i(r, \psi, \omega)$ versus ψ , measured. However, the radial position r is a function of the angle ψ , $r = z/\cos \psi$, and this dependence must be removed before a meaningful field pattern can be obtained. When the measurement point is in the far zone of the antenna, the electric field is proportional to $\exp(-jkr)/r$. This dependence can be used to transfer the fields measured at different angles ψ , therefore at different radial distances r , to the common radial distance r_0 :

$$\begin{aligned} E^i(r_0, \psi, \omega) &\approx \frac{-jV(r, \psi, \omega)}{\omega C \cos \psi} \frac{r(\psi)}{r_0} e^{jk(\omega)[r(\psi) - r_0]} \\ &\approx \frac{-jzV(z/\cos \psi, \psi, \omega)}{\omega C \cos^2 \psi} e^{jk(\omega)[z/\cos \psi - r_0]} \end{aligned} \quad (7)$$

where $r_0 \geq z/\cos \psi_{\max}$.

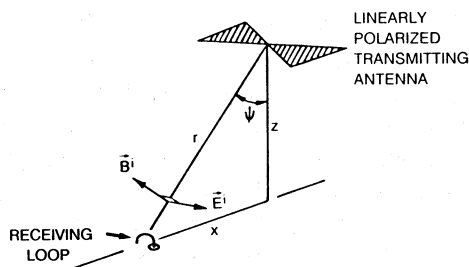


Fig. 4. Coordinates for reception of transmitted field.

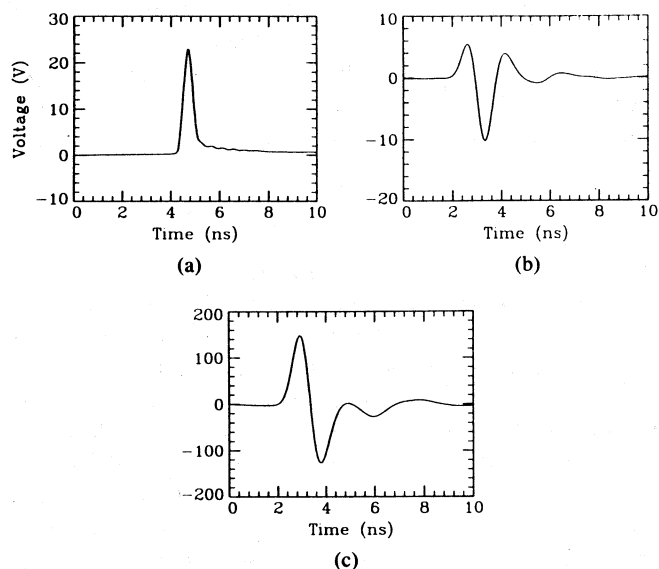


Fig. 5. Waveforms measured with model antenna 0.5-cm above air/emulsion interface. (a) Pulse from generator. (b) Pulse at terminals of receiving loop. (c) Integral of waveform (b). Units for vertical scales on (b) and (c) are arbitrary.

Equation (7) is a result that applies in the Fourier transform or frequency domain. The measurements made with the sampling oscilloscope are in the time domain. To apply (7) to these results, the following procedure is used: the measured voltage is transformed to the frequency domain using a discrete Fourier transform (DFT), $V(r, \psi, t) \rightarrow V(r, \psi, \omega)$. Equation (7) is applied to these results, with $k(\omega)$ determined from (2) and the electrical parameters of the emulsion ϵ_r and σ . An inverse DFT is used to obtain the electric field in the time domain, $E^i(r_0, \psi, \omega) \rightarrow E^i(r_0, \psi, t)$.

Fig. 6 shows a time-domain field pattern measured using the procedure described above. Here the time-domain signal $E^i(r_0, \psi, t)$ at a radial distance $r_0 = 62.8$ cm is shown as a function of the angle ψ , $0^\circ \leq \psi \leq 40^\circ$. These results are for the resistively loaded "bow-tie" antenna described earlier, located 0.5 cm above the air/emulsion interface. The radiated pulse is seen to decrease in magnitude and undergo a small amount of distortion with an increase in the angle ψ . The physical size of the tank prohibited measurements at angles greater than $\psi = 40^\circ$.

A different representation of the field pattern is obtained by plotting the peak-to-peak value for the time-domain

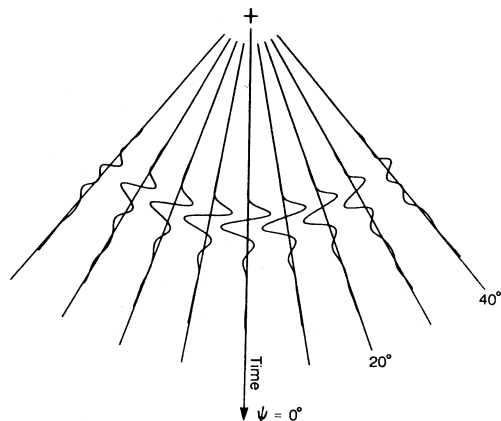


Fig. 6. Field of model antenna (time domain) at the radial distance $r_0 = 62.8$ cm as a function of the angle ψ . Antenna is 0.5-cm above air/emulsion interface.

signal $E^i(r_0, \psi, t)$ versus the angle ψ . Fig. 7 shows this type of pattern for three different antenna heights, 0.0, 0.5, and 2.0 cm above the air/emulsion interface. Note that the main lobe of the pattern narrows as the antenna is elevated. This phenomenon, which is explained in [7], is associated with the coupling into the earth (emulsion) of the evanescent waves in the plane-wave spectrum for the field of the antenna.

When making field pattern measurements, one has to be certain that reflections from the walls of the tank are not corrupting the direct signal measured with the loop. This can be accomplished by noticing the change in the received signal (pulse) when a metal plate is placed on the wall of the tank. The sign of the reflection coefficient for the emulsion/metal interface is opposite to the sign of the reflection coefficient for the emulsion/plastic/air interface.

The scale-model system can be used to study the scattering characteristics of different targets. For a radar like the one shown in Fig. 3, a pulse is radiated from antenna A, reflected from a buried target, then received by antenna B. The received signal, the signature, is processed to identify the target.

To measure the signature of a target using the scale-model system, a signal is first measured with the target absent. This background signal has several components: the direct coupling between the antennas, the reflection from the sides of the tank and metal plate at the bottom, etc. Next, a signal is measured with the target present. The difference in the two signals, with and without the target present, is the signature of the target.

This procedure was used to measure the signatures for several buried pipes; the arrangement is shown in Fig. 8. The two antennas are centered over the pipe, which is at a depth of 33 cm. The electric field radiated by the transmitting antenna is parallel to the axis of the pipe. Fig. 9 shows the measured signatures for five different pipes; all are approximately 3.5 cm in diameter. The results are for a metallic pipe (copper) (Fig. 9(a)), and plastic pipes (PVC, 0.35-cm wall thickness) filled with water (Fig.

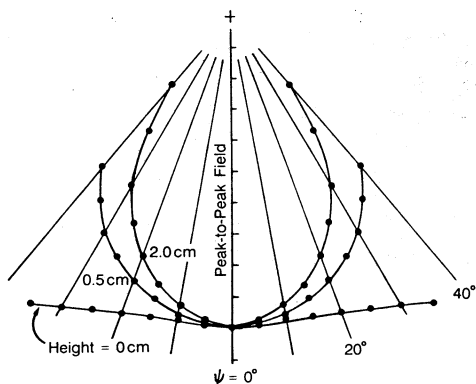


Fig. 7. Peak-to-peak value of field (time domain) as a function of the angle for various heights of model antenna above air/emulsion interface, $r_0 = 62.8$ cm.

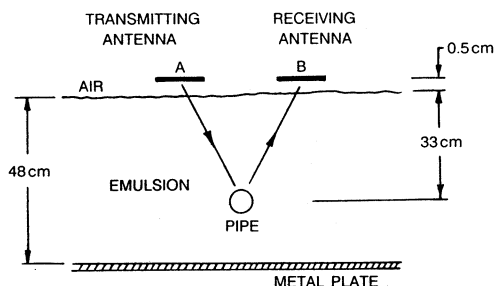


Fig. 8. Radar used to measure signatures of buried pipes.

9(b)), air (Fig. 9(c)), half air/half water (Fig. 9(d)), and emulsion (Fig. 9(e)). This last case is to represent a plastic pipe filled with earth. The variation of the signatures with pipe composition and filling is evident. Such information is useful in designing algorithms that are applied to measured signatures to locate and identify buried pipes. For example, the metallic pipe (Fig. 9(a)) can be distinguished from the water-filled pipe (Fig. 9(b)) by the sense of the signature; Fig. 9(b) is roughly the negative of Fig. 9(a).

Experimentally obtained radar signatures, like those in Fig. 9, are particularly useful, since comparable results are very difficult to calculate theoretically. The scattering from an object, like a pipe, can be calculated in the frequency domain and used with a Fourier transform to determine the scattered signal for pulse excitation. The radar signature of an object, however, involves not only the scattering from the object but the response of the radar's antennas on transmission and reception. The antennas used with these systems are lossy and dispersive. In addition, their characteristics are strongly dependent on their location above the earth, as Fig. 7 attests. Hence they are very difficult to theoretically model.

IV. CONCLUSION

A scale model was developed for experimentally studying ground penetrating radars. The model is particularly useful in comparing the performance for different configurations of a radar, such as different antenna and target orientations, different target compositions, etc. A unique feature of this model is the use of an emulsion which accurately represents the electrical parameters of the earth, including the dispersion in the conductivity. The attenuation experienced by a wave (pulse) propagating through the earth is one of the most important parameters for a ground-penetrating radar, and the attenuation is accurately modeled only when the conductivity is accurately modeled.

The emulsion described in this paper was formulated to model red-clay earth; however, emulsions can be easily formulated to model other types of earth [6].

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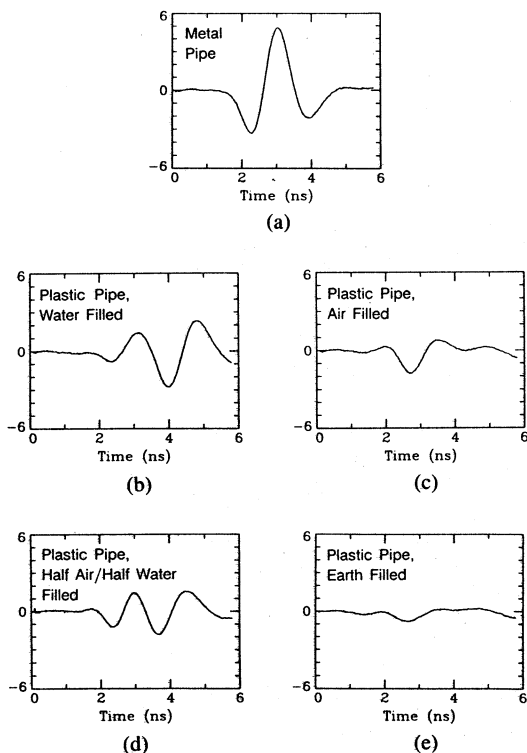
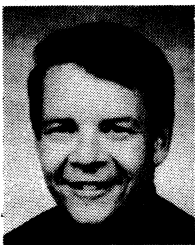


Fig. 9. Measured radar signatures for various buried pipes. Units for vertical scales are arbitrary.

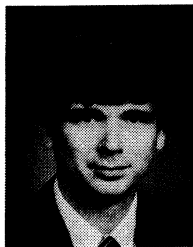


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