Radio Science, Volume 33, Number 2, Pages 267–272, March–April 1998

Observations of coherent emissions from soils

T. J. Schmugge and T. J. Jackson
Hydrology Laboratory, USDA Agricultural Research Service, Beltsville, Maryland

P. E. O'Neill
Laboratory for Hydrospheric Processes, Hydrological Sciences Branch, NASA Goddard Space Flight Center
Greenbelt, Maryland

M. B. Parlange
Department of Geography and Environmental Engineering, Johns Hopkins University, Baltimore, Maryland

Abstract. Observations of the microwave emissions at 1.413 GHz (L band) and 2.65 GHz (S band) from a silt loam soil exhibited an oscillatory behavior in time as the soil was being irrigated. The oscillations are attributed to interference between reflections from the air-soil interface and the wet soil–dry soil interface as the latter moved down in the soil. The magnitude of the first oscillation at L band was 56 K, and at S band it was 40 K, with oscillation damping out after about three cycles to the brightness temperature expected for the wet soil. The emission was modeled using a coherent model, and the results show qualitative and quantitative agreement with the observations.

1. Introduction

The observation of coherency effects in the emission from natural surfaces is a rare event. In a recent paper, *Jackson et al.* [1997b] presented one such observation, where oscillations of the brightness temperature emitted from a soil were observed as the soil was watered. In the present paper we demonstrate using a coherent model radiative transfer model that these oscillations arise from the interference of reflections from the air-soil interface and the wet soil–dry soil interface as the latter moved down in the soil. These observations implied that the thickness of the wet layer had sufficient horizontal uniformity over the radiometer footprint of several meters to prevent the washing out of the interference. Also, the strength of the interference implied that the dry-to-wet interface was rather sharp, i.e., a fraction of a wavelength. These observations were made at wavelengths of 11 and 21 cm in air. The emission was modeled using the coherent model developed by *Wilheit* [1978] and assumed moisture and temperature profiles for the soil. The results are in good qualitative and reasonable quantitative agreement with the observations.

Paper number 97RS02614.
0048-6604/98/97RS-02614$11.00

2. Observation System

The S and L band microwave radiometer (SLMR) [*Jackson et al.*, 1997a] is a dual-frequency system operating at 2.65 and 1.413 GHz, i.e., wavelengths of 11.3 and 21.2 cm, respectively. The radiometric sensitivity for each channel is 0.1 K for a 1-s integration time. Each radiometer has a linearly polarized microstrip patch antenna which is configured as a 4×4 phased array. They have a 20° 3-dB beam width with a main beam efficiency of 97% and were mounted in this experiment to receive horizontally polarized radiation. The antenna and receiver of each radiometer are packaged together in a thermally controlled enclosure. The calibration of the radiometers was checked using external reference targets which typically were the cold sky (~5 K) and an ambient absorber (~300 K). If available, a water target was also used to provide a calibration target over a range of temperatures as a function of angle. The radiometers were on a truck-mounted hydraulic boom at a nominal height of 8 m with a 10° incidence angle. At this height the 3-dB field of view was about 3 m, and the centers of the beams for the two radiometers were separated by about 1 m.

In addition to the SLMR a thermal infrared (TIR) radiometer and a color video camera were mounted on the radiometer platform. The TIR radiometer operated in the 8- to 14-μm band and was used for

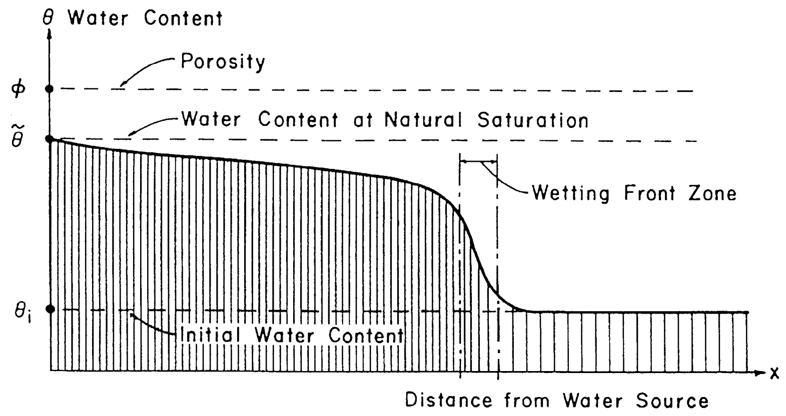

Figure 1. Schematic representation of the shape of the wetting front in a soil. It shows the sharp transition from reasonably uniform wet soil above the front to the dry soil below. (Adapted from *Morel-Seytoux* [1979], reprinted by permission.)

surface temperature determination. The video camera provided a visual record of the observations.

3. Field Site

The measurements were made on June 12, 1995, on an agricultural research field at the University of California, Davis. The soil at this location has been extensively studied [*Greminger et al.*, 1985; *Buchter et al.*, 1991]. The soil is a Yolo silt loam (20% sand and 20% clay texture) with a bulk density of 1.4 g/cm^3. *Buchter et al.* [1991] estimated that the saturated water content is 44% and the saturated conductivity is 0.44 cm/h. The field was very dry (6% by volume) prior to irrigation, with a smooth bare surface.

The irrigation was initiated in the early evening at a rate of about 0.5 cm/h. This time of day was chosen in order to minimize losses due to evaporation and wind. In prior experiments [*Parlange et al.*, 1992] this irrigation system was found to have a uniformity coefficient of 0.88, indicating an even distribution of water over the field. This level of uniformity is very important for our observations. The rate of application was comparable to saturated conductivity for the soil. Hence there was minimal ponding on the surface, and water moved down in the soil, producing a sharp transition between the wet upper soil and dry soil below. This transition is called the wetting front. Figure 1 is a schematic representation of the shape of a wetting front in a soil. It shows the sharp transition from reasonably uniform wet soil above the front to the dry soil below. This transition is called the wetting front zone. We would expect the thickness of this zone to be of the order of a few centimeters. For the Yolo silt loam the porosity or saturated water content is 44%, and the water content at natural saturation or field capacity is 35%.

The resulting observed brightness temperatures are given in Figure 2 for both the S and L band radiometers. Prior to irrigation we observed a T_B of about 285 K for both channels, with the expected sharp drop after the onset of irrigation. What is surprising is the subsequent rise after this initial drop and continued oscillatory behavior. The distance between the adjacent minima is about 2.5 hours for the first pair and 2 hours for the second pair at L band. At S band the separation is about 1.3 hours. This is the time for the wetting front to move a half wavelength in the soil.

4. Model Results

The microwave emission model we have chosen to use is that developed by *Wilheit* [1978]. In this model the soil is treated as a layered dielectric. The solutions to Maxwell's equations and the boundary conditions are used to calculate the electric fields in each layer. These fields are used to calculate the energy fluxes and thus obtain the fractional absorption (f_j) in each layer. If T_j is the temperature of the jth layer, this layer contributes $f_j T_j$ to the resulting brightness temperature T_B. Thus

$$T_B = \sum_{j=1}^{N} f_j T_j \qquad (1)$$

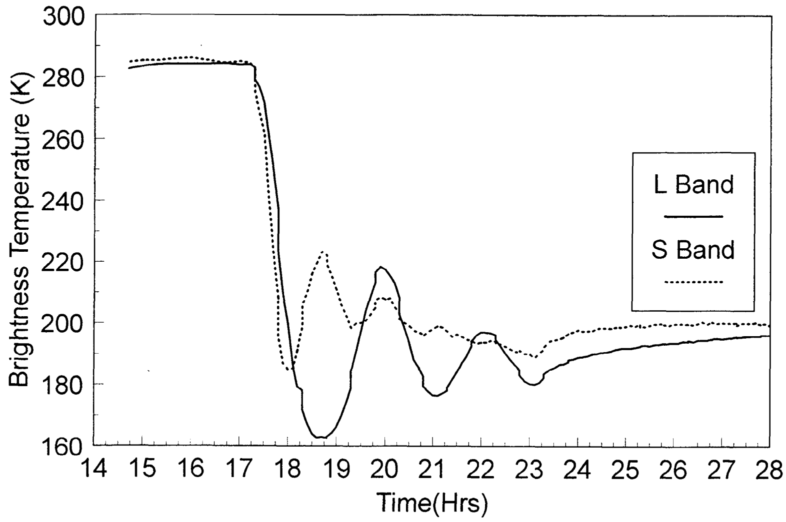

Figure 2. The observed temporal variations of the T_B at 11 and 21 cm as functions of time after initiating the irrigation.

The layer thicknesses were 0.05 cm down to 15 cm and 0.1 cm from 15 to 35 cm. To perform these calculations, we need values for the dielectric constant and temperature as functions of depth. Here we assumed a constant temperature of 300 K. The soil temperature cooled dramatically when the water was added to the soil and ended up at about 22°C (295 K). The moisture profile shown in Figure 1 is approximated by linear segments as shown in Figure 3. The surface moisture was set at 40%, or about 90% of porosity, with a linear decrease with depth to 35%, the field capacity value, at the top of the wetting front. The dry soil moisture was taken, as measured, to be 6%. We assumed a linear transition between the two

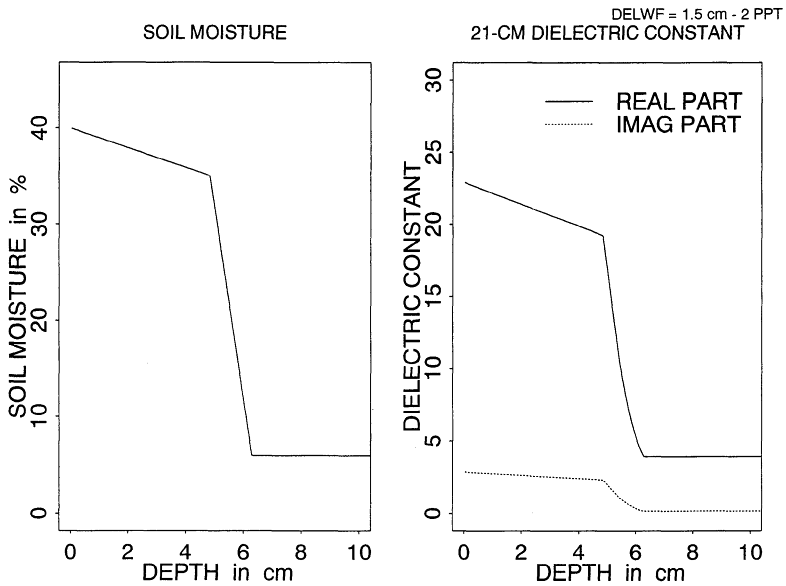

Figure 3. Typical soil moisture and dielectric profile used for modeling the emission. This profile is for a wetting front thickness of 1.5 cm and is a snapshot taken when the wetting front was at the depth of 5 cm.

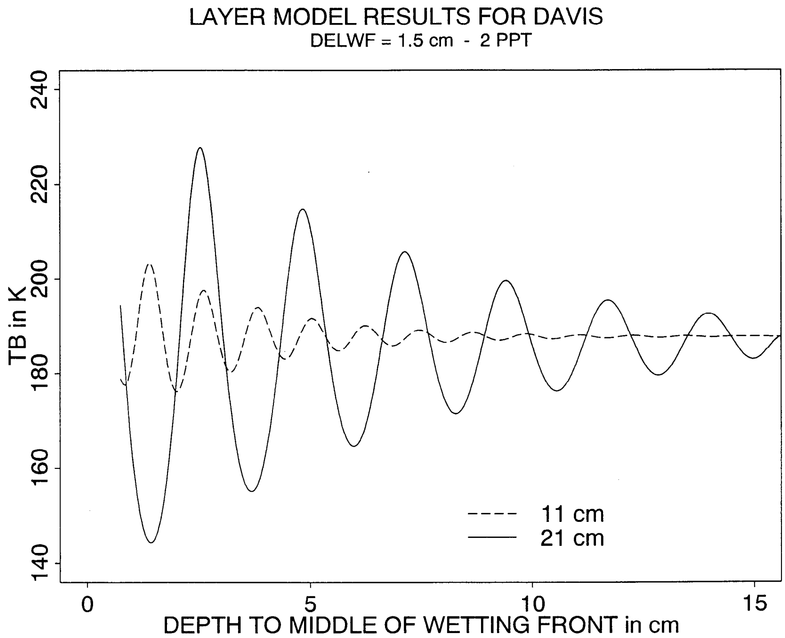

Figure 4. Modeled values of T_B at 21 and 11 cm for the case of wetting front thickness of 1.5 cm and salinity of 2 ppt. The horizontal axis is the depth to the middle of the transition or wetting front zone.

moisture levels over the thickness of the wetting front (DELWF), which could be varied. The dielectric constants were calculated using the *Wang and Schmugge* [1980] model and were based on the soil texture and density and an assumed salinity of 2 ppt for the soil water, which is reasonable for irrigated soils. The dielectric profile is also shown in Figure 3. A minimal value of 0.1 was assumed for the roughness parameter h, to account for the effects of surface roughness on the emission [*Choudhury et al.*, 1979]. The results of the calculation are presented in Figure 4 for the two wavelengths for a wetting front zone width (DELWF) of 1.5 cm. The oscillatory behavior is seen to be similar to that in the observations. The distance between adjacent minima is about 2.2 cm at L band and about 1.2 cm at S band. Comparing this with the time separation noted in Figure 2 for both bands indicates that the wetting front is moving at the rate of about 1 cm/h or slightly more. Considering the irrigation rate of 0.5 cm/h, the initial and final moisture the rate should be somewhat faster, of the order of 1.7 cm/h. The reasons for this discrepancy are not clear at the present. At L band the amplitude of the oscillations is greater (83 K) in the calculations versus 56 K in the observations. At S band the observed (37 K) and calculated (27 K) amplitudes are in better agreement. The number of cycles is much greater in the calculations, six at S band versus three in the observations. This is perhaps due to neglecting any variations in the depth to the wetting front over the footprint in the calculations. We would expect there to be perhaps a 10% variation over the field based on the uniformity coefficient (0.88) mentioned above. This effect is discussed later.

The sensitivity of the T_B to the soil salinity and the thickness of the wetting front zone between 1 and 2 cm was studied. Tables 1 and 2 give the results for the range of T_B, the maximum of the first peak minus the prior minimum, at the two wavelengths. Varying the salinity had minimal effect on the results, i.e., 10–14 K at L band and less than half that at S band. This difference is because the conductivity losses due to

Table 1. Calculated values of ΔT_B at 21 cm

	Salinity		
DELWF, cm	1 ppt	2 ppt	3 ppt
1.0	106.1	99.1	92.8
1.5	89.5	83.4	77.9
2.0	68.1	63.2	58.7

Observed value is 56 K, and values are given in kelvins.

Table 2. Calculated values of ΔT_B at 11 cm

DELWF, cm	Salinity 1 ppt	2 ppt	3 ppt
1.0	67.1	64.6	62.2
1.5	28.3	26.6	25.0
2.0	20.8	19.8	18.9

Observed value is 56 K, and values are given in kelvins.

salinity decrease with frequency. The thickness of the wetting front zone (DELWF) had a much stronger effect on the results, about 34–38 K at L band and 43–56 K at S band. Here the higher frequency, shorter wavelength channel is more strongly affected because the transition layer is a larger fraction of the wavelength. From these tables it is clear that a DELWF > 2 cm would reduce the oscillations at S band to almost zero and thus that a transition thickness of about 1.5 cm appears appropriate. For this case the calculated ΔT_B at L band is greater than that observed, while it is less for S band. This is the case plotted in Figure 4. The resulting final T_B values for both channels are in good agreement with the observations (190–195 K).

To study the sensitivity of the calculations to variations of DELWF and angle, we used arithmetic averages of calculations for a realistic range of DELWFs and angles and found little sensitivity to these variations. We also considered variations in the depth to the wetting front, and in this case there was a significant effect, as shown in Figure 5. This was done by passing a low-pass Gaussian filter of variable width over the results given in Figure 4. This had the effect of averaging the results from adjacent depths to reflect a distribution of depths over the footprint. The width of the filter increased with depth to reflect the probable increased spread of depths over the footprint as the wetting front moved down in the soil. For example, at the 10-cm depth the spread in depths was approximately ±1.5 cm, about that expected by the 0.88 uniformity coefficient. The result of this approach was to reduce the number of oscillations in the model results, to come into closer agreement with the observations.

5. Conclusions

This paper reported on the observation of a coherency effect in microwave emission from a natural surface. In this case it was caused by the interference of reflections from the air-soil interface and wet soil–dry soil interface (wetting front) as the soil was irrigated. The observation of the interference pattern as the wetting front moved down implied that it

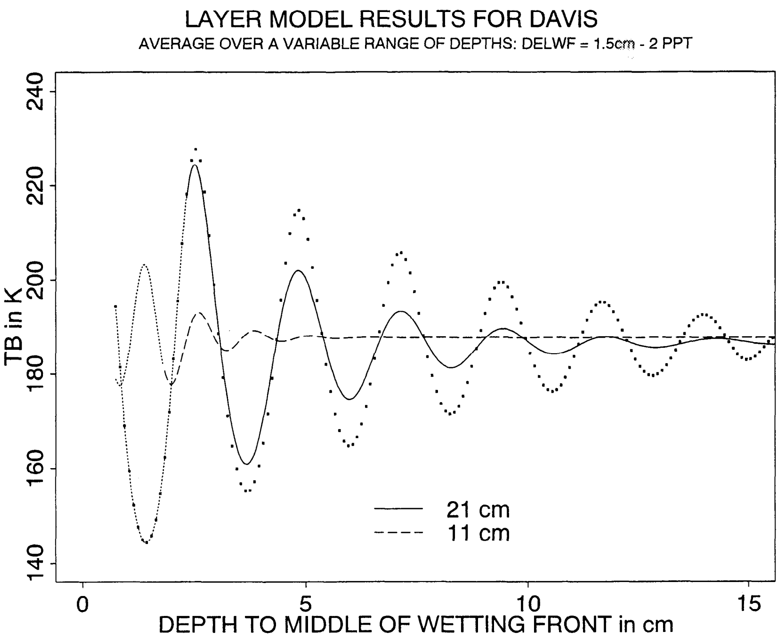

Figure 5. Same as Figure 4 but with the values averaged over a range of depths around the listed depth. The dots are the values for the 21-cm wavelength given in Figure 4.

remained parallel to the surface and at about the same level over the radiometers' footprints. Calculations with a coherent radiative transfer model indicated that the thickness of the wetting front is about 1.5 cm. The calculations also indicate little sensitivity to soil salinity over the expected range or to variations in the thickness of wetting front. However, there was considerable sensitivity to variations in the wetting front depth over the footprint, which had the effect of damping out the oscillations. By comparing the distance between the peaks in observed and calculated brightness temperatures, we were able to infer that the front was moving at the rate of 1 cm/h, which is somewhat slower than that expect for the rate at which water is applied.

References

Buchter, B., P. O. Aina, A. S. Azari, and D. R. Nielsen, Soil spatial variability along transects, *Soil Technol.*, *4*, 297–314, 1991.

Choudhury, B. J., T. J. Schmugge, A. Chang, and R. W. Newton, Effect of surface roughness on the microwave emission from soils, *J. Geophys. Res.*, *84*, 5699–5706, 1979.

Greminger, P. J., Y. K. Sud, and D. R. Nielsen, Spatial variability of field-measured soil water characteristics, *Soil Sci. Soc. Am. J.*, *49*, 1075–1082, 1985.

Jackson, T. J., P. E. O'Neill, and C. T. Swift, Diurnal observations of soil moisture with microwave radiometers, *IEEE Trans. Geosci. Remote Sens.*, *IEEE Trans. Geosci. Remote Sens.*, *35*, 1210–1222, 1997a.

Jackson, T. J., T. J. Schmugge, W. J. Rawls, P. E. O'Neill, and M. B. Parlange, Soil water infiltration observation with microwave radiometers, in *1997 International Geoscience and Remote Sensing Symposium Proceedings*, pp. 1099–1101, IEEE Press, Piscataway, N. J., 1997b.

Morel-Seytoux, H. J., Wetting front, in *Encyclopedia of Soil Physics*, edited by R. W. Fairbridge and C. W. Finkl, pp. 602–608, Van Nostrand Reinhold, New York, 1979.

Parlange, M. B., G. G. Katul, R. H. Cuenca, M. L. Kavvas, D. R. Nielsen, and M. Mata, Physical basis for a time series model of soil water content, *Water Resour. Res.*, *28*(9), 2437–2446, 1992.

Wang, J. R., and T. J. Schmugge, An empirical model for the complex dielectric permittivity of soils as a function of water content, *IEEE Trans. Geosci. Remote Sens.*, *GE-18*, 288–295, 1980.

Wilheit, T. T., Radiative transfer in a plane stratified dielectric, *IEEE Trans. Geosci. Electron.*, *GE-16*, 138–143, 1978.

T. J. Jackson and T. J. Schmugge, Hydrology Laboratory, USDA Agricultural Research Center, Building 007, BARC West, Beltsville, MD 20705-2350. (e-mail:tjackson@hydrolab.arsusda.gov; schmugge@hydrolab.arsusda.gov)

P. E. O'Neill, Laboratory for Hydrospheric Processes, Hydrological Sciences Branch, NASA Goddard Space Flight Center, Greenbelt, MD 20771. (e-mail: peggy@hydro4.gsfc.nasa.gov)

M. B. Parlange, Department of Geography and Environmental Engineering, Johns Hopkins University, Baltimore, MD 21218. (e-mail: mbparlange@jhu.edu)

(Received April 3, 1997; revised August 27, 1997; accepted September 19, 1997.)