Soil Water Infiltration Observation with Microwave Radiometers

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Abstract—Experiments were conducted using truck-based microwave radiometers operating at 1.41- (L-band) and 2.65-GHz (S-band) horizontal polarization to observe small plots during and following sprinkler irrigation. These experiments were conducted on a sandy loam soil in 1994 and a silt loam in 1995. Sandy loam soils typically have higher infiltration capabilities than clays, and in our studies, we were not able to exceed this with the irrigation system. The observed brightness temperature (T_B) quickly reached a nominally constant value during irrigation. When the irrigation was stopped, the T_B began to increase as drainage took place. Contributing depth-related differences were observed for L- and S-band as expected. The irrigation rates in 1995 with the silt loam soil exceeded the saturated conductivity of the soil. During irrigation, the T_B values exhibited a phenomenon that had not been previously observed and identified and is associated with coherent interference. The L- and S-band exhibited similar patterns but were not identical due to contributing depth. These results suggested the existence of a sharp dielectric boundary (wet over dry soil) that was increasing in depth with time. The temporal description of the wetting front boundary was used with a coherent radiative transfer model to predict T_B for L- and S-band.

Index Terms—Microwave, radiometry, soil moisture.

I. INTRODUCTION

INFILTRATION is the process of water entry into the soil from rainfall, irrigation, or snowmelt. It is interrelated with soil water movement and redistribution. These processes control surface runoff, evaporation, and erosion as well as critical water-quality transport phenomena. Point-scale infiltration modeling is well understood and can be modeled from basic physical laws. Extrapolating this theory spatially and determining the necessary soil characteristics remains a challenge. In this investigation, the role of remote sensing in infiltration studies is addressed. Remote sensing can provide a spatially integrated measurement that could play an important role in scaling. Of particular interest is microwave remote sensing.

The measurement provided by a microwave radiometer is the brightness temperature (T_B). The T_B of a surface can be approximated as emissivity multiplied by physical tempera-

ture. If the physical temperature is estimated independently, emissivity can be determined. Emissivity can be related to the dielectric constant of the soil, which is a composite of the values of its components: air, soil particles, and water. Values of the real part of the dielectric constant for air and soil particles are one and five, respectively. Water has a value of about 80 at the longer wavelengths considered here (>5 cm). The basic reason microwave remote sensing is capable of providing soil moisture information is this large difference between water and the other components. Using a dielectric mixing model [1], [2], the volume fraction of water (soil moisture) can be estimated.

There are well-known theories describing the emission from a soil profile with uniform or varying properties [3]–[5]. The computations involve a nonlinear weighting that decays with depth. Some modeling studies have suggested that this dominant depth is 1/10 the wavelength [4]. Field experiments [6] suggest that the contributing depth is about 1/4 the wavelength (based on a wavelength range from 2 to 21 cm).

Previous research focusing on the use of remote sensing and infiltration has been very limited [7], [8]. Several recent investigations have examined new approaches to estimating infiltration parameters that depend on temporal observations of soil moisture [9]–[11].

The work described here focuses on the results obtained in experiments using passive microwave radiometers installed on a truck-based observing platform. Unique aspects of these studies are the use of multifrequency microwave measurements, high temporal resolution (as compared with typical remote-sensing field observations), and a spatial resolution on the order of 2 m.

II. S- AND L-BAND MICROWAVE RADIOMETER (SLMR) SYSTEM

The S- and L-band Microwave Radiometer (SLMR) is a dual-frequency passive sensor system operating at S-band (2.65 GHz or 11.3 cm) and L-band (1.413 GHz or 21.2 cm). The radiometric sensitivity of each radiometer is 0.1 K for a 1-s integration time. Each linearly polarized microstrip patch antenna is configured as a 4 × 4 phased array providing 20° of beamwidth with a main beam efficiency of 97%. The antenna and receiver are packaged together in a thermally controlled enclosure for each frequency. System software monitors the thermal status of the radiometers and attempts to maintain
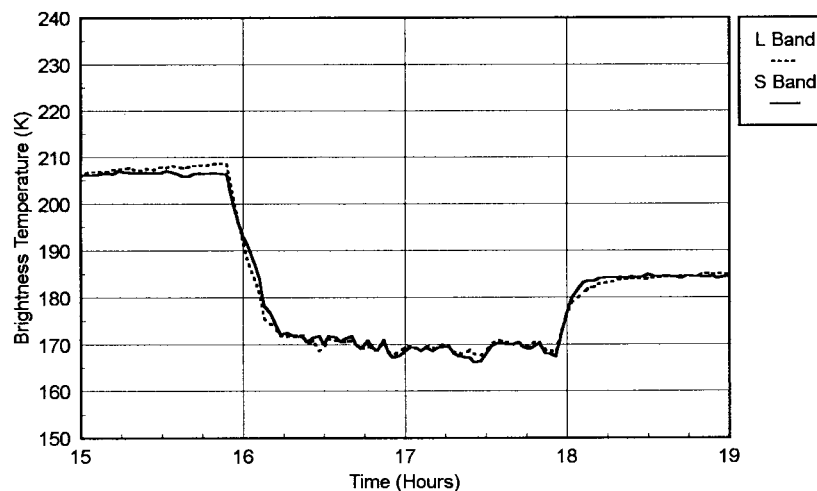
Fig. 1. Observed T_B during and after infiltration on September 27, 1994, on a bare sandy loam soil at Beltsville.

thermal equilibrium at the defined goal temperature through the distributed heater network.

For the 1994 experiments, the SLMR system was mounted on a boom truck described in [12]. This vehicle is equipped with a 9-m hydraulic boom. The antennas were mounted to observe horizontal polarization. At the nominal operating height of 5 m with the specified field of view of the radiometers (20°), the footprint size was 1.5 m at a viewing angle of 10° off nadir. The centers of the S- and L-band radiometers are offset by approximately 1 m in the installation; therefore, the centers of the ground footprints will be offset. The beams do overlap, but there is the potential for some variation in target properties in the area contributing to the two individual measurements.

In 1995, a different truck system was used [13]. Observations were made at an elevation of 8 m, which resulted in footprints closer to 2.5 m for each of the sensors.

In addition to the two microwave radiometers, several other supporting instruments were also mounted on the truck platform. A small portable thermal-infrared radiometer was used to estimate the surface temperature by measuring thermal emission in the 8–14-microns wavelength range. Target location for the microwave radiometers was achieved with a color video camera installed on the platform between the two antennas. The look angle of the instrument platform was determined by an inclinometer system.

Calibration of the radiometers is based on external reference targets. The external targets typically used are sky (~5 K) and absorber (~300 K). These are usually quite stable references, cover the entire range of instrument response, and are easy to obtain. Water calibration was also conducted occasionally. Water has well-known T_B values as functions of temperature and angle. By varying the angle, reference T_B values between 50 and 110 K can be obtained. Water calibration is more difficult to obtain frequently since it usually must be done at some location other than test sites.

III. EXPERIMENT DESCRIPTIONS

The experiments were conducted at two sites using sprinkler irrigation to apply water. In 1994, plots at the Beltsville

Agricultural Research Center (BARC), Beltsville, MD, were used. The soil was a sandy loam (70% sand and 6% clay) with a smooth surface. Bulk density averaged 1.45 g/cm^3. Hydraulic conductivity was measured as 0.338 cm/h using disc permeameters at 4-cm tension. From this, the saturated hydraulic conductivity was estimated as 22 cm/h.

In 1995, the experiments were conducted at facilities of the University of California, Davis. Soil conditions were quite different from 1994. This was also a smooth bare soil. The soil at this location has been extensively studied [14], [15]. The particular area these measurements were conducted in was a Yolo silt loam (20% sand and 20% clay). Bulk density was measured after irrigation as 1.4 g/cm^3. Some relevant soil properties reported in [15] for the 30-cm layer include the following: saturated water content = 44%, saturated conductivity = 0.44 cm/h, and bulk density = 1.39 g/cm^3.

IV. RESULTS AND DISCUSSION

A. Beltsville 1994

Three sets of observations were made: September 27 (bare), October 3 (bare), and October 4 (corn). The irrigation system performed well over the bare plots, resulting in a uniform application. Total water application amounts were estimated as 4.2 cm on September 27 and October 3, and 2.5 cm on October 4. Due to problems in trying to uniformly apply water to the mature corn canopy, the corn data were not used here. Prior to September 27, there had been a rainfall event the previous night (>2.5 cm) that left the soil very wet at the outset of irrigation. A rainfall event on October 1 of more than 1 cm resulted in moderately wet conditions for the October 3 observations.

Microwave data were collected every 2 min. Figs. 1 and 2 show the T_B versus time for the two dates. Several common features can be observed in these figures. Prior to the water application, values for both the S- and L-band T_B were constant. The S-band T_B is slightly higher than L-band, which would be expected for a drying bare soil. Following the start of irrigation, there is a brief (~15 min) interval during which the
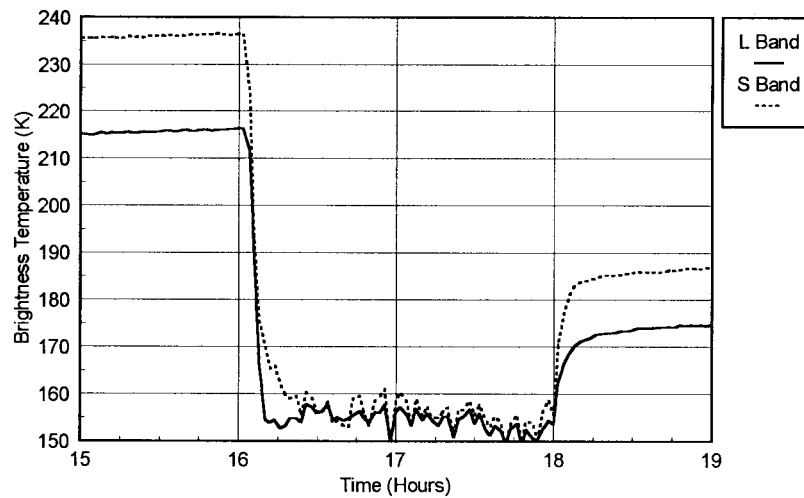
Fig. 2. Observed T_B during and after infiltration on October 3, 1994, on a bare sandy loam soil at Beltsville.
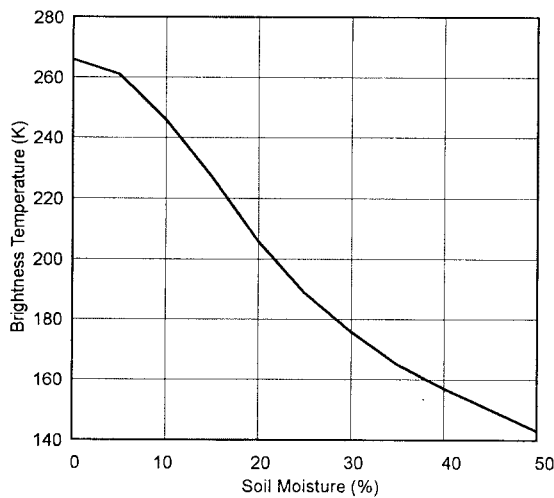

Fig. 3. Predicted relationship between T_B and soil moisture for a sandy loam soil.

T_B plunges to a new constant value for both S- and L-band. It remains at this value until the water application stops. When the irrigation ends, there is a rapid rise in T_B followed by an extended period of much slower changes in T_B.

The level of T_B during irrigation varies between the two bands and with date. Causes of this can be the irrigation rate and sprinkler pattern, which also varied, as well as antecedent conditions. Visual observations indicated that ponding (water pooling on the surface) did not occur. Considering the high-saturated conductivity of this soil and the relatively low water application rates possible with the sprinkler irrigation system, no ponding was expected. The minimum T_B values observed would indicate a soil moisture close to, but not at, saturation for this soil.

Using a simple radiative transfer model that assumes that the Fresnel equation assumptions on profile homogeneity apply [16], a relationship between T_B and soil moisture was predicted for the soil under investigation and is shown in Fig. 3. This can be used to interpret the observations in Figs. 1

and 2; the comments will focus on Fig. 2. The initial condition T_B for L-band indicates a soil moisture of about 17%. The constant value T_B during irrigation is estimated as 155 K from Fig. 2. Using Fig. 3, this T_B would result in an estimated soil moisture of 41%. This soil moisture is very close to the total porosity or saturated soil moisture for this soil ($\sim$45%).

Due to the spatial offset of the centers of the two radiometers and the observed variations in surface wetness during water application, a detailed comparison of the behavior of the curves is difficult. This is especially true during the initial phases of water application.

A close examination of the T_B curves at the end of irrigation in Fig. 2 also reveals wavelength-specific effects that reflect the differences in the contributing depth of the S- and L-bands. After the end of the irrigation, the water in the soil column should drain to the 1/3 bar tension (sometimes called field capacity) soil moisture value. Without evaporation, the soil moisture should remain at this nominal level. The results shown in Fig. 2 indicate a more rapid increase in T_B for S-band than L-band, which would be expected because a shallower (more rapidly drying) depth contributes to the measurement at S-band. This pattern is not observed in Fig. 1. A possible explanation may be that the initially wetter conditions present for Fig. 1 produce a more uniform profile. The longer term variations include some thermal effects due to diurnal (nighttime) temperature changes.

These results show extremely interesting patterns that are obviously correlated with infiltration. Different results for different wavelengths suggest that near-surface profile information can be extracted. Unfortunately, the infiltration rates on this particular soil are very high and changes occur rapidly. Therefore, this would not be a practical solution to observing infiltration without high temporal resolution.

B. Davis 1995

1) General Observations: The soil at the Davis site was very dry prior to irrigation performed on June 12. Limited sampling indicated the following volumetric soil moisture
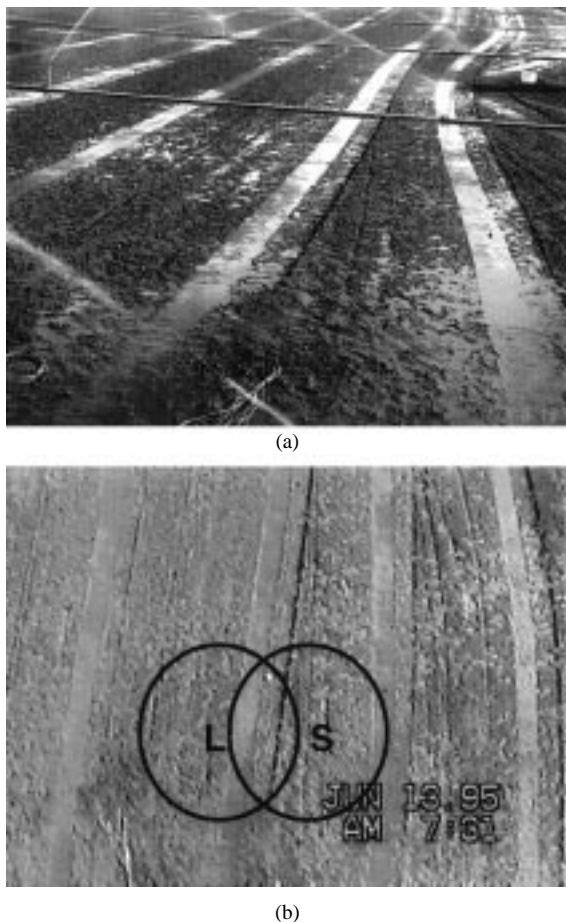
(a)

(b)

Fig. 4. Photographs of conditions at the Davis site (a) during irrigation and (b) the nominal footprint locations of the radiometers.

profile: 0–5 cm 6%, 5–10 cm 11%, and 10–15 cm 19%. Visual observation of the 0–5-cm layer indicated uniform conditions. For a silt loam soil, the 15 bar tension moisture content is on the order of 10% and the 1/3 bar is on the order of 35%.

Irrigation at a rate of approximately 0.5 cm/h was initiated in the early evening to minimize losses to evaporation and blowing. In contrast to the Beltsville experiment, the irrigation rate was approximately the same as the saturated conductivity for the soil (∼0.44 cm/h). There was some ponding of water on the soil surface, as illustrated in Fig. 4(a). The sensor footprints are illustrated in Fig. 4(b). It is obvious that the sensor observes what visually looks like a mixed condition of standing water and soil.

Fig. 5 shows the T_B trace observed for S- and L-band. At the outset of irrigation, large decreases in T_B were observed as expected. However, as time progressed, oscillation began to occur. The pattern of oscillation was similar to that which is predicted using coherent radiative transfer models [3] for a layered media having a sharp dielectric boundary.

This is the first time that coherent reflection has been observed in soil moisture studies. Previous soil related investigations designed to study coherent reflection have utilized buried plate experiments [17], [18]. In these studies, a metal plate (which has a very high reflectivity) is buried at increasing depths in a uniform soil. As the soil thickness above the plate

increases, the oscillatory pattern predicted from coherent models has been observed. Since no soil moisture field experiments have ever reported this phenomenon, it has been assumed that the sharp dielectric boundaries needed to produce the effect do not occur in nature with sufficient uniformity over an area the size of a radiometer field of view.

There are several features of the coherent reflectivity that can be readily observed in Fig. 5. For an individual wavelength, the time between peaks is consistent. In addition, the magnitude of the oscillation decreases with time. Theory [3] predicts that the reflectivity will oscillate as the depth to the dielectric boundary increases and the peaks will occur at fixed depth intervals of $(\lambda/\epsilon_{\mathrm{soil}}^{0.5})/2$, where λ is the wavelength and ϵ_{soil} is the dielectric constant of the soil layer. As illustrated in Fig. 6, for L-band measurements on a wet soil (when the soil moisture is near saturation or 40% here), this oscillation interval would be on the order of 2–3 cm. The decrease in oscillation amplitude with time (or depth) is attributed to the decreasing impact of this layer interface as it gets deeper in the soil column and approaches a depth at which the profile can be treated as uniform.

In addition to the individual wavelength behavior, the S- and L-band results can be compared. It appears that the time period for S-band is roughly half that of L-band and the oscillations stop sooner than for L-band. Both of these features would be expected from the coherent reflection.

2) Wetting Front Movement: Before examining the relationship between the observed and theoretical T_B during infiltration, it is necessary to convert the observed trace from T_B versus time to T_B versus depth. This requires some knowledge of the rate and duration of water application. At the scale we are observing, this involves a few assumptions to offset some missing information. It is very difficult to achieve a uniform application using sprinkler irrigation; therefore, the rate and amount of water applied is a source of uncertainty. On the average, the rate of application was measured as 0.5 cm/h.

The advancement of soil wetting during infiltration is illustrated in Fig. 7, which is derived from results obtained by Bodman and Colman [19] for a Yolo silt loam soil. The curves in this figure show the moisture content as a function of depth at specific points in time during infiltration. This was a laboratory study, and the entire column was very dry with a high water application rate. The moisture profile can be subdivided into four sections: a very wet (saturated) near-surface layer, a wet layer with a slightly lower soil moisture, a layer of rapidly changing soil moisture at the wetting front, and the initial dry soil. As part of this work, Bodman and Colman [19] attempted to evaluate soil moisture conditions at the wetting front. The authors note the difficulty in trying to measure very thin layers and were only able to achieve a minimum layer thickness of 0.5 cm. For the Yolo silt loam, the measured moisture content of this wetting layer averaged 16.8% and remained constant as the wetting front increased in depth.

For analysis, it is necessary to set some boundaries on the wetting front location. As noted previously, the initial soil moisture in the 0–5-cm soil layer was on the order of 6%. Total porosity for a soil with a bulk density of 1.4 g/cm^3 would be
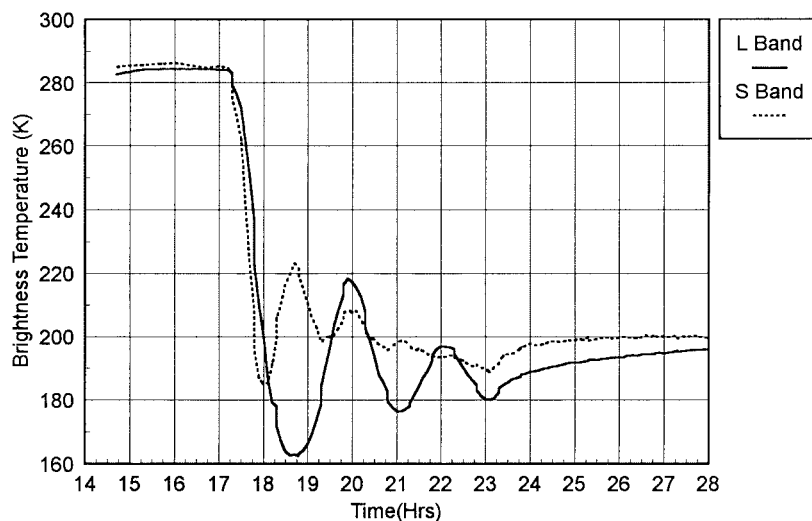
Fig. 5. Observed T_B during and after infiltration on June 12, 1995, on a silt loam soil at Davis.
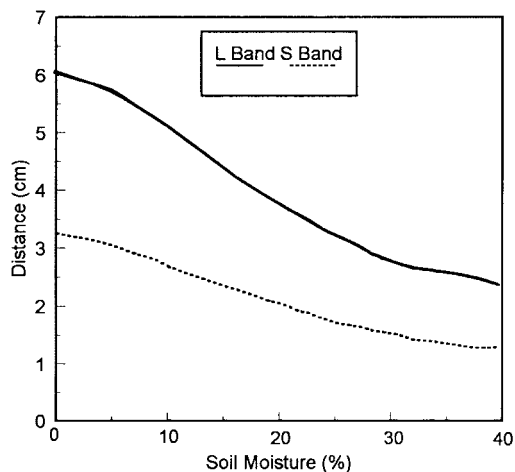

Fig. 6. Effect of soil moisture at the wetting front boundary on the distance (d) between successive minima in coherent reflectivity.
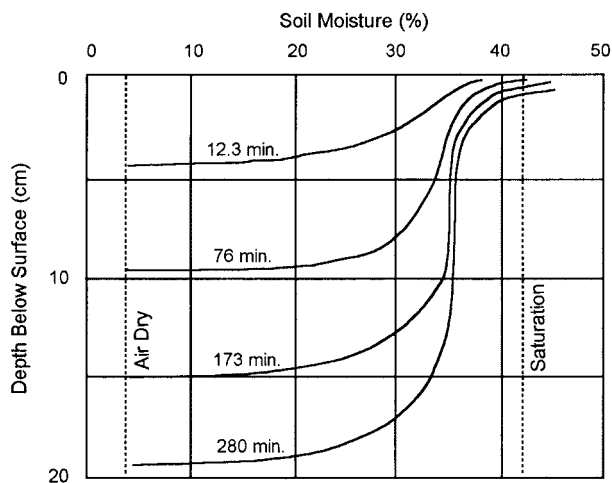

Fig. 7. Observed behavior of the soil wetting front during infiltration for a Yolo silt loam, based on data in Bodman and Colman [19].

47%. The difference between these two values (41%) is the available pore space. If all pore space was filled behind the wetting front, the depth of the wetting front at any point in time with the irrigation rate of 0.5 cm/h would be [(0.5 cm/h)*no. hours]/0.41. This represents the minimum rate of wetting front advancement. Fig. 8 is a graph of observed T_B versus wetting front depth under these assumptions. If the wetting behaves more like Fig. 7 with a wetting layer, the rate of the wetting front advancement could be higher since all pores would not be filled.

3) Prediction Using a Radiative Transfer Model: The coherent radiative transfer model described in [4] was used with estimates of the soil dielectric properties based on [20] to predict the T_B as a function of the thickness of a wet soil layer over a dry soil. This particular model requires the specification of a layer structure (0.05-cm layers to 15 cm and 0.1-cm layers between 15 and 35 cm) and a set of parameters for each layer (dielectric constant and temperature).

A constant temperature of 300 K was used based on field observations. The typical moisture profiles shown in Fig. 7 were approximated by linear segments representing the nearly saturated surface layer, the initial dry profile, and a wetting front transition between the two. The nearly saturated surface layer was defined with a 40% soil moisture at the surface that transitioned linearly to 35% (nominally, the field capacity) at the top of the wetting front. The wetting front was defined by a linear function between 35% at the top and 6% (the measured initial soil moisture). The dielectric constants were calculated using [20] based on the soil texture and density and an assumed salinity of 2 ppt for the soil water, which is reasonable for irrigated soils. A minimal value of 0.1 was assumed for the roughness parameter h to account for the effects of surface roughness on the emission [21]. The results of the calculation are presented in Fig. 9 for the two wavelengths for a wetting front width of 1.5 cm.

The oscillatory behavior in Fig. 9 is similar to that in the observations. The distance between adjacent minima is
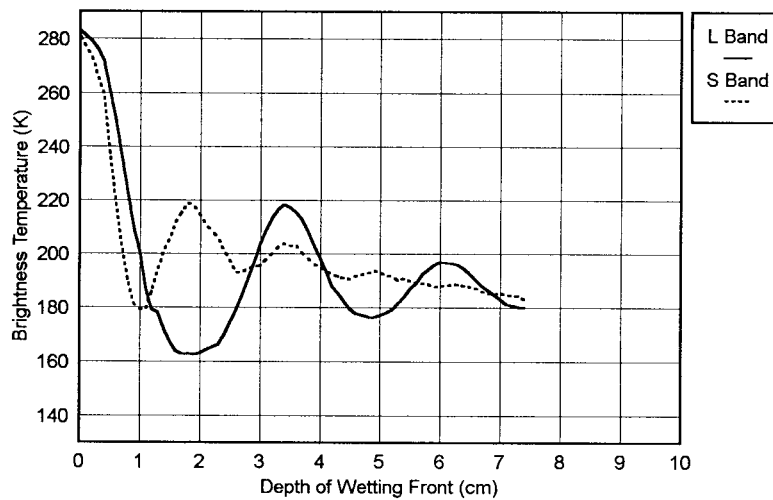
Fig. 8. Observed T_B versus the predicted wetting front depth for the June 12, 1995, experiments.
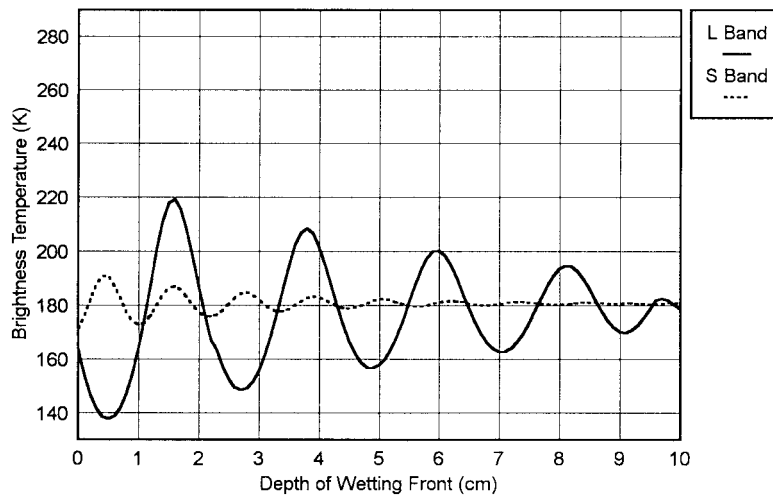

Fig. 9. Modeled values of T_B at 21 and 11 cm for the case of wetting front thickness of 1.5 cm and salinity of 2 ppt.

about 1.2 cm at S-band and about 2.2 cm at L-band, which can be compared with Fig. 8. The amplitude of the L-band oscillations is greater in the calculations (83 K) than in the observations (56 K). At S-band, the observed and calculated amplitudes are comparable, except for the first cycle. 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 thickness of the wetting front over the footprint. The fact that the period of the oscillations observed matches with the model supports the assumption that the coherent model is an adequate representation.

The sensitivity of the T_B to the soil salinity and the thickness of the wetting front between 1 and 2 cm was studied. Varying the salinity had minimal effect on the results, i.e., 10-K variation at L-band and about half that at S-band. This is because the conductivity losses due to salinity decrease with frequency. The thickness of the wetting front had a much stronger effect on the results, about 34 K at L-band and 43 K at S-band. Here the higher frequency, shorter wavelength is

more strongly affected because the transition layer is a larger fraction of the wavelength. These results imply that a transition thickness of 1.5 cm is appropriate for this case; the calculated T_B at L-band is greater than that observed, while it is less for S-band. The post irrigation T_B values for both channels are in agreement with the observations, 190–195 K.

V. SUMMARY

Experiments were conducted using truck-based microwave radiometers to observe small plots during and following sprinkler irrigation. Data were collected using microwave radiometers operating at 1.41- (L-band) and 2.65-GHz (S-band) horizontal polarization mounted on a boom-type truck over loamy sand soil in 1994 and a silt loam in 1995. For the sandy loam soils with infiltration capabilities exceeding the water application rate, the observed T_B quickly reached a nominally constant value during irrigation. When the irrigation was stopped, the T_B began to increase as drainage took place. Contributing depth-related differences were observed for L- and

S-band as expected. The irrigation rates in 1995 with the silt loam soil exceeded the saturated conductivity of the soil. During irrigation, the T_B values exhibited a phenomenon that had not been previously observed and identified. The temporal variation in T_B exhibited the pattern that is associated with coherent reflection. The L- and S-bands exhibited similar patterns but were not identical due to contributing depth. These results suggested the existence of a sharp dielectric boundary (wet over dry soil) that was increasing in depth with time.

The observation of the coherent reflectivity oscillation is quite unique. The fact that the observations match with the theory should be expected in principle, but it is still remarkable considering the variability in many aspects of the physical target. Since these match so well, it may be possible to infer information on the near-surface infiltration properties of the soil profile directly from the T_B observations and the coherent model.

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