NONCONTACT MEASUREMENTS OF FOUNDATIONS AND PAVEMENTS WITH SWEPT-FREQUENCY RADAR

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Radar waves will be partially reflected whenever they encounter a change in electrical properties of the material in which they are traveling. Because highway profiles are formed of layered materials whose electrical properties differ, reflectance curves, as measured with a swept-frequency radar system, will contain information relating to the physical properties and the thicknesses of these layers. Analytical methods were developed to extract values for the electrical properties and layer thicknesses from the reflectance curves. Those methods are demonstrated on theoretical reflectance curves from typical profiles of an asphalt highway and a concrete highway. Swept-frequency radar measurements from either an air platform or a land vehicle show much promise for reducing both costs and time in the testing of old construction foundations and in the control of new construction.

• FOR A number of years the U. S. Army Engineer Waterways Experiment Station has conducted studies in the microwave spectral region to determine the feasibility of utilizing microwave techniques as a means of rapidly acquiring environmental data remotely. In these laboratory studies, the environmental parameters considered were limited for the most part to those dealing with soils, i.e., soil moisture content, soil composition, and layering profiles. The results of these laboratory studies indicated the following:

1. Imaging radar systems are not generally suitable for directly obtaining quantitative information on soil parameters. This type of radar system is sensitive only to the magnitude of the return signal and is not designed to discern individual components of the signal resulting from surface and subsurface reflections.
2. A number of different types of radar systems including frequency modulated, monopulse, and swept frequency can be used to distinguish between surface and subsurface returns. The swept-frequency radar system was chosen for further studies because it is the easiest to maintain and can be calibrated readily.
3. There is a direct correlation between a soil's dielectric constant and soil-water content.
4. Soil type per se has little effect on the return signal measured.
5. Swept-frequency radar techniques can be used to measure the optical thickness of layered materials and thus provide a means of estimating the physical thickness and the dielectric constant of that layer.

Based on the results of these laboratory studies and the layered structure of foundations and pavements, swept-frequency measurement techniques may provide an important remote-sensing tool in various construction procedures.

In this paper, the swept-frequency measurement technique and its mathematical development are described as they apply to foundations and pavements. In addition, the results of reflectance calculations on typical highway profiles are presented along with a summary of future applications.

REFLECTANCE ANALYSIS

Swept-Frequency Radar System Operation

A variable-frequency radar system can be used for layer measurements with relatively simple radar equipment consisting of a wide-band radar receiver and a transmitter with a variable-frequency output. This system can operate with either a pulsed or a continuous wave transmitter output. The speed of the frequency variation is not critical but must be slow enough so that the frequencies of the returns from the surface and the subsurface layers are essentially the same. In operation, the transmitter and receiver are positioned at vertical incidence to the surface to be measured and the frequency is varied. If a subsurface reflection occurs, the return received will decrease with frequency to a minimum, increase to a maximum, and then repeat the cycle over and over. The only measurement required is the frequency difference between either 2 adjacent maximums or 2 adjacent minimums. A block diagram of the variable-frequency radar system is shown in Figure 1, and the derivation of the depth-determination formula is given in the following. For the geometry shown in Figure 2, the return to the receiver will be a minimum. The phase shift between the surface and subsurface reflections is given by

$$\phi = (2X/\lambda)(2\pi) = 4\pi X/\lambda \tag{1}$$

and

$$\lambda = (c/\sqrt{\epsilon_r})(1/f) = c/\sqrt{\epsilon_r}f \tag{2}$$

where

ϕ = phase difference, rad;
X = depth of the medium, m;
λ = wavelength of wave in the medium, m;
c = speed of light, 300×10^6 m/sec;
ϵ_r = relative dielectric constant; and
f = frequency of radar wave, H_2.

The term $c/\sqrt{\epsilon_r}$ gives the speed of an electromagnetic wave in a medium with the conductivity term neglected (the conductivity term has little effect on wave velocity at frequencies above 200 MHz for soil samples thus far tested). From Eqs. 1 and 2,

$$\phi = [(4\pi X) f \sqrt{\epsilon_r}]/c \tag{3}$$

For a minimum, ϕ must be some odd multiple of π such as π, 3π, or 5π. This can be shown by $\phi = 2\pi n - \pi$, where n is an integer. There will be 2 adjacent minimums as the frequency is increased from f_1 to f_2 when n is increased by 1 unit.

$$\phi_1 = 2\pi n - \pi = [(4\pi X)(\sqrt{\epsilon_r})(f_1)]/c \tag{4}$$

$$\phi_2 = 2\pi(n + 1) - \pi = [(4\pi X)(\sqrt{\epsilon_r})(f_1)]/c \tag{5}$$

Subtracting Eq. 4 from Eq. 5 yields

$$\phi_2 - \phi_1 = 2\pi = [(4\pi X)(\sqrt{\epsilon_r})(f_2 - f_1)]/c \tag{6}$$

or

$$X = (1/2\sqrt{\epsilon_r})[(300 \times 10^6)/(f_2 - f_1)] \tag{7}$$

This derivation is good for either a pair of minimums at f_1 and f_2 or a pair of maximums at f_1 and f_2 because only the frequency difference, Δf, is used in the calculation for depth. From the formula, the only other variable besides the frequencies is that of relative dielectric constant, ϵ_r. The relative dielectric constant can be estimated from the average power reflectance of this variable-frequency radar system as in the following equation:

$$\epsilon_{r1} = \epsilon_{r2} \left[(1 + \sqrt{R})/(1 - \sqrt{R})\right]^2 \qquad (8)$$

where

ϵ_{r1} = relative dielectric constant for material beneath the reflecting interface;
ϵ_{r2} = relative dielectric constant for material in which the incident wave is traveling (if material is air, $\epsilon_{r2} = 1$); and
R = power reflectance.

Calculation of Reflectance Coefficients

An insight to the problem of swept-frequency measurements can be gained by calculating the reflectance coefficients as a function of frequency for various layered profiles. The equations used for these calculations are extracted from transmission line theory with the following assumptions:

1. The electrical properties, relative dielectric constant ϵ_r, and conductivity σ are not frequency dependent over the range of interest—a valid assumption based on past work (1);
2. Transition zones between layers do not exist or are small enough to be neglected (thus a reflection is obtained at the interface between layers, e.g., air-soil interface, air-pavement interface, pavement-soil interface, or an interface between soil layers with differing electrical properties); and
3. Layers have homogeneous electrical properties.

One set of equations that can be used to calculate the reflectance of the layered profiles is as follows:

$$Z_{Ln} = Z_{on} \left\{\left[Z_{Ln+1} \text{ COSH}(\gamma_n \ell_n) + Z_{on}/\text{SINH}(\gamma_n \ell_n)\right] / \left[Z_{on} \text{ COSH}(\gamma_n \ell_n) + Z_{Ln+1} \text{ SINH}(\gamma_n \ell_n)\right]\right\} \qquad (9)$$

$$Z_{on} = \sqrt{\mu_n/\epsilon_n^*} \qquad (10)$$

$$R = \left[(Z_{L1} - Z_{AIR})/(Z_{L1} + Z_{AIR})\right]^2 \qquad (11)$$

where

Z_{Ln} = load impedance for nth layer;
Z_{on} = characteristic impedance for nth layer;
R = power reflectance;
γ = propagation factor;
ℓ = layer thickness;
μ = magnetic permeability;
ϵ^* = complex dielectric constant; and
Z_{AIR} = characteristic impedance for air (377 ohms).

Each layer has a characteristic impedance as calculated from Eq. 8. The characteristic impedance at the last layer of assumed infinite depth (the foundation) acts as the load impedance for the preceding layer. Equation 9 can then be used to transform the impedance through the layer to the bottom of the next succeeding layer. The transformed impedance, in turn, acts as a load impedance for the next layer and so on until

Figure 1. Variable-frequency radar system.

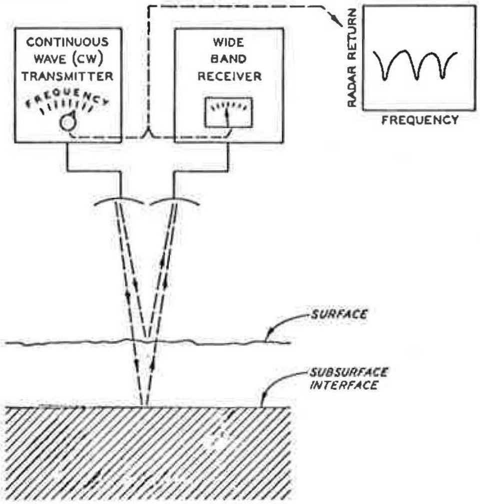


Figure 2. Wave phase change in soil.

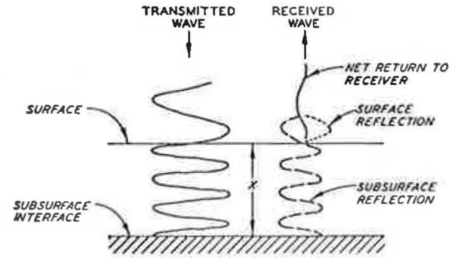
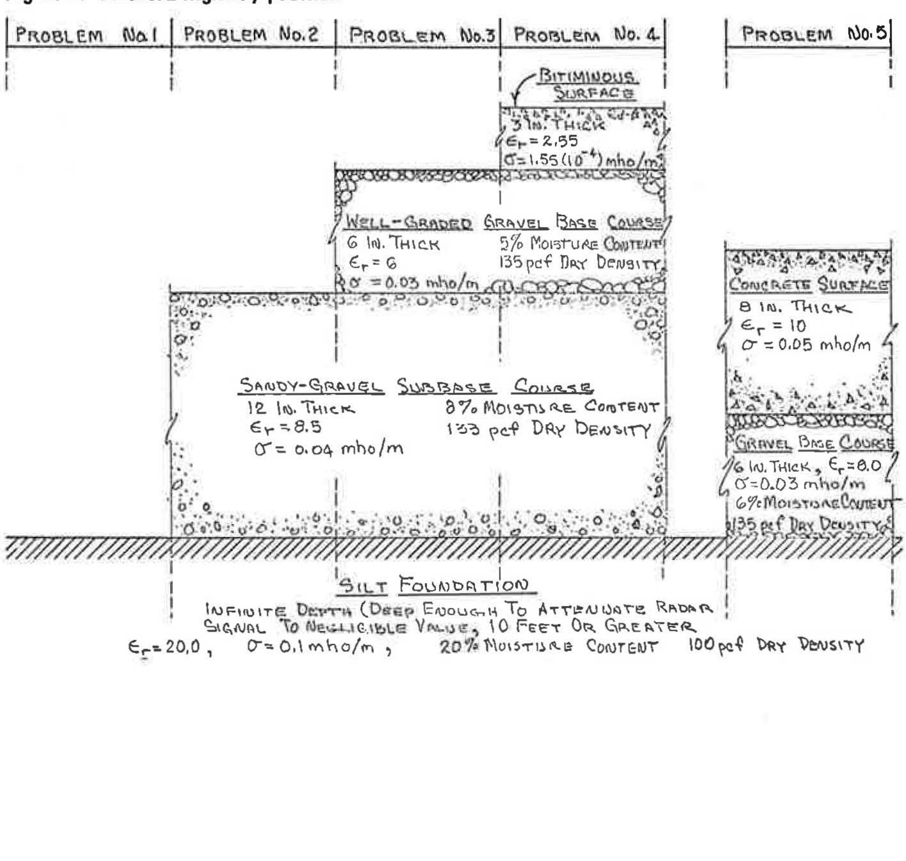


Figure 3. Selected highway profiles.



the surface is reached. The air-surface mismatch will govern the power reflected back to the radar receiver., The reflectance coefficient for this situation is calculated from Eq. 11.

Because of the repetitive nature of the calculation, a considerable amount of time and effort can be saved by using a computer. Programs were written for a GE 400 series computer, and the results of calculations for some typical foundations and pavements are given in the next section. The impedance equations are transcendental, and thus a direct solution for the input parameters in terms of the calculated reflectance values is not possible. Simplifying assumptions must be made in the analysis of the reflectance curves such that the problem is broken into a number of smaller subproblems. These subproblems can then be solved and the results combined for a final solution.

RESULTS OF CALCULATION

A number of highway profiles were selected for further study. These profiles were a series of layers in which each new profile was formed by adding another layer on top of the previous profile. This would be similar to that expected during the actual construction of a highway if one were to take a measurement after each new construction phase. The profiles for the problems are shown in Figure 3 where the electrical properties were estimated from the physical properties of each layer. Calculated values for power reflectance were obtained from the procedures discussed earlier and are shown versus frequency in Figures 4 and 5 for each of the problems shown in Figure 3. These power reflectance values should be the same as those obtained from actual swept-frequency radar measurements after corrections are made to allow for surface irregularities, minor transition zones, and small nonhomogeneous zones within the layers. The results of the following data analysis are given in Table 1.

Problem 1

The profile for this problem was the silt highway foundation by itself. Its reflectance curve starts at a value of 0.4073 at 500 MHz and decreases to 0.4028 at 2,400 MHz (Fig. 4). The following conclusions can be drawn from this curve:

1. The uniformity of the curve (no cyclic patterns) denotes a deep homogeneous material with no layered structure.
2. The reflectance values are less influenced by the conductivity value at high frequencies than at low frequencies. The curve appears to be asymptotic to a value of 0.4027. This value can be used to estimate the relative dielectric constant as shown in the following, and this in turn can be used to estimate the volumetric water content of the soil:

$$\epsilon_r = [(1 + \sqrt{R})/(1 - \sqrt{R})]^2 = [(1 + \sqrt{0.4027})/(1 - \sqrt{0.4027})]^2 = 20.0$$

The conductivity can be calculated by using the reflectance curve data at the low frequencies and the asymptotic reflectance value. Any differences are due to the conductivity term.

Problem 2

The profile for this problem was the silt foundation covered by a 12-in. subbase course of sandy gravel. Its reflectance curve is characterized by a cyclic pattern throughout the 500- to 2,400-MHz frequency range and of a lower amplitude level than for problem 1 (Fig. 4). The average reflectance decreases with increasing frequency in a manner similar to that of problem 1. The following conclusions can be drawn from the curve:

1. The magnitude of the oscillations can be used to estimate the electrical properties of the subsurface material.
2. The magnitude of the surface reflectance can be used to estimate the relative dielectric constant of the surface soil as in problem 1. The power reflectance curve

Figure 4. Reflectance curves for base materials.

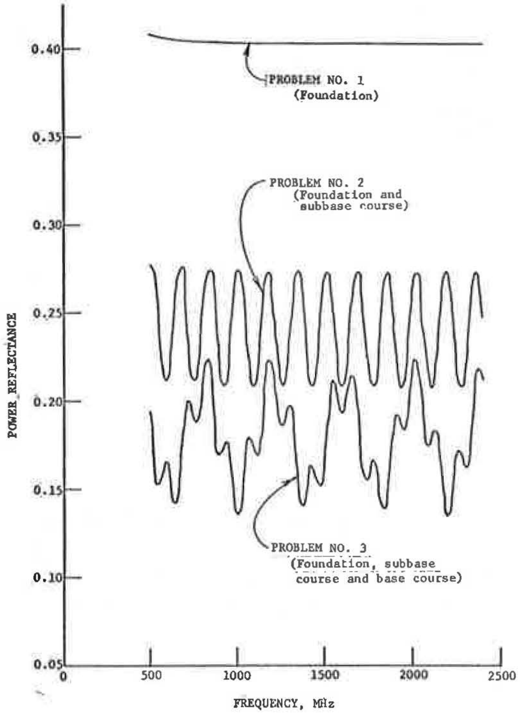


Figure 5. Reflectance curves for pavements.

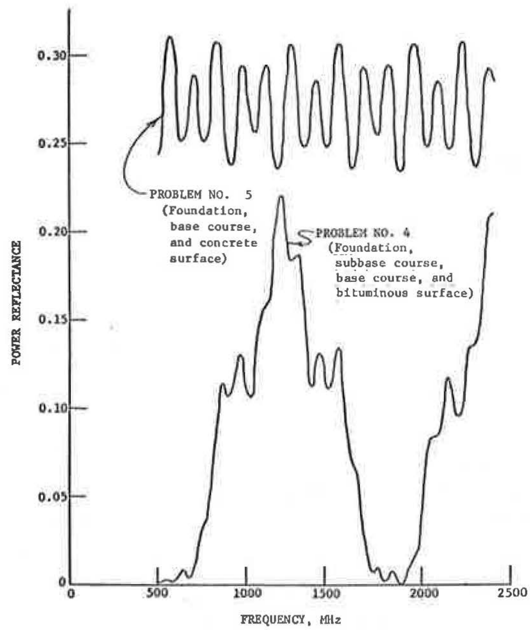


Table 1. Summary of analysis results.

Type of Highway	Layer	Original Input Data: E_r	Original Input Data: Layer Thickness (in.)	Problem	Analysis Result: E_r	Analysis Result: Layer Thickness (in.)
Bituminous	Surface	2.55	3.0	4	2.60	3.05
	Base	6.0	6.0	4		6.01
				3	6.03	6.02
	Subbase	8.5	12.0	4		12.30
				3		12.01
				2	8.52	12.00
	Foundation	20.0		1	20.0	
Concrete	Surface	10	8.0	5	9.97	8.02
	Base		6.0	5		6.05

can (on the basis of voltage interactions) be separated into a constant surface power reflection and an oscillating subsurface reflection component as follows: surface power reflectance, R = 0.2398, and normalized subsurface power return, P_B = 0.001062. As in problem 1, the relative dielectric constant can be calculated by

$$\epsilon_r = [(1 + \sqrt{R})/(1 - \sqrt{R})]^2 = [(1 + \sqrt{0.2398})/(1 - \sqrt{0.2398})]^2 = 8.52$$

3. The cyclic pattern of the reflectance curve (Δf = 168.5 MHz where Δf is the difference in frequency between successive reflectance maximum or minimum) indicates the presence of a subsurface interface (the interface between the subbase course and the foundation). The layer thickness can be calculated from the oscillation period, Δf, as

$$\begin{aligned} X &= (300 \times 10^6)/2\sqrt{\epsilon_r}\ \Delta f \\ &= (300 \times 10^6)/[2\sqrt{8.52}\ (168.5 \times 10^6)] \\ &= 0.3046 \text{ m or } 12 \text{ in.} \end{aligned}$$

Problem 3

The profile for this problem was the silt foundation, a 12-in. sandy gravel subbase course, and a 6-in. well-graded gravel base course. The reflectance curve is characterized by a lower amplitude than those for problems 1 or 2 (Fig. 4). It contains oscillations of 2 different periods throughout the 800- to 2,400-MHz range. The following conclusions can be drawn from this curve:

1. The magnitudes of the oscillations can be used to estimate the electrical properties of the subsurface materials.
2. The magnitude of the surface reflectance can be used to estimate the relative dielectric constant of the surface soil as in problems 1 and 2. The smaller amplitude of this curve compared to those of problems 1 and 2 denotes a smaller relative dielectric constant. Separating the total reflectance curve into 2 components gives surface power reflectance, R = 0.1775, and normalized subsurface power return, P_B = 0.002545. The surface relative dielectric constant can then be calculated as

$$\epsilon_r = [(1 + \sqrt{R})/(1 - \sqrt{R})]^2 = [(1 + \sqrt{0.1775})/(1 - \sqrt{0.1775})]^2 = 6.03$$

3. The cyclic patterns of 2 different periods (Δf_1 = 118.6 MHz and Δf_2 = 400 MHz) indicate the presence of 2 subsurface interfaces. The short period oscillation (Δf_1 = 118.6 MHz) is associated with the interface between the subbase course and the foundation. The long period oscillation (Δf_2 = 400 MHz) is associated with the interface between the base course and the subbase course. The layer thicknesses, X_1 and X_2, can be calculated as follows by using the relative dielectric constants of 6.03 and 8.52 for the first (top) and second layers respectively as computed previously. For the top layer (base course) thickness

$$\begin{aligned} X_1 &= (300 \times 10^6)/2\sqrt{\epsilon_r}\ \Delta f \\ &= (300 \times 10^6)/[2\sqrt{6.03}\ (400 \times 10^6)] \\ &= 0.53 \text{ m or } 6.02 \text{ in.} \end{aligned}$$

For the second layer (subbase course) thickness, the optical depth to the second interface must first be calculated.

$$\begin{aligned} X_0 &= (300 \times 10^6)/2\Delta f \\ &= (300 \times 10^6)/[2(118.6 \times 10^6)] \\ &= 1.265 \text{ m} \end{aligned}$$

The second layer thickness, X_2, is then computed by

$$\begin{aligned} X_2 &= (X_0 - X_1 \sqrt{\epsilon_{r1}})/\sqrt{\epsilon_{r2}} \\ &= (1.265 - 0.153\sqrt{6.03})/\sqrt{8.52} \\ &= 0.3048 \text{ m or } 12.01 \text{ in.} \end{aligned}$$

Problem 4

The profile for this problem was the silt foundation, a 12-in. sandy-gravel subbase course, a 6-in. well-graded gravel base course, and a 3-in. bituminous surface. This reflectance curve is characterized by a still lower amplitude than those for problems 1, 2, or 3 (Fig. 5). It has oscillations of 3 different periods throughout the 500- to 2,400-MHz range. The following conclusions can be drawn from this curve:

1. The magnitude of the oscillation can be used to estimate the electrical properties of the subsurface materials.

2. The magnitude of the surface reflectance can be used to estimate the relative dielectric constant of the surface soil as before. The reflectance curve can be separated into 2 components (in this case, equal components): surface power reflectance, $R = 0.055$, and normalized subsurface power return, $P_B = 0.055$. The surface relative dielectric constant can be calculated as

$$\epsilon_r = [(1 + \sqrt{R})/(1 - \sqrt{R})]^2 = [(1 + \sqrt{0.055})/(1 - \sqrt{0.055})]^2 = 2.6$$

3. The cyclic patterns of 3 different periods ($\Delta f_1 = 106.2$ MHz, $\Delta f_2 = 300$ MHz, and $\Delta f_3 = 1{,}200$ MHz) indicate the presence of 3 subsurface interfaces. The short period oscillation ($\Delta f_1 = 106.2$ MHz) is associated with the interface between the subbase course and the foundation, the medium period oscillation ($\Delta f_2 = 300$ MHz) is associated with the interface between the base course and the subbase course, and the long period oscillation is associated with the interface between the bituminous material and the base course. The layer thicknesses, X_1, X_2, and X_3, can be calculated as follows by using the relative dielectric constant values previously calculated: 2.6, 6.03, and 8.52 for the top, middle, and bottom layers respectively. The top layer (bituminous surface) thickness, X_1, is

$$\begin{aligned} X_1 &= (300 \times 10^6)/2\sqrt{\epsilon_r}\ \Delta f \\ &= (300 \times 10^6)/[2\sqrt{2.6}\,(1{,}200 \times 10^6)] \\ &= 0.0775 \text{ m or } 3.05 \text{ in.} \end{aligned}$$

The optical depth to the second interface is

$$\begin{aligned} X_{02} &= (300 \times 10^6)/2\Delta f \\ &= (300 \times 10^6)/[2(300 \times 10^6)] \\ &= 0.5 \text{ m} \end{aligned}$$

The second layer (base course) thickness X_2 is

$$\begin{aligned} X_2 &= (X_{02} - X_1 \sqrt{\epsilon_{r1}})/\sqrt{\epsilon_{r2}} \\ &= (0.5 - 0.0775\sqrt{2.6})/\sqrt{6.03} \\ &= 0.1527 \text{ m or } 6.01 \text{ in.} \end{aligned}$$

The optical depth to the third interface is

$$X_{03} = (300 \times 10^6)/2\Delta f$$

$$= (300 \times 10^6)/[2(106.2 \times 10^6)]$$
$$= 1.412 \text{ m}$$

The third layer (subbase course) thickness X_3 is

$$X_3 = (X_{03} - X_{02})/\sqrt{\epsilon_{r3}}$$
$$= (1.412 - 0.5)/\sqrt{8.52}$$
$$= 0.3123 \text{ m or } 12.3 \text{ in.}$$

Problem 5

The profile for this problem was slightly different from those of problems 2, 3, and 4. The foundation is silt as before but the subbase course has been eliminated. A 6-in. base course of gravel covers the foundation that in turn is capped by an 8-in. layer of concrete. The reflectance curve from this profile is characterized by a general amplitude between those of problems 1 and 2 (Fig. 5). It has a somewhat random cyclic appearance that can be resolved into oscillations with 2 different periods of nearly constant amplitude over the 500- to 2,400-MHz range. The following conclusion can be drawn from this curve:

1. The magnitude of the oscillations can be used to estimate the electrical properties of the subsurface materials.
2. The magnitude of the surface reflectance can be used to estimate the relative dielectric constant of the concrete surface. Separating the reflectance curve into 2 components gives surface power reflectance, R = 0.269, and normalized subsurface power return, P_B = 0.001303. The surface (concrete) relative dielectric constant can be calculated as

$$\epsilon_r = [(1 + \sqrt{R})/(1 - \sqrt{R})]^2 = [(1 + \sqrt{0.269})/(1 - \sqrt{0.269})]^2 = 9.97$$

3. The cyclic patterns of 2 different periods (Δf_1 = 139.13 MHz and Δf_2 = 233.33 MHz) indicate the presence of 2 subsurface interfaces: between the base course and the foundation (Δf_1) and between the concrete and the base course (Δf_2). The layer thicknesses X_1 and X_2 for the concrete and base course can be calculated by using the relative dielectric constant value of 9.97 for concrete previously calculated and selecting a relative dielectric constant of 8.0 for the base course. The concrete layer thickness X_1 is

$$X_1 = (300 \times 10^6)/2\sqrt{\epsilon_{r1}}\,\Delta f$$
$$= (300 \times 10^6)/[2\sqrt{9.97}\,(233 \times 10^6)]$$
$$= 0.2036 \text{ m or } 8.02 \text{ in.}$$

The optical depth to the second interface is

$$X_0 = (300 \times 10^6)/2\Delta f$$
$$= (300 \times 10^6)/[2(139.13 \times 10^6)]$$
$$= 1.078 \text{ m}$$

The second layer (base course) thickness is

$$X_2 = (X_0 - X_1\sqrt{\epsilon_{r1}})/\sqrt{\epsilon_{r2}}$$
$$= (1.078 - 0.2036\sqrt{9.97})/\sqrt{8.0}$$
$$= 0.154 \text{ m or } 6.05 \text{ in.}$$

CONCLUSIONS

The following conclusions are based on the measurement procedure and the results of analysis reported in this paper:

1. The results of analysis demonstrate the feasibility of using swept-frequency techniques in estimating the properties and thicknesses of layered materials;
2. These results show promise for reducing time and money spent on testing old highways, landing strips, or other construction foundations (for example, swept-frequency techniques could be used to make measurements on layer thicknesses beneath the pavement wearing surface, to detect cavities or voids under the pavement surface, or to detect water pockets in the subsurface layers); and
3. The swept-frequency measurements may aid in the control of new construction (for example, these techniques could be used to rapidly evaluate the thickness of an asphalt surface layer placed on an old concrete highway, measure the uniformity of materials in both quality and thickness, or measure the depth to reinforcing steel in concrete).

REFERENCE

1. Lundien, J. R. Terrain Analysis by Electromagnetic Means. Rept. 5, Aug. 1970.