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Measuring the Layer–Average Volumetric Water Content in the Uppermost 5 cm of Soil Using Printed Circuit Board TDR Probes

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Newly designed printed circuit board TDR probes (PCBP) were made, and they were calibrated by indoor experiment. A regression equation for estimating the volumetric water content from the dielectric constant measured with the PCBP was determined, which is almost the same as the well-known Topp's equation when the soil is rather wet while the difference becomes larger as the soil dries. The PCBP was designed to measure the average water content over a soil layer 5 cm thick because the thickness of soil layer involved in measuring water content by microwave remote sensing is several centimeters. A comparison experiment of measurements with PCBP and those by microwave remote sensing was conducted in an arid area in the northwest of China. The results of this experiment show that the newly designed TDR probe is promising as the sensor to get ground truth of the surface wetness. This paper describes only the calibration of probes and the observations taken using them.

INTRODUCTION

To know the water content in the uppermost few centimeters of soil is of great importance in understanding the land–atmosphere interaction in many hydrological and meteorological processes. There are two promising techniques for measuring the water content based on the large dielectric contrast between water and soils, microwave remote sensing and time domain reflectometry (TDR). The large value of the apparent relative dielectric permittivity, or the dielectric constant (K_a) for water results from the fact that it is a polar molecule and thus K_a is a function of the frequency of applied electromagnetic field, temperature and salinity (Jackson et al., 1986). However, since the real part of K_a decreases rapidly with decreasing wavelength in the range of 1 to 10 cm, the range of wavelength longer than about 20 cm should be used.

The microwave remote sensing uses the relation between the reflectance and/or the emittance and the dielectric constant, while the TDR uses the relation between the propagation velocity of an electromagnetic wave and the dielectric constant. Although the goal of the present study is to compare the two techniques, this paper describes only the results of the calibration of newly designed printed circuit board probe (PCBP) and of

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field experiments to measure the layer-average soil water content of the top 5 cm with them. This is because a soil layer involved in the measurement of the dielectric constant by microwave technique is approximately a few tenths of a wavelength thick (Jackson et al., 1986); that is, if the wave length is 21 cm, the thickness is 4~6 cm.

PRINTED CIRCUIT BOARD PROBE (PCBP)

Topp et al. (1980) measured the dielectric constant of soils placed in a container of 5 cm inside diameter, which is, however, unsuitable for most field soils. Therefore, parallel-wire (two-wire) transmission line probes, or three- and four-wire probes have been invented for field use (Zegelin et al., 1989). However, a lower limit of the TDR probe length exists, which depends on the rise time of the reflected square wave (Nissen et al., 1999). The rise time of the Tektronix 1502C cable tester, which was used in the present experiment, is shorter than 200 ps. Thus, the length of the probe should be longer than 10 cm and it seems impossible to measure the layer-average wetness of the uppermost few centimeters of soil directly with a TDR sensor.

Selker et al. (1993) invented a noninvasive TDR probe (NIP) to measure the surface wetness of hard materials, which consisted of a pair of parallel wires configured in a serpentine pattern and backed by an acrylic plastic. In their case, the 1.59 m brass wave guides were attached to an about 10×10 cm acrylic pad with epoxy such that one-half of the bare wire is above the pad surface. Nissen et al. (1999) used a thin sheet of circuit laminate, 1×5 cm area, with a copper cladding on both sides. A serpentine three-wire wave guides was produced by printing the serpentine onto the metal cladding and etching away the metal outside the serpentine in an acid bath. The wave guides on each side of the circuit laminate were interconnected, resulting in a total wave-guide length of approximately 12.7 cm. This type of TDR probe is called a printed circuit board probe, or PCBP.

In this study, a newly designed PCBP, which was made of a 1.5×6 cm paper-phenol resin of about 0.13 cm thickness with a copper cladding on one side, was used. Serpentine two-wire wave guides, 15.8 cm long, were produced by printing two parallel rods 0.7 mm in width at a 2.3 mm spacing onto the copper cladding and by etching away the metal outside of them. The probe design is shown in Fig. 1. The dielectric constant of the paper-phenol laminate is 4.6~5.5 for frequencies in the MHz region (Tokyo Astronomical Observatory, 1979), while those of dry soils and sands are about 3 and 2.5, respectively (Tokyo Astronomical Observatory, 1996). Therefore, the dielectric constant obtained with this probe ($K_{a,PCBP}$) seems to be a weighted mean of the laminate ($K_{a,L}$) and

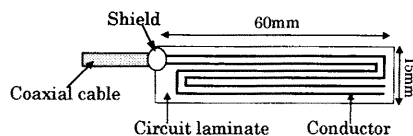


Fig. 1. Serpentine layout of newly designed wave guides.

the medium of interest ($K_{a,m}$) (Nissen et al., 1999).

$$(K_{a,PCBP})^n = w_L (K_{a,L})^n + (1-w_L)(K_{a,m})^n \quad (1)$$

where w_L and $1-w_L$ are weighing factors which describe the fractional contribution of the laminate and the medium of interest, respectively. The exponent n summarizes the geometry of the medium with relation to the applied electromagnetic field and takes a value between 1 and -1. According to Nissen et al. (1999), the values of w_L and n are expected to be close to 0.5 and 1, respectively.

CALIBRATION

Indoor experiment

An indoor experiment was conducted to calibrate the newly designed PCBP. The Tottori-Dune sand, the physical properties of which are shown in Table 1, was packed into containers. The container was made of two 5-cm-long acrylic resin tubes of 10 cm inside diameter, which were joined end to end with adhesive, waterproof tape to be a cylinder 10 cm long. The bottom of the cylinder was made of wire netting, which was covered with a filter paper of 10 cm diameter before the air-dried sand was packed into it.

Nineteen containers were constructed and two PCBP were embedded vertically in the uppermost 5 cm of sand in each sample container, and water was poured on the surface until drainage from the bottom occurred. Once in a few days, measurements of the dielectric constant were made with Tektronix 1502C cable tester for 3~5 sample containers. The average of the two measurements was taken to be $K_{a,PCBP}$ (hereafter designated as K_a unless otherwise mentioned) of each container. After that, a soil-sampling pipe of 5 cm long and 100 cm³ in volume was inserted from the surface and a soil specimen was sampled from each sample container and used to measure the gravimetric water content and the bulk density.

Field experiment

An experiment to calibrate the PCBP was conducted also on a field of the White Pagoda Hill Park in Lanzhou, China, during the period 11 to 21 June in 2000. The physical properties of the soil are shown in Table 1. Six spots were fixed in the field and two PCBP were stuck vertically into a bare-soil surface at each spot on 11 June, when a fair amount of water was sprinkled over the spot to guarantee the good contact of the

Table 1. Physical properties of sample soils.

Particle size	Tottori-Dune sand	Lanzhou field soil
	by weight	by weight
>2 mm	0%	11.1%
2.0~0.42 mm	14.9%	19.9%
0.42~0.075 mm	80.9%	18.9%
0.075~0.005 mm	1.3%	} 50.2%
0.005>	2.9%	
Bulk density	1.50 gcm ⁻³	0.971 gcm ⁻³
Porosity	0.434	0.634

PCBPs with the soil.

Measurements of the dielectric constant and water content were made at about 1430 BST during 10 days from 12 to 21 June. The equipment and technique used in this experiment were the same as those used in the indoor experiment.

Results and discussion

Figure 2 shows the relationship between the dielectric constant (K_a) and volumetric water content (θ_v) for the Tottori Dune sand. The solid line describes the third-order polynomial regression equation that is fit to the indoor experiment data.

$$K_a = 3.62 + 27.5 \theta_v - 108.0 \theta_v^2 + 639.0 \theta_v^3 \quad (2)$$

The dashed line shows the relationship obtained by Topp et al. (1980) using the coaxial transmission line soil column, which is written

$$K_a = 3.03 + 9.3 \theta_v + 146.0 \theta_v^2 - 76.7 \theta_v^3 \quad (3)$$

As the water content decreases, the value of K_a measured with the PCBP at a particular water content becomes larger than that estimated using Eq.(3) at the same water content. This is because the measured value is, in reality, $K_{a,PCBP}$ that is a weighted mean of $K_{a,L}$ ($=4.6 \sim 5.5$) and the real dielectric constant (see Eq.(1)). If the sand is dry ($\theta_v=0$), K_a is 3.62 from Eq.(2), which is approximately equal to an arithmetic mean of $K_{a,L}$ and K_a of sands (≤ 2.5).

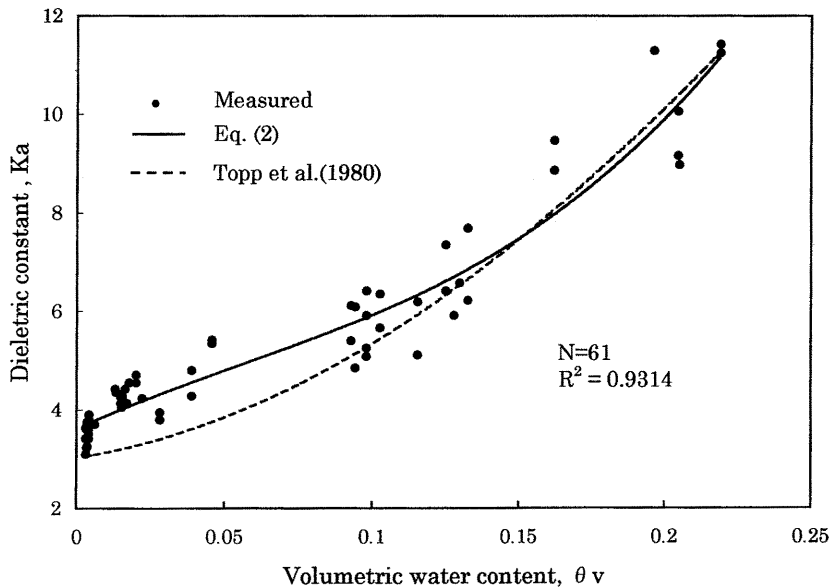


Fig. 2. Relationship between K_a and θ_v for the Tottori-Dune sand. The relationship obtained by Topp et al. (1980) is also shown for reference.

When we want to estimate θ_v of a soil from the measurement of K_a , we need the regression line of θ_v on K_a .

$$\theta_v = 0.13 + 3.15 \times 10^{-2} K_a + 2.47 \times 10^{-3} K_a^2 - 2.3 \times 10^{-4} K_a^3 \quad (4)$$

This is based on the same data as Eq. (2), and is drawn by a solid curve in Fig. 3. The inverse function of Eq. (3)

$$\theta_v = -0.25 + 1.11 \times K_a - 1.10 \times 10^{-2} K_a^2 + 4.2 \times 10^{-4} K_a^3 \quad (5)$$

is shown by a dotted curve. This is different from the well-known regression equation given by Topp et al. (1980),

$$\theta_v = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} K_a - 5.5 \times 10^{-4} K_a^2 + 4.3 \times 10^{-6} K_a^3 \quad (6)$$

which is also shown in Fig. 3 by a dashed curve.

Since two equations (5) and (6) are the regression equations obtained based on the same data (Topp et al., 1980), the volumetric water content calculated from them are almost the same except for very dry soils. On the other hand, although the water contents calculated using the present equation (4) are almost the same as those obtained from the Topp's equations when K_a is larger than about 6, the water content at a particular value of K_a less than 6 is much smaller than those calculated from the Topp's equations. These results support the expectation that the dielectric constant obtained with PCBP ($K_{a,PCBP}$) would be a weighted mean of the circuit laminate ($K_{a,L}$) and the

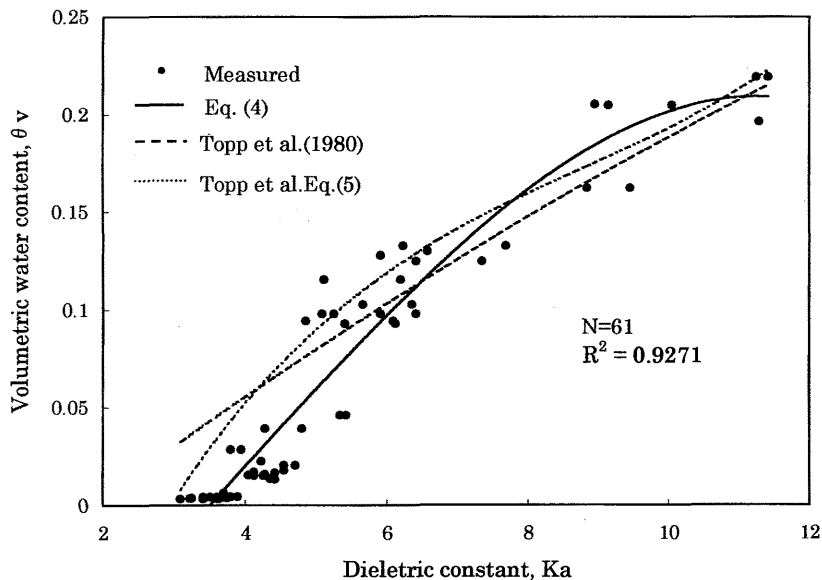


Fig. 3. Regression line of θ_v on K_a for the Tottori-Dune sand. The relationships obtained by Topp et al. (1980) are also shown for reference.

medium of interest ($K_{a,m}$) as mentioned in the previous section.

Figures 4 and 5 show the relationships between K_a and θ_v obtained by the field experiment in Lanzhou. The scatter in those relationships seems mainly due to spatial variations in soil density and soil moisture within measurement spots. Since field soils are smaller in particle size and hence larger in specific surface area than sands (Table 1), the degree of freedom of water molecules absorbed in field soils at a particular water content seems to be smaller than in sands at the same water content. Therefore, especially in dry conditions, the value of K_a for fine soils seems to be smaller than sands if water content is the same.

The regression line of K_a on θ_v was obtained by fitting a two-order polynomial to the data, because the application of higher order polynomials does not seem reasonable in this case due to the lack of statistical significance.

$$K_a = 4.27 - 13.1 \theta_v + 183.9 \theta_v^2 \quad (7)$$

The regression line of θ_v on K_a is given by

$$\theta_v = -0.036 + 3.9 \times 10^{-2} K_a - 1.7 \times 10^{-3} K_a^2 \quad (8)$$

This is drawn by a solid curve in Fig. 5. The inverse function of Eq. (7) can be written

$$\theta_v = -0.191 + 8.0 \times 10^{-2} K_a - 4.2 \times 10^{-3} K_a^2 \quad (9)$$

and also shown by a dotted curve in Fig. 5. When we estimate the water content from the dielectric constant, Eq. (9) seems to be preferred to Eq. (8) because the dotted curve is

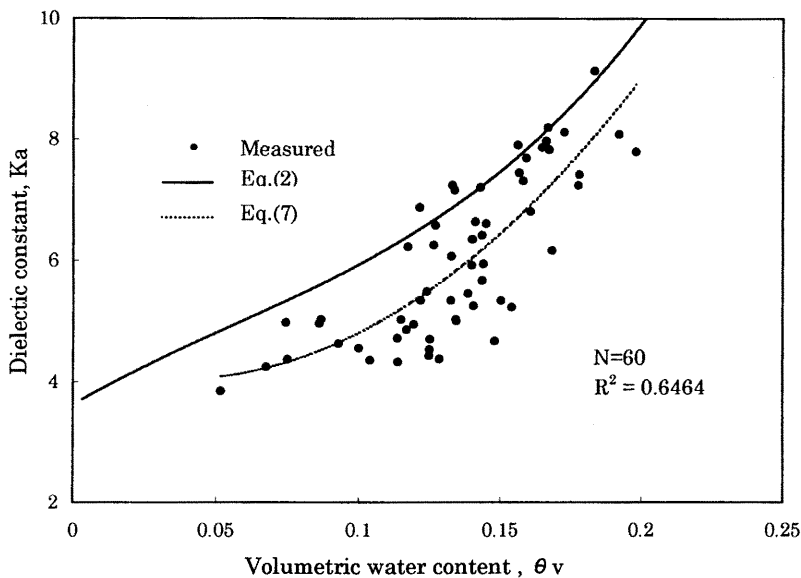


Fig. 4. Relationship between K_a and θ_v for a field soil in Lanzhou, China. The relationship for the Tottori-Dune sand is also shown for reference.

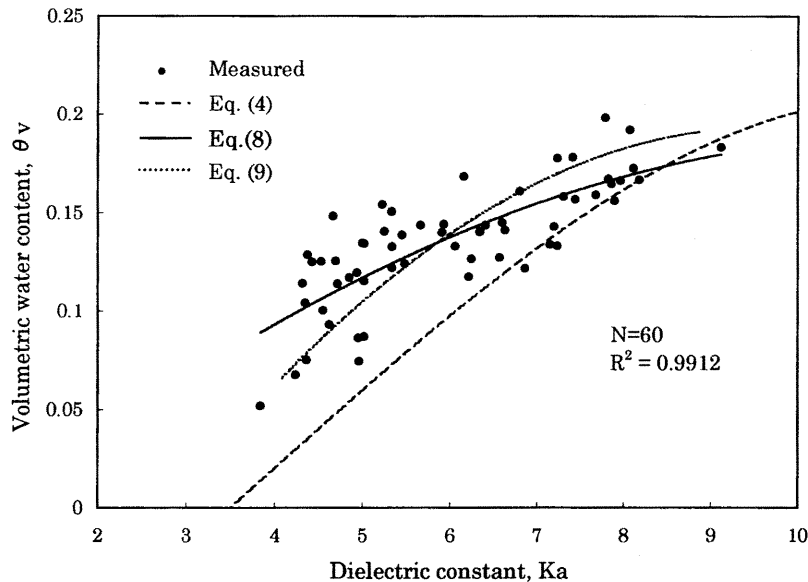


Fig. 5 Regression line of θ_v on K_a for the field soil in Lanzhou (solid). See text for the explanation of the dotted and dashed curves.

almost parallel to the dashed curve that describes the relationship obtained by indoor experiment for the Tottori–Dune sand (Eq. (4)). The adequacy of using this regression equation for the estimation of soil water content, of course, should be tested against further experimental evidence.

OBSERVATION

Site and method

In arid regions the land surface is mainly covered with bare–soil surfaces, and spatial variation in the surface wetness under dry conditions is smaller compared to wet conditions. Therefore, we selected Dunhuang in the northwest of China as an experimental area to conduct a comparison test of the two techniques for measuring the surface wetness, microwave remote sensing and TDR. Since the annual precipitation is only several tens millimeters in and around Dunhuang, soil water content in the upper layers except for the period immediately after rainfall events is inevitably very small.

Three stations (Sand dune, Gobi, Field) were selected to make measurements of water content and temperature in the uppermost soil layers (Table 2). In each station two or three spots were fixed and two PCBP and a semiconductor thermometer (HIOKI 3650) were installed at each spot. The thermometer consists of a small button-shaped sensor (1.7 cm in diameter and 0.6 cm thick) with a built-in recording instrument, and a

Table 2. Outlines of observation sites.

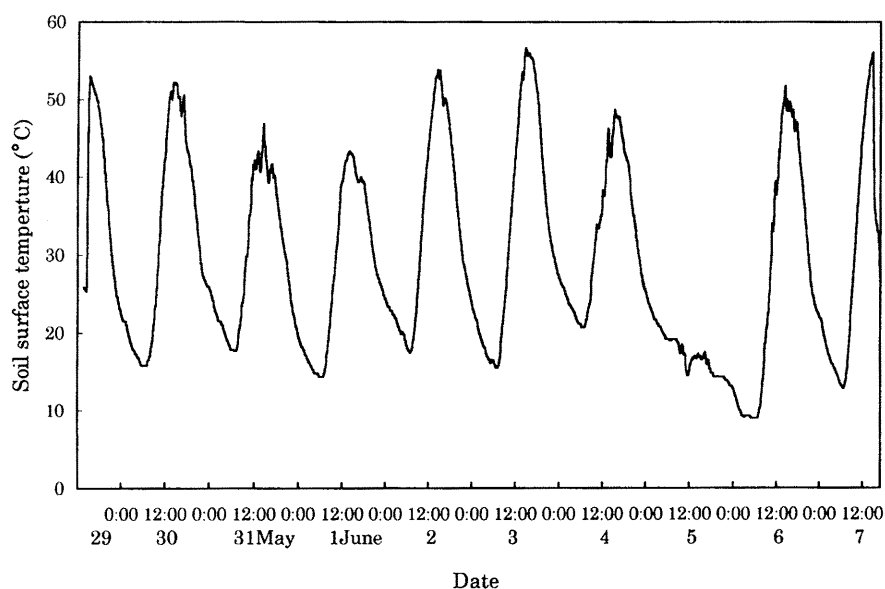
Station	Distance and direction	Surface conditions	Bulk density	Remarks
Sand dune	7 km south of Dunhuang*	on a small and flat sand dune	1.67 gcm ⁻³	
Gobi	15 km west of Dunhuang	in an extensive Gobi desert	1.50 gcm ⁻³	Gobi station of Dunhuang Project
Field	3 km east of Dunhuang	on an unvegetated observation field	1.21 gcm ⁻³	Dunhuang Meteorological Observatory

* Dunhuang is located in lat. 40° 10' and long. 92° 48'E, the mean level being approximately 1100 meters above sea level.

data reader. The sensor was embedded horizontally so that its top surface almost coincided with the soil surface and was covered with a thin layer of sand particles. PCBP's were set under the ground on 27 May in 2000 in the same manner as in the calibration experiment in Lanzhou, though water was not sprinkled over the surface. Gravimetric soil water content was measured with the soil-sampling pipe in the same way as in the indoor experiment. Measurements were made in the mid-afternoon during the period 28 May to 7 June in 2000.

Results and discussion

Figure 6 shows the time variation in the average soil surface temperature of the three spots in the Sand dune station for the observation period, which gives an outline of the weather during the period. In sunny afternoon soil surface temperature increased above

**Fig. 6.** Time variation in the average soil surface temperature at the Sand dune station.

55 °C, while on 5 June when a storm came up soil surface temperature kept decreasing and reached below 10 °C before sunrise in the next morning.

The surface water content measured gravimetrically was almost zero when soil surface temperature was higher than about 50 °C. Kobayashi et al. (2000) showed that the wetness of the superficial layer of soil under dry conditions could be estimated from its temperature in the mid-afternoon. Taking their results into consideration, it seems realistic to regard the surface water content as zero when the soil surface temperature is higher than 50 °C. This conclusion may be useful when we would try to estimate the evaporation from deserts by remote sensing (Kobayashi et al., 2000).

Figure 7 shows the results obtained at the three stations in and around Dunhuang during the period 28 May to 7 June in 2000. The mean value of the dielectric constants measured with PCBP at each station was substituted into Eq. (4) to estimate the volumetric water content, which is denoted by the solid circle in the figure. The diamond in the bottom panel expresses the estimate made by using Eq. (9). The open circle

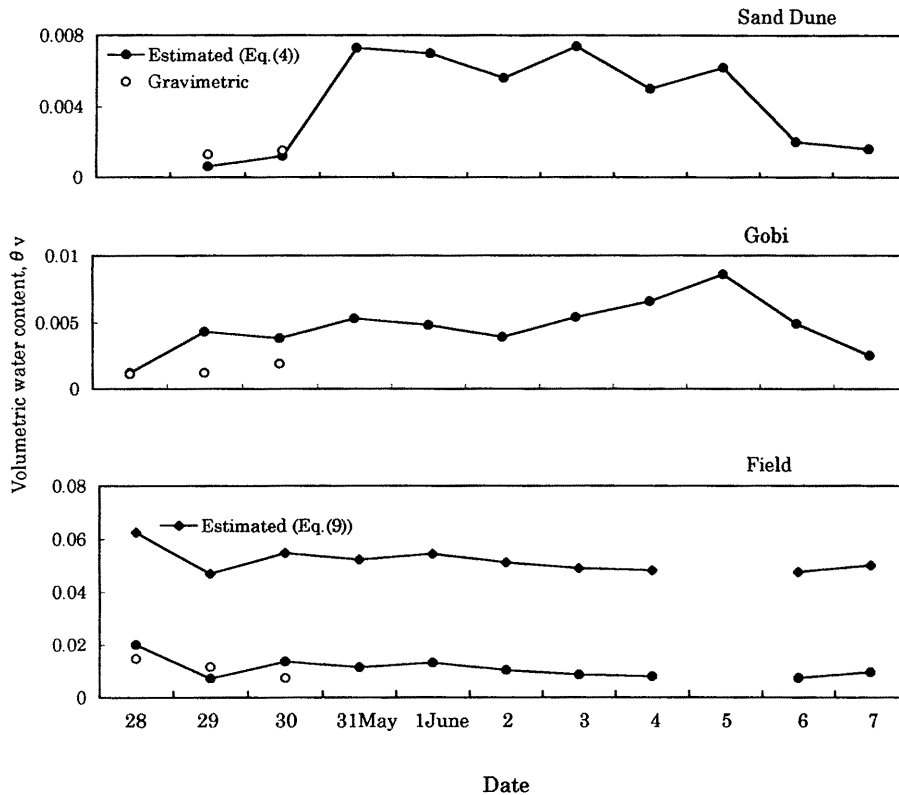


Fig. 7. Time variation in the layer-average volumetric water content in the top 5 cm of soil at the three stations in and around Dunhuang. The open circles denote the gravimetric values.

represents the average gravimetric water content of two or three measurements made in each station.

The upper part of Fig. 7 shows the time variation in the layer-average volumetric water content in the uppermost 5 cm of soil at the Sand dune station. The top layer was exceedingly dry (the thickness of the dry surface layer was about 55 cm) and the wetness in the layer was almost unchanged during the ten-day observation period. A comparison of those estimates with the gravimetric water contents indicates a good agreement, though the size of data is too small to draw a final conclusion. The middle part is the same as the upper part except for at the Gobi station. On the stormy day (5 June), although the surface was moderately wetted, the layer-average water content increased only a little. It can be said that the agreement between the estimates and the gravimetric measurements is fairly good.

Two kinds of estimates for the Field station are shown in the lower part of Fig. 7, one is made by Eq. (4) (solid circles) and the other is by Eq. (9) (diamonds). Their comparison with the gravimetric water contents shows that Eq. (9) is not suitable for use at this station, though the soil type at this station looked similar to that in the field of the White Pagoda Hill Park, where the calibration experiment was conducted. This seems to mean that the difference in specific surface area between the two soils is large, because the larger the specific surface area is, the larger the water content at a particular dielectric constant. However, the estimates made by Eq. (4) were in fairly close agreement with the gravimetric measurements as the other two soils.

CONCLUDING REMARKS

If we want to make measurements of the surface wetness by remote sensing, we must begin with verifying the information extracted from remote sensing data, and hence reference data or ground truth must be taken. Since spatial variation in soil water content over a bare-soil surface becomes larger as the wetness increases, reference data could be taken much easily under dry conditions. However, since microwave remote sensing of water features depends on the large dielectric constant for water, it may be said that dry conditions are not suitable for getting ground truth of the surface wetness, because, as the soil dries, not only the amount of water but also the degree of freedom of water molecules become smaller and the microwave information will be contaminated by the dielectric properties of soils. In spite of these demerits, spatial uniformity is very attractive. Therefore, we tried to measure the surface wetness using PCBP's under dry conditions.

The results obtained in this study are summarized as follows:

- (a) Newly designed PCBP was shown to be promising for measuring the volumetric water content of soil not only in wet conditions, where the regression curve was almost the same as the well-known Topp's equation, but also in dry conditions if the regression curve obtained in the present experiment (Eq. (4)) was used.
- (b) Layer-average volumetric soil water content in the top 5 cm of the profile in an arid area (in and around Dunhuang in the northwest of China) was estimated using PCBP's with a satisfactory degree of accuracy.
- (c) Layer-average water content in the top 5 cm of soil in this arid area hardly changed

during the 10-day observation period, which means that estimates of the surface wetness made by microwave remote sensing at a time could be compared with the reference data obtained within ten days of the time.

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