NASA

Technical Memorandum 80688

A COMPARISON OF RADIATIVE TRANSFER MODELS FOR PREDICTING THE MICROWAVE EMISSION FROM SOILS

T. J. SCHMUGGE

B. J. CHOUDHURY

(NASA-TM-80688) A COMPARISON OF RADIATIVE TRANSFER MODELS FOR PREDICTING THE MICROWAVE EMISSION FROM SOILS (NASA) 32 p HC A03/MF A01 CSCL 08M N80-27777

Unclas G3/43 25203

MAY 1980

National Aeronautics and Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

A COMPARISON OF RADIATIVE TRANSFER MODELS FOR PREDICTING THE MICROWAVE EMISSION FROM SOILS

T. J. SCHMUGGE
Hydrological Sciences Branch
NASA/Goddard Space Flight Center
Greenbelt, Maryland

and

B. J. CHOUDHURY
Computer Sciences Corporation
Silver Spring, Maryland

ABSTRACT

Two general types of numerical models for predicting microwave emission from soils are compared—coherent and noncoherent. In the former, radiation in the soil is treated coherently, and the boundary conditions on the electric fields across the layer boundaries are used to calculate the radiation intensity. In the latter, the radiation is assumed to be noncoherent, and the intensities of the radiation are considered directly. The results from the two approaches may be different because of the effects of interference, which can cause the transmitted intensity at the surface (i.e., emissivity) to be sometimes higher and sometimes lower for the coherent case than for the noncoherent case, depending on the relative phases of the reflected fields from the lower layers. This coupling between soil layers in the coherent models leads to greater soil moisture sampling depths observed with this type of model, and is the major difference that is found between the two types of models. In noncoherent models, the emissivity is determined by the dielectric contract at the air/soil interface. The subsequent differences in the results are functions of both the frequency of the radiation being considered and the steepness of the moisture gradient near the surface. The

calculations were performed at frequencies of 1.4 and 19.4 GHz and for two sets of soil profiles. Little difference was observed between the models at 19.4 GHz; and only at the lower frequency were differences apparent because of the greater soil moisture sampling depth at this frequency.

A COMPARISON OF RADIATIVE TRANSFER MODELS FOR PREDICTING MICROWAVE EMISSION FROM SOILS

T. J. SCHMUGGE
Hydrological Sciences Branch
NASA/Goddard Space Flight Center
Greenbelt, Maryland

and

B. J. CHOUDHURY
Computer Sciences Corporation
Silver Spring, Maryland

INTRODUCTION

Soil moisture information is important in a variety of disciplines (e.g., hydrology, agriculture, and meteorology). Attempts to monitor world food supply, predict watershed runoff, and model boundary layer heat and moisture conditions are but a few of many specific areas in which surface and subsurface soil moisture information is needed. To this end, both active and passive microwave remote sensing techniques are being studied (Ulaby et al., 1978 and 1979; Schmugge, 1978) to provide efficient and cost-effective means of estimating average moisture content in wide areas.

A key parameter in understanding and interpreting remotely sensed data is the dielectric constant of the target medium, which has a large effect on the reflective and emissive properties of the surface. Microwave frequencies are ideally suited for soil moisture remote sensing because at these frequencies the dielectric constant changes rapidly with moisture content. In fact, radiance measurements obtained by ground-based, airborne, and satellite-borne radiometers have indicated emissivities from as low as 0.6 when wet to 0.95 when dry. Microwave radiative transfer models have been developed to provide the theoretical basis for this relationship.

Three recent papers have presented theoretical models for microwave emission from soils (Njoku and Kong, 1977; Wilheit, 1978; and Burke, et al., 1979). These models considered the emission from the soil for a range of moisture and temperature profiles and studied the effects of variations in these subsurface properties on the emission from the surface. The purpose of this paper is to compare these models in terms of their fundamental approaches and their results for a set of standard soil profiles. The models will be compared at the microwave frequencies of 1.4 and 19.4 GHz (wavelengths of 21 and 1.55 cm).

For homogeneous media (i.e., those with constant moisture and temperature profiles), the emissivity (e) for a smooth surface can be calculated from the soil's dielectric properties using the Fresnel equations for surface reflectivity (r). For perpendicular incidence, these equations reduce to:

$$e = 1 - r = 1 - \left|\frac{\sqrt{\epsilon} - 1}{\sqrt{\epsilon} + 1}\right|^2 \tag{1}$$

where ϵ is the dielectric constant of the soil.

Difficulties arise when both the temperature and moisture content of the soil vary with depth in the soil. The basic approach for solving this problem is to break the soil volume into thin layers and then numerically sum the contributions of each layer. The various ways of treating this numerical summation through the soil layers form the basis of major differences between the particular radiative transfer models.

There are two alternate approaches to studying microwave emission from soils based on the assumed characteristics of radiation within the soil (i.e., whether it is treated coherently or noncoherently).

If radiation within the soil is assumed to be coherent, its intensity must be obtained by calculating the electromagnetic field vectors from a solution to Maxwell's equations. However, if radiation within the soil is assumed to be incoherent, the intensity of radiation can be considered directly. The type of assumption made will affect the performance of the models since intensities calculated for coherent and incoherent radiations may be different because of wave interference effects associated with coherent radiation. These interference effects cause the coherent intensity to be sometimes higher and other times lower than the incoherent intensity. Oscillations of the intensity as a function of frequency is an indication of coherency effects in the radiation.

The need for using a coherent model to study thermal emission that is intrinsically a noncoherent process may be questioned. However, if a spatial filter (e.g., a dielectric slab) is introduced, the emerging radiation will be partially coherent, which should be manifested in interference phenomena.

Indeed, radiometric observations of interference effects have been obtained for sandbox experiments in which a metal plate is buried by increasing thicknesses of sand (Blinn, et al., 1972) and for oil films on water (Hollinger and Mannella, 1973). In an analysis of this problem, Carver (1977) concluded that if the layer thicknesses were less than the coherence length of the emitted photons (L) given by

$$L = c/(\Delta f \sqrt{\epsilon}) \qquad (2)$$

where c is the velocity of light, Δf is the bandwidth of the radiometer, and ϵ is the dielectric constant of the medium, then coherence effects are important. At 1.42 GHz, Δf is generally 27 MHz, the bandwidth of the radio astronomy band at this frequency, and ϵ of soil will range from 4 to 25, yielding a value of L between 5 and 2 meters. This range is much greater than that of any of the layer thicknesses used in the models considered here and thus coherent effects may be important. The thicknesses were chosen to be much less than the distance over which there was a substantial change in soil properties. These major changes in soil moisture content occur in distances much less than L. For these reasons, it is necessary to consider coherent models. As will be noted, coupling between reflectivity at the surface and the subsurface dielectric properties occurs in the coherent models but not in the noncoherent models and leads to the major differences between the two approaches.

All three models assume that scattering by pebbles or other discontinuities in the soil is insignificant. In a study of the microwave emission from a scattering medium, England (1975) found that scattering effects will be significant when the scattering albedo (ω_0) is greater than 0.1, where ω_0, the ratio of the scattering loss to the total loss, is given by:

$$\omega_0 = \frac{N\sigma}{N\sigma + 2\beta} \tag{3}$$

where σ is the scattering cross section of the pebble, β is the loss in the medium, and N is the number of pebbles per unit volume. Assuming appropriate values for the dielectric properties of pebbles and wet soils and assuming a fractional pebble volume of 1 percent, it can be found from England's equations that volume scattering will be significant only if $d/\lambda > 1/7$, where d is the pebble size and λ is the wavelength (0.5-cm pebbles in the 3-cm or X-Band wavelength region). Even if the size or number of particles becomes larger, volume scattering would have little effect if $\lambda > 10$ cm and will therefore be neglected in this paper.

In the next section, the three models to be considered will be briefly described. The results obtained using these models on the soil profiles published in the Njoku and Kong paper are presented and compared in Section 3. Further calculations were performed using the Burke, Wilheit, and a simpler radiative transfer model for some actual profiles that possessed steep moisture gradients near the surface. These results are also presented in Section 3.

COMPARISON OF THE MODELS

Noncoherent Models

The microwave emission model developed by Burke, et al. (1979), hereafter referred to as the Burke model, is based on the assumption of incoherent radiation. Radiation intensity is calculated from solution of the radiative transfer equation:

$$\frac{dT_p}{dZ} = -\gamma(z)\,T_p + \gamma(z)\,T(z) \tag{4}$$

where γ is the absorption in the layer, T_p is radiation intensity expressed in terms of a temperature, T is the physical temperature of the soil, z is the path length, and subscript p indicates the polarization of the radiation.

Soil is treated as a layered dielectric; each layer is homogeneous and of arbitrary thickness. Thickness (Δz_j), absorption coefficient (γ_j), and temperature (T_j) of each soil layer are specified. The radiative transfer equation for each layer is then solved. The radiative transfer equation in the first layer may be written as:

$$\frac{dT_p}{d(\gamma_1 z)} = -T_p + T_1 \tag{5}$$

This equation can be integrated from a point just below the surface to a point just above the interface between the first and second layers. Because the dielectric properties are assumed to be constant across the layer,

$$T_p(1^-) = T_1\left(1 - e^{-\gamma_1 \Delta z_1}\right) + T_p(2^+)\,e^{-\gamma_1 \Delta z_1} \tag{6}$$

The argument (N±) implies that the measurement is made above (plus) or below (minus) the Nth interface. The first term on the right-hand side accounts for radiation emitted within the first layer which comes directly to the surface. The second term describes upwelling radiation at the bottom of the first layer. This in turn has two components: (1) radiation emitted in the first layer and reflected at the interface between the first and second layers; and (2) radiation transmitted from lower layers.

$$T_p(2^+) = R_{p2}\, T_1\, (1 - e^{-\gamma_1 \Delta z_1}) + T_p(2^-)(1 - R_{p2}) \tag{7}$$

R_{p2} is the absolute value squared of the Fresnel coefficient for the p polarization. The radiation field just above the surface is the value just below multiplied by the transmittance $(1 - R_{p1})$

$$\begin{aligned} T_p(1^+) &= (1 - R_{p1})\, T_p(1^-) \\ &= (1 - R_{p1})\left\{T_1(1 - e^{-\gamma_1 \Delta z_1})(1 + R_{p2}\, e^{-\gamma_1 \Delta z_1}) + (1 - R_{p2})\, T_p(2^-)\, e^{-\gamma_1 \Delta z_1}\right\} \end{aligned} \tag{8}$$

The radiative transfer equation can be integrated again to calculate $T_p\ (2^-)$. Repeating the procedure for N layers gives the brightness temperature as:

$$\begin{aligned} T_B(1^+) = &\sum_{i=1}^{N} T_i(1 - e^{-\gamma_i \Delta z_i})(1 + R_{p,i+1} e^{-\gamma_i \Delta z_i}) \\ &\prod_{j=1}^{i}\left[1 - R_{p,j}\right] \exp - \left(\sum_{j=2}^{i} \gamma_{j-1}\, \Delta z_{j-1}\right) \end{aligned} \tag{9}$$

Beginning with the deepest layer of the soil, the intensity emerging from each layer is calculated to obtain the observed microwave intensity. Results from this model were compared with actual observations at the 2.8- and 21-cm wavelengths (Burke, et al., 1979), with layer thickness corresponding to observed soil moisture values in sampling depths of 0 to 1, 1 to 2, 2 to 5, 5 to 9, and 9 to 15 cm from the surface. Some of the conclusions from the study were that: (1) the emitted intensity at both wavelengths correlates best with the near-surface moisture; (2) the slope of the intensity/moisture curves decrease in going from day to dawn; and (3) increased near-surface moisture at dawn is characterized by increased polarization.

Coherent Models

Microwave emission models developed by Wilheit (1978) and by Njoku and Kong (1977), hereafter referred to as the Njoku model, are based on the assumption of coherent radiation. In Wilheit's model, soil is treated as a layered dielectric. Solutions of Maxwell's equations and the boundary condition at the interfaces are used to calculate the electric field in each layer. These electric-field values are used to calculate the energy fluxes and thus the fractional absorption in each layer:

$$f_j^p = \frac{S_{j-1}^p - S_j^p}{S_1^p} \tag{10}$$

where S_{j-1}^p is the electromagnetic field energy (i.e., Poynting vector) entering the jth layer at the (j-1)th interface, S_j^p is the energy for the (j+1)th layer at the jth interface, and S_1^p is the energy incident on the first interface. The superscript (p) designates thc polarization of radiation. These energy values are calculated using Poynting's theorem for electric fields. If T_j is the temperature of the jth layer, under thermodynamic equilibrium, the layer radiates energy equal to the product of the fractional absorption (f_j^p) and the temperature (T_j). The brightness temperature is given by

$$T_B^p = \sum_{j=1}^{N} f_j^p T_j \tag{11}$$

The conservation of energy at the air/soil interface determines the reflectivity of the soil R^p as:

$$R^p = 1 - \sum_{j=1}^{N} f_j^p \tag{12}$$

Computations with the model have indicated that radiation from the soil is characterized by two sampling depths: reflective and thermal (Wilheit, 1978). The reflectivity is characterized by changes in the real part of the index of refraction over a sampling depth: $\delta_r \simeq 0.1\ \lambda$, where λ is the wavelength in the medium. The thermal sampling depth is determined by the imaginary part of the index in the medium and is given by:

$$\delta_T = \frac{\sum x_i f_i}{\sum f_i} \tag{13}$$

where x_i is the depth of the ith layer. For a uniform dielectric, this reduces to

$$\delta_T = \frac{\lambda}{4\pi\ \mathrm{Im}(n)} \tag{14}$$

For a low-loss dry soil, δ_T will be an order of magnitude larger than δ_r, whereas for a wet soil, it will be only slightly larger.

Another parameter of interest is the average soil temperature over this thermal sampling depth, which is referred to here as the effective radiating temperature of the soil and is given by:

$$T_{eff} = \frac{\sum T_i f_i}{\sum f_i} \tag{15}$$

where T_i is the physical temperature of the ith layer. The ratio of T_B to T_{eff} is an effective emissivity for the soil.

Recently, this model, incorporating the effect of surface roughness on the transmission coefficient, was used to explain observed emission intensities for 1.55- and 21-cm radiations (Choudhury, et al., 1979). Although the agreement was generally satisfactory, in some cases the wave interference effect may have lead to the prediction of higher intensities than those observed.

The Njoku model is based on the coherent radiative transfer formulation of Stogryn (1970) for a thermally and dielectrically nonhomogeneous medium. In this formulation, the fraction of energy absorbed at different depths within the medium is obtained from the solution of a differential equation with a flux conservation boundary condition at the air/soil interface. This method of calculation is the same as the one used for calculating the reflectivity of a nonhomogeneous dielectric. By integrating the product of fractional absorption and blackbody emission intensity, the observed intensities are obtained. For a set of simulated moisture and temperature profiles, Njoku and Kong (1977) have given illustrative results for wavelength dependence of the emitted intensity.

A continuous nonhomogeneous dielectric can be well approximated by a layered dielectric, using appropriate choice of layer thicknesses. It may thus be expected that Wilheit and Njoku's models will closely agree with one another because both are based on the assumption of coherent radiation. However, the method of calculating the observed intensities are quite different in the two models. Physically and numerically, Wilheit's model is simpler and more efficient. The following section presents a numerical comparison of these models.

In the algorithm used for Wilheit's model, the soil was divided into 100 layers whose thicknesses varied with soil depth. Beginning at the surface, there are 10 layers having each of the thicknesses 0.1, 0.2, 0.3, and 0.4 cm, followed by 20 layers 0.5-cm thick and 40 layers 1.0-cm thick for a total soil depth of 60 cm. With this soil grid, moisture and temperature values are obtained from the analytical expressions given by Njoku and Kong, and the dielectric constants are interpolated from the values presented by them. The brightness temperature and effective radiating temperature are calculated using the Fortran routines provided in Wilheit's paper.

In the Burke model, there are also 100 soil layers whose thicknesses varied exponentially with depth. The surface layer thickness is about 0.003 cm, increasing to 1 cm at a depth of 9 cm and 5 cm at a depth of 40 cm. The total soil depth in this model is 100 cm.

QUANTITATIVE COMPARISONS

To compare the three models quantitatively, values of T_B were calculated for both the Wilheit and the Burke models, using the soil profiles given in the Njoku and Kong paper. The values of T_B obtained in this way were compared to those interpolated from the figures in the Njoku and Kong paper. The moisture ($\rho(z)$) and temperature ($T(z)$) profiles used are given by the following equations:

$$\rho(z) = \rho_s + \Delta\rho \frac{[e^{-\beta z} - 1]}{[e^{-\beta d} - 1]} \qquad \text{for } 0 \leq z \leq d \tag{16}$$

$$= \rho(d) \qquad \text{for } z > d$$

$$T(z) = T_0 + \Delta T_1 e^{-\gamma_1 z} + \Delta T_2 e^{-\gamma_2 z} \tag{17}$$

Table 1 lists the values of the parameters used in these equations, and Figure 1 graphically presents the resulting moisture and temperature profiles. These profiles cover a range that is representative of those that could realistically be encountered in nature.

The soil dielectric constants used were those given in the Njoku and Kong paper. Therefore, the results obtained using the Burke and Wilheit models should be comparable to those given by Njoku and Kong. The calculations were performed at 1.4 and 19.35 GHz (21 and 1.55 cm) frequencies. Comparisons at both frequencies appear in Tables 2a through f.

Table 1
Parameters of the Moisture and Temperature Profiles
(from Njoku and Kong, 1977)

Profile No.	Moisture Profile				Temperature Profile				
	ρ_s	$\Delta\rho$	$\beta_1 m^{-1}$	d,m	T_o	ΔT_1	ΔT_2	γ_1	γ_2
1	30.0	-5.0	10.0	0.5	300.0	15.0	0.0	0.13	–
2	15.0	10.0	50.0	0.5	300.0	-15.0	0.0	0.13	–
3	5.0	18.0	20.0	0.5	300.0	-15.0	20.0	0.13	0.25
4	2.0	18.0	5.0	0.5	300.0	0.0	0.0	–	–
5	2.0	10.0	30.0	0.5	315.0	-30.0	0.0	0.05	–
6	2.0	20.0	-10.0.	0.5	290.0	15.0	0.0	0.1	–

At both frequencies, the agreement among the three models is good; the maximum difference is less than 4 K at 1.4 GHz and about 2 K at 19.4 GHz. There are, however, significant differences between the results at the two frequencies. For the wetter profiles (numbers 1 and 2), the 1.4 GHz has lower T_B's because of the larger dielectric constant for wet soils at this frequency. Also the lower frequency, longer wavelength, has a greater temperature sampling depth. This tendency can be observed by comparing the differences between temperature profiles 1 and 2 for the two frequencies, which have a 3 K difference at the surface but are equal at about 35 cm. This is particularly noticeable for moisture profile 4, the driest, where there is a 5 K difference in response at 1.4 GHz compared with 22 K at 19.4 GHz.

The weighting functions for each model were also determined; the results agreed with those presented in the Njoku and Kong paper and will not be presented here. Since the weighting functions describe

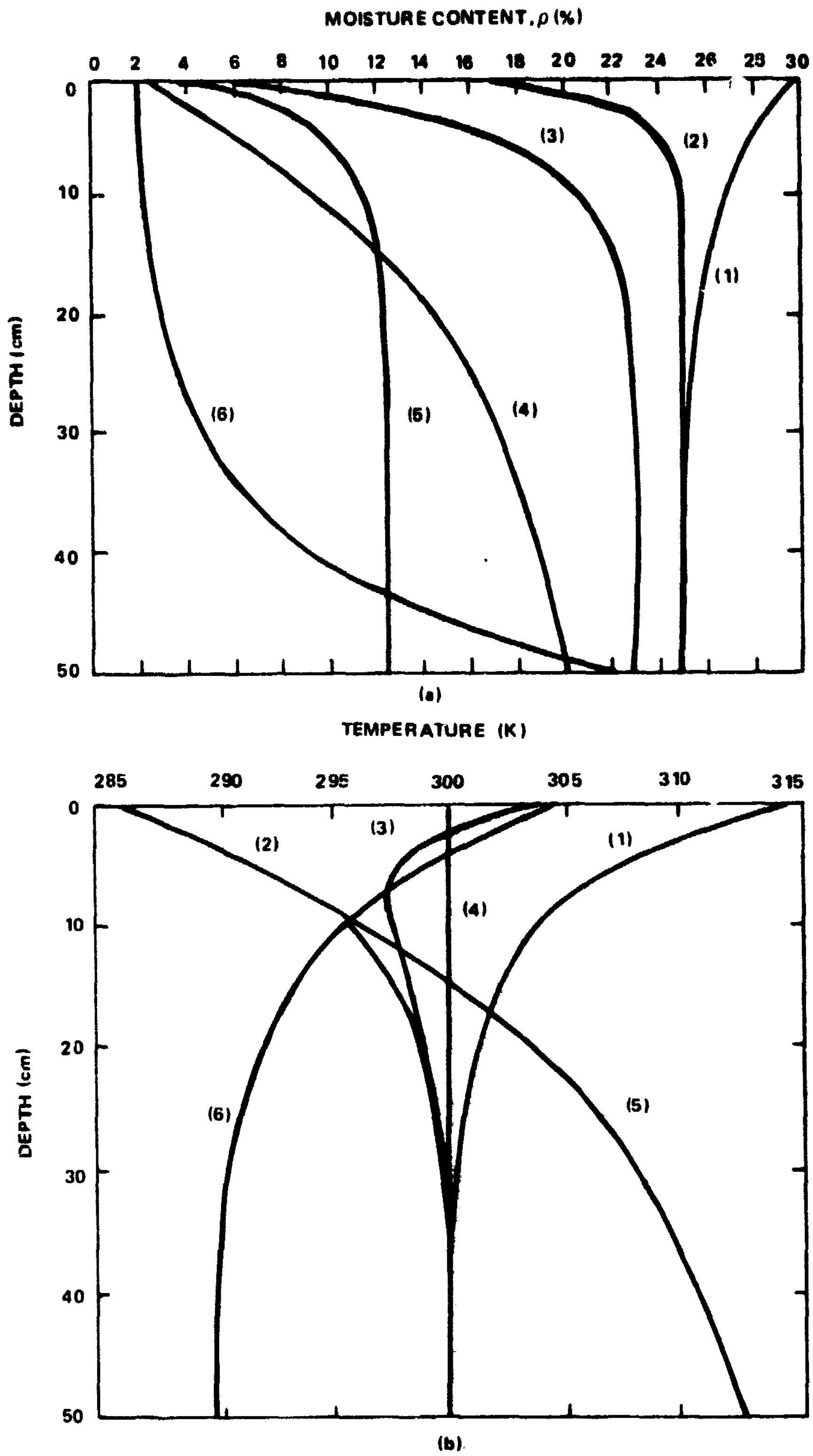

Figure 1. Moisture and temperature profiles representative of various soil-moisture conditions. Profiles correspond to parameters of Table 1 (from Njoku and Kong, 1977).

Table 2
Calculator Brightness Temperatures for the Njoku and Kong Soil Profiles

(a) Temperature Profile #1

Moisture Profile	1.4-GHz Frequency		
	Burke	Wilheit	Njoku
1	191.9	192.0	193.0
2	233.0	230.5	230.0
3	267.3	263.5	264.0
4	278.9	280.5	277.5

Moisture Profile	19.4-GHz Frequency		
	Burke	Wilheit	Njoku
1	203.6	203.6	206.0
2	242.3	241.9	242.0
3	279.3	279.5	280.0
4	289.7	289.6	289.0

(b) Temperature Profile #2

Moisture Profile	1.4-GHz Frequency		
	Burke	Wilheit	Njoku
1	184.5	184.6	185.0
2	225.4	223.0	222.5
3	260.4	256.7	257.0
4	274.2	275.9	272.5

Moisture Profile	19.4-GHz Frequency		
	Burke	Wilheit	Njoku
1	184.5	184.6	187.0
2	219.9	219.5	219.0
3	254.5	254.7	256.0
4	267.1	266.9	267.0

(c) Temperature Profile #3

Moisture Profile	1.4-GHz Frequency		
	Burke	Wilheit	Njoku
1	187.7	187.8	188.0
2	228.4	226.0	226.0
3	262.8	259.1	260.0
4	275.7	277.3	274.0

Moisture Profile	19.4-GHz Frequency		
	Burke	Wilheit	Njoku
1	197.1	197.1	199.0
2	234.5	234.1	234.0
3	270.0	270.2	271.0
4	279.8	279.7	278.0

(d) Temperature Profile #4

Moisture Profile	1.4-GHz Frequency		
	Burke	Wilheit	Njoku
1	188.2	188.3	189.0
2	229.2	226.8	227.0
3	263.8	260.1	261.0
4	276.5	278.2	275.0

Moisture Profile	19.4-GHz Frequency		
	Burke	Wilheit	Njoku
1	194.1	194.1	196.0
2	231.1	230.7	230.0
3	266.9	267.1	268.0
4	278.4	278.3	276.0

Table 2 (continued)

(e) Temperature Profile #5

Moisture Profile	1.4-GHz Frequency		
	Burke	Wilheit	Njoku
1	185.9	186.0	186.0
2	227.6	225.2	225.0
3	263.6	260.0	261.0
4	279.5	281.2	278.0

Moisture Profile	19.4-GHz Frequency		
	Burke	Wilheit	Njoku
1	184.5	184.5	187.0
2	219.8	219.5	219.0
3	254.3	254.5	256.0
4	266.6	266.5	267.0

(f) Temperature Profile #6

Moisture Profile	1.4-GHz Frequency		
	Burke	Wilheit	Njoku
5	268.8	266.2	266.0
6	266.4	270.4	268.5

Moisture Profile	19.4-GHz Frequency		
	Burke	Wilheit	Njoku
5	281.5	281.7	280.0
6	279.6	279.6	278.0

the depth distribution of the sources of the radiation, this agreement indicates that all the three models yield the same effective radiating temperature and that any differences should arise from their effective emissivities. This can best be seen using the results for constant temperature profile number 4 in Table 2d. The emissivity can be obtained directly by dividing the calculated T_B by the soil temperature, 300 K. These results are given in Table 3.

The biggest difference between the coherent and noncoherent models appears for moisture profiles with the steepest gradient near the surface (i.e., for profiles 2 and 3 in Table 3 emissivity results from the noncoherent model are greater by 0.01 at 1.4 GHz, with no difference between the models at 19.4 GHz) because the emissivity calculated in the Burke model corresponds to the Fresnel transmission coefficient calculated for the surface moisture value. Since it is predominantly influenced by surface moisture, the Burke model emissivity will increase with decreasing surface

Table 3
Emissivities Determined from the Brightness Temperature
Results for Profile 4 (T(z) = 300 K)

Moisture Profile	1.4-GHz			19.4-GHz		
	Burke	Wilheit	Njoku	Burke	Wilheit	Njoku
1	0.627	0.628	0.630	0.647	0.647	0.653
2	0.764	0.756	0.757	0.770	0.769	0.767
3	0.879	0.867	0.870	0.890	0.890	0.893
4	0.922	0.927	0.917	0.928	0.928	0.920

moisture, irrespective of the nature of the actual soil moisture profile. In coherent models, however, the emissivity is dependent on the moisture profile just below the surface because the phase information introduces a connection between the surface and the soil layers beneath it. Thus, the coherent models will depend on the average moisture content of the soil moisture sampling depth (which Wilheit estimates to be about one-tenth of the wavelength in the medium). Therefore, the agreement between the coherent and noncoherent models would be better if the thickness of the surface layer could be chosen to be equal to this sampling depth.

To study the effect of these steep moisture gradients in more detail, calculations were performed for a series of soil moisture profiles measured at the U. S. Water Conservation Laboratory in Phoenix (Jackson, 1973) as a field dried out after an irrigation in March 1971. The profiles presented in Figure 2 are midday profiles that had the steepest moisture gradients near the surface. In addition to the Burke and Wilheit models, a variant of the Burke model was also investigated. In this model, the Fresnel reflectivity at all layer interfaces except for the soil/air interface was set to zero (i.e., it was assumed that all the soil interfaces were transparent). The rationale behind this

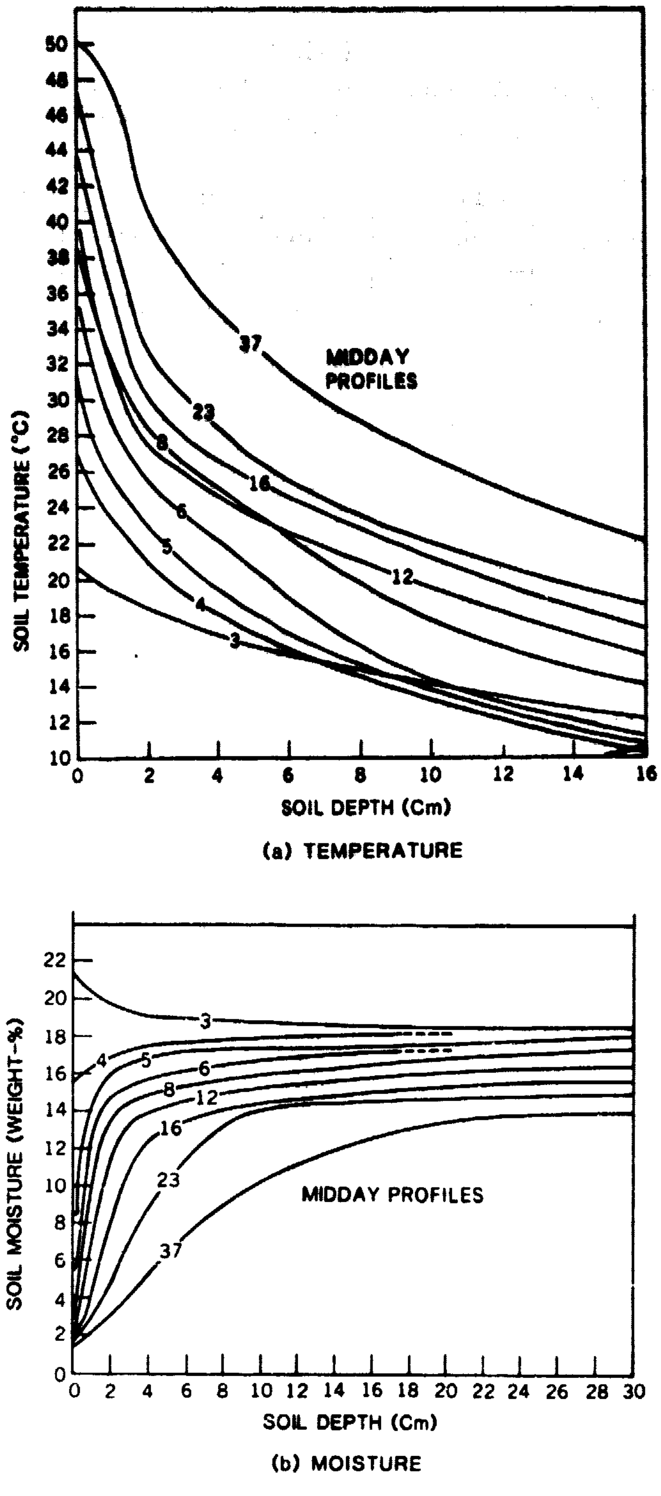

Figure 2. Soil-moisture and temperature profiles observed at the U. S. Water Conservation Laboratory. The curves are labeled by the number of days after irrigation.

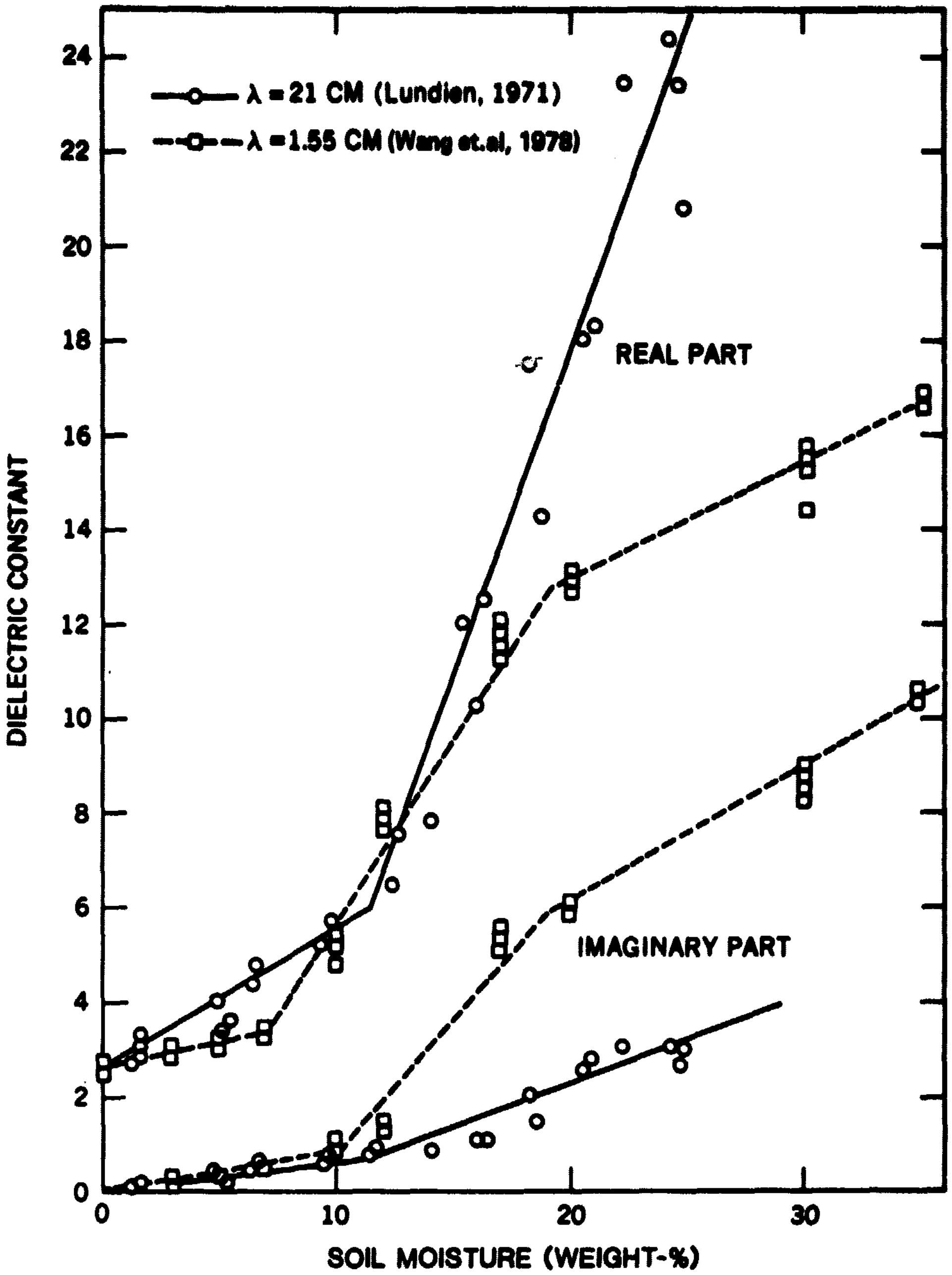

Figure 3. Real and imaginary parts of the dielectric constant for soils with textures similar to those of the soil at the U. S. Water Conservation Laboratory. The data are from laboratory measurements at the frequencies of 1.4 (λ = 21 cm) and 19.4 (λ = 1.55 cm) GHz.

model is that, if the layer thicknesses are chosen so that the dielectric constants of two adjacent layers are nearly equal, the interface reflectivity will be negligible. For this model to be valid, the layer thicknesses should be reduced as the moisture profile gets steeper. The brightness temperature in this model is given by:

$$T_B^p = (1 - R_p) \int_{-\infty}^{0} T(z)\,\gamma(z) \exp\left(- \int_{z}^{0} \gamma(z^1)\,dz^1 \right) dz \tag{18}$$

$$= (1 - R_p)\,T_{eff} \tag{19}$$

Note that, as in the Burke model, the first factor on the right side is the Fresnel transmissivity of the polarization (p) calculated for the surface moisture value, and the second factor is the direct integration of the radiative transfer equation (1) for the intensity just below the soil surface which yields the effective radiating temperature (T_{eff}) of the medium. The layer thicknesses used for the Burke model were also used for this model. This model was presented in equation 10 of the Njoku and Kong paper and will be called the radiative transfer model. The results of Njoku and Kong indicate that there is good agreement between the radiative transfer model and their coherent model for frequencies above about 5 GHz but that differences arise for lower frequencies. This difference will be illustrated further by calculations made using the soil profiles given in Figure 2. The dielectric constants used with these profiles appear in Figure 3. These data are for soils with textures similar to that of the soil at the U. S. Water Conservation Laboratory.

Table 4 gives the results for the three models (Burke, Wilheit, and radiative transfer) in terms of both T_B and emissivity ($e = T_B/T_{eff}$). Note the excellent agreement between the Burke and radiative transfer models for all profiles. There are only small differences between the Burke and Wilheit results for the 19.4-GHz calculations, but there are substantial differences in the 1.4-GHz

Table 4
Brightness Temperatures Calculated for the Profiles in Figure 2 at 1.4 and 19.4 GHz.*

Profile	1.4 GHz			19.4 GHz		
	Radiative Transfer	Burke	Wilheit	Radiative Transfer	Burke	Wilheit
3	177.3	177.5	173.2	191.0	191.2	195.6
4	203.9	204.1	202.7	212.6	212.9	217.1
5	250.7	249.2	229.4	272.0	271.6	275.5
6	262.0	260.4	242.1	279.9	279.2	281.2
8	270.3	269.0	258.4	285.0	284.4	286.8
12	271.6	270.5	268.3	284.7	284.3	287.0
16	273.6	272.6	273.0	287.5	287.2	288.7
23	273.9	272.9	276.1	290.4	290.4	291.1
37	278.9	278.0	279.1	295.7	295.7	296.3

*The profiles are identified by the number of days after irrigation.

calculations–up to 20 K for the profiles with the steepest gradients (i.e., profiles 5, 6, and 8). The good agreement of the 19.4-GHz results indicate that the layer thicknesses used for the noncoherent models are approximately the same as the sampling depth. The differences in the 1.4-GHz results indicate that the sampling depth is greater than the first layer thickness used in the noncoherent models.

The 1 K differences between the radiative transfer and Burke models indicates that, although the reflectivity is small between the soil layers, there is some minor effect. However, as shown here at 1.4 GHz, the effect would generally be negligible.

The emissivities for these profiles can be determined by using the effective radiating temperature as defined by equations 15 and 19. Because both the Burke and Wilheit models were found to have the same weighting functions, the effective temperature could be calculated by using either model, and in this case the results from the Wilheit model were used. Table 5 presents the values of T_{eff}

Table 5
Emissivities for Soil Profiles Given in Figure 2

Profile	1.42 GHz				19.4 GHz				
	T_{eff}*	δ_T** (cm)	Burke	Wilheit	T_{eff}*	δ_T** (cm)	Burke	Wilheit	T_{surf}
3	289.4	6.4	0.613	0.598	293.9	0.15	0.651	0.666	294
4	290.1	7.1	0.704	0.699	299.5	0.20	0.711	0.725	299
5	290.7	7.8	0.857	0.789	301.2	0.49	0.902	0.915	304
6	291.4	8.3	0.892	0.8[illegible]9	304.2	0.66	0.918	0.924	308
8	294.5	9.0	0.913	0.877	306.4	0.85	0.928	0.936	311
12	294.7	9.6	0.918	0.910	305.8	1.0	0.930	0.938	312
16	295.9	10.5	0.921	0.923	308.0	1.3	0.932	0.937	317
23	296.3	11.8	0.921	0.932	310.3	1.5	0.936	0.938	320
37	299.7	14.7	0.928	0.931	315.1	1.9	0.938	0.940	323

*Effective radiating temperature obtained from Equation 15.
**Thermal sampling depth obtained from Equation 13.

plus the subsequently derived emissivities. The measured surface (depth = 1 mm) temperatures are listed for comparison.

The effect of the greater temperature sampling depths at 1.4 GHz is apparent in the values of T_{eff}. At 1.4 GHz, there is a 10 K increase from wet to dry (profiles 3 and 37) and at 19.4 GHz there is a 21 K increase for the same 29 K increase in surface temperature. For the wet profile, the values of T_{eff} at 19.4 GHz are close to the surface temperature, but, as the soil dries, the two temperatures diverge because the microwave thermal radiation originates at deeper depths in the soil where it is cooler for these profiles. Table 5 also gives the thermal sampling depths defined by equation 13 for these two frequencies.

On the days with the steepest moisture gradients (i.e., 5, 6, and 8), the largest differences between the models occur because, as noted previously, the Burke model uses the moisture content of the surface layer only to determine the emissivity. These differences cannot be accounted for by the fact that different layer thicknesses were used for our calculations with the two models. The moisture content in the 1-mm surface layer used for the Wilheit model is essentially the same as that for the 0.03-mm layer used in the Burke model. In fact, it was the thinness of the layers used in the noncoherent models that afforded the excellent agreement between the radiative transfer and Burke models. The difference between the Burke and Wilheit models could be reduced if a thicker surface layer were used in the calculations with the noncoherent models.

An estimate of this desired thickness can be obtained by comparing the emissivities obtained with the Wilheit model with those calculated using the equation for a uniform dielectric. Emissivities calculated using the Fresnel equations are given in Figure 4 based on the dielectric values presented in Figure 3. For example, on day 5 the emissivity calculated with the Wilheit model is 0.789, which intersects the curve in Figure 4 at a moisture of 12.5 percent for a uniform soil. Table 6 lists the results of this comparison for days 4, 5, 6, 8, and 12 and the average soil moistures in the 0- to 1-cm and the 0- to 2.5-cm layers of the soil.

In Table 6, the Fresnel moisture is obtained from the intersection of the model calculated emissivity with the curve in Figure 4. For days 4, 5, and 6, there is good agreement of the Wilheit value with the average measured moisture in a 0- to 2.5-cm layer. As would be expected, the Burke value is drier than the 0- to 1-cm layer for all profiles. An interesting feature is that, for the drier days (8 and 12), the Wilheit value indicates a moisture as dry or drier than the 0- to 1-cm layer. This could result from a positive interference effect increasing the effective transmission across the surface. Interference effects undoubtedly cause the higher emissivities calculated with the Wilheit model compared with Burke model for days 16, 23, and 37. This effect was also noted in some other calculations with the coherent model (Choudhury, et al., 1979).

Table 6
Comparison of Model and Fresnel Emissivities

Day	Wilheit Emissivity	Fresnel Moisture	Burke Emissivity	Fresnel Moisture	Soil Moisture (weight-%)	
					0 - 1 cm	0 - 2.5 cm
4	0.699	15.7	0.704	15.3	16.1	16.5
5	0.789	12.5	0.857	7.7	11.0	13.8
6	0.829	10.8	0.892	4.5	8.4	12.0
8	0.877	6.0	0.913	2.7	5.6	9.9
12	0.910	3.0	0.918	2.1	4.4	8.3

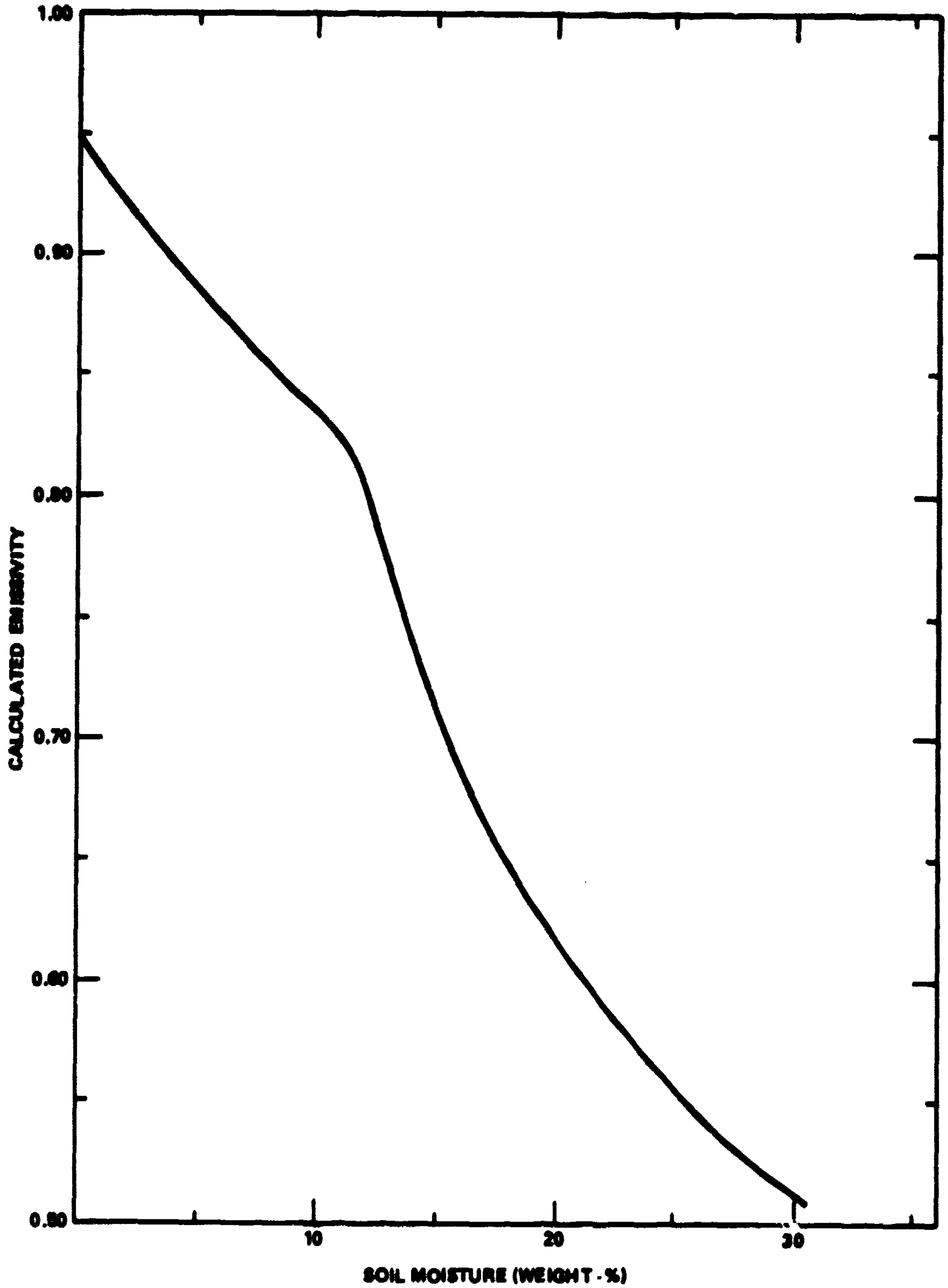

Figure 4. Calculated values of the emissivity at 1.4 GHz using the dielectric constants from Figure 3 in Equation 1.

CONCLUSIONS

Several models for estimating microwave emission from soils were compared—the Njoku, Wilheit, Burke, and radiative transfer models. On the basis of their fundamental approach, they can be classified into noncoherent (Burke and radiative transfer) and coherent (Njoku and Wilheit) models; the former is based on the intensity and the latter on the amplitude of the radiation field. Associated with this difference in fundamental approach, results obtained from these two types of models differed, especially in regard to their apparent soil moisture sampling depth. In the noncoherent models, emissivity is determined by the dielectric contrast at the air/soil interface; therefore, for a soil with a steep moisture gradient at the surface, this emissivity will depend on layer thicknesses used. Because the coherent models keep track of the phase of the fields in the soil, the value of the emissivity at the surface is coupled to the dielectric properties of the layers below the surface.

Due to the dependence of the emissivity in the noncoherent models on the air-soil dielectric contrast, these models do not predict accurate soil moisture sampling depths. The magnitude of the difference of this sampling depth between the coherent and noncoherent models will depend on the microwave frequency and the steepness of the soil-moisture gradient in the soil. Njoku and Kong showed that, for their profiles, there was no difference for frequencies above 4 GHz.

As noted previously, interference effects can occur in the coherent models; however, these effects are not likely to be observed in nature because of the roughness of the surface and horizontal inhomogeneities in the soil. Therefore, care must be exercised when interpreting the results from the coherent models.

All of the models appeared to have the same weighting functions for distributing the sources of the radiation, and, as a result, they all have the same thermal sampling depth and predicted the same effective radiating temperature.

REFERENCES

Blinn, J. C., III, J. E. Conel, and J. G. Quade, 1972: Microwave Emission from Geological Materials: Observations of Interference Effects. J. Geophys. Res., 77, pp. 4366-4378.

Burke, W. J., T. Schmugge, and J. F. Paris, 1979: Comparison of 2.8 and 21 cm Microwave Radiometer Observations over Soils with Emission Model Calculations. J. Geophys. Res., 84, pp. 287-294.

Carver, K. R., 1977: Radiometric Recognition of Coherence. Radio Sci., 12, pp. 371-379.

Choudhury, B. J., T. J. Schmugge, R. W. Newton, and A. Chang, 1979: Effect of Surface Roughness on the Microwave Emission from Soils. J. Geophys. Res., 84, pp. 5699-5706.

England, A. W., 1975: Thermal Microwave Emission from a Scattering Layer. J. Geophys. Res., 80, pp. 4484-4496.

Hollinger, J. P., and R. A. Mennella, 1973: Oil Spills: Measurements of Their Distributions and Volumes by Multifrequency Microwave Radiometry. Science, 181, pp. 54-56.

Jackson, R. D., 1973: Diurnal Soil-Water Content Changes During Drying, Field Soil Water Regime. SSSA Special Publication No. 5, Soil Sciences Society of America, Madison, Wisconsin.

Lundien, J. R., 1971: Terrain Analysis by Electromagnetic Means. Technical Report 3-693. Report 5. U. S. Army Waterways Experiment Station, Vicksburg, Mississippi.

Njoku, E. G., and J. A. Kong, 1977: Theory for Passive Microwave Sensing of Near-Surface Soil Moisture. J. Geophys. Res., 82, pp. 3108-3118.

Schmugge, T., 1978: Remote Sensing of Surface Soil Moisture. J. of Appl. Meteor., 17, pp. 1549-1557.

Stogryn, A., 1970: Brightness Temperature of a Vertically Structured Medium. Radio Sci., 5, pp. 1397-1406.

Ulaby, F. T., P. P. Batlivala, and M. C. Dobson, 1978: Microwave Backscatter Dependence on Surface Roughness, Soil Moisture, and Soil Texture: Part I – Bare Soil. IEEE Trans. Geo. Electron., GE-16, pp. 286-295.

Ulaby, F. T., G. A. Bradley, and M. C. Dobson, 1979: Microwave Backscatter Dependence on Surface Roughness, Soil Moisture, and Soil Texture: Part II – Vegetation-Covered Soil. IEEE Trans. Geo. Electron., GE-17, pp. 33-40.

Wang, J., T. Schmugge, and D. Williams, 1978: Dielectric Constants of Soil at Microwave Frequencies, II. NASA TP-1238.
II. NASA TP-1238.

Wilheit, T. T., 1978: Radiative Transfer in a Plane Stratified Dielectric. IEEE Trans. Geo. Electron., GE-16, pp. 138-143.