Diurnal measurement of near-surface water content using Ground Penetrating Radar (GPR) - Implications for large scale hydrological studies using radar measurements

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Abstract—*Ground-penetrating radar (GPR) was utilized to measure near surface diurnal soil reflectivity and dielectric properties to determine change in soil water content. Measurements were performed over both bare and vegetated surfaces. From these measurements, soil volumetric water contents were determined via surface reflectivity and in one instance from propagation time. Soil water content was ground truthed gravimetrically.*

Measurements show that water content changes at the surface follow patterns reported by Jackson (1973), albeit that changes in the soil profile as measured from propagation time data may follow a different pattern.

Diurnal variations in soil reflectivity do not show evidence for increases in bulk soil dielectric permittivity due to thermodielectric bound water desorption effects as air and soil temperatures appear to have been too low to induce desorption of bound water layers.

Results here suggest that continuous monitoring of soil dielectric properties and water content would improve the accuracy of large-scale SAR and scatterometer measurements. Furthermore, such data should be used to correct for differences between soil water content at the time of gravimetric sampling and the time of radar measurement.

Introduction

The near-surface soil water content is an important forcing factor, of which spatial variations can have major impacts on both short- and long-term climactic modeling (Dubois et al., 1995). Furthermore, soil water content is important for agricultural and flood prediction applications. Remote and in-situ microwave methods have been shown to effectively estimate near surface water content, due to the dependency of soil bulk dielectric properties (ε_b) upon water content (Topp et al., 1980; Ulaby et al., 1996). Research by Or and Wraith (1999) utilizing time domain reflectometry (TDR) showed that soil ε_b is also dependent on temperature, with low surface area soils such as sands displaying a decrease in ε_b while high surface area soils such as clays show increases in ε_b when temperature increased but soil water content remained constant. Serbin et al. (2001) then showed that these thermodielectric effects could propagate into radar backscatter and bias remotely measured water content inferences. These workers have shown that such thermodielectric effects could be used to map differing soil texture units based upon the measured diurnal dielectric response of the soil to temperature.

While space- and airborne systems have exhaustive spatial mapping capabilities, they lack the temporal resolution necessary to measure diurnal changes in soil reflectivity (a function of ε_b). Ground-penetrating radar (GPR) utilizing horn antennas offers not only the option of continuous temporal resolution but also a well defined and directional ground footprint, and the ability to sense below the ground surface. Such measurements may be used to describe on the small-scale thermodielectric soil properties that affect large-scale synthetic aperture radar (SAR) measurements and may also be ground truthed in-situ with TDR, temperature and gravimetric water content methods.

The objectives of this study were (a) to evaluate the use of a GPR unit with a directional horn antenna for measurement of soil water content, (b) to see if changes in near-surface soil temperature induced thermodielectric bound water desorption effects on soil bulk dielectric constant and (c) to evaluate the effects of a low, dense vegetation on surface soil reflectivity.

Theoretical considerations

Soil dielectric properties

The dielectric properties of soils in the microwave region are functions of frequency (Debye, 1929; Hasted, 1973), mineralogy (von Hippel, 1954), particle size, shape and orientation to the imposed EM field (Jones and Friedman, 1999) surface area, bulk density, temperature, salt content, and volumetric water content (Or and Wraith, 1999). The dielectric constants of soil solid and gaseous phases are assumed to be constant with respect to frequency for the entire microwave region dealt with in this work.

In most soils the one factor that varies the most is that of water content, with the dielectric constant of most soils increasing with increase in water content due to the large difference between the dielectric constant of free water ε_r=78~81 and that of soil solids ε_r=3~8. The soil water may be decomposed into free and bound water, where bound water refers to the first two molecular water layers to bound solid surfaces that are rotationally hindered by surface forces (Bockris et al, 1966). Bound water typically has dielectric a dielectric constant around 6 and 20~40 for the first and second molecular layers, respectively, and is temperature dependent (Bockris et al., 1966; Dobson et al., 1985; Or and Wraith, 1999; Serbin, 2001; Jones and Or, 2002).

Topp et al. (1980) derived a commonly used empirical equation relating bulk soil dielectric constant ε_b to volumetric water content θ_v:

$$\Theta_v = -0.053 + 0.0292\varepsilon_b - 5.5\cdot10^{-4}\varepsilon_b^2 + 4.3\cdot10^{-6}\varepsilon_b^3 \quad [m^3/m^3] \qquad (1)$$

Reflections of electromagnetic radiation at dielectric boundaries

Incident EM waves will reflect at the boundary between two media with differing dielectric and/or magnetic materials. The magnitude of this reflection and subsequent transmission of the wave into the second medium is dependent upon the intrinsic impedances of the two media (Ulaby, 1999). As most soil and plant components are nonmagnetic, the reflection coefficient Γ for normal incidence at a dielectric/ magnetic interface may be expressed as (Ulaby, 1999):

$$\Gamma_0 = \frac{E^r_{0,n}}{E^i_{0,n}} = \frac{\sqrt{\varepsilon_n} - \sqrt{\varepsilon_{n+1}}}{\sqrt{\varepsilon_n} + \sqrt{\varepsilon_{n+1}}} \qquad (2)$$

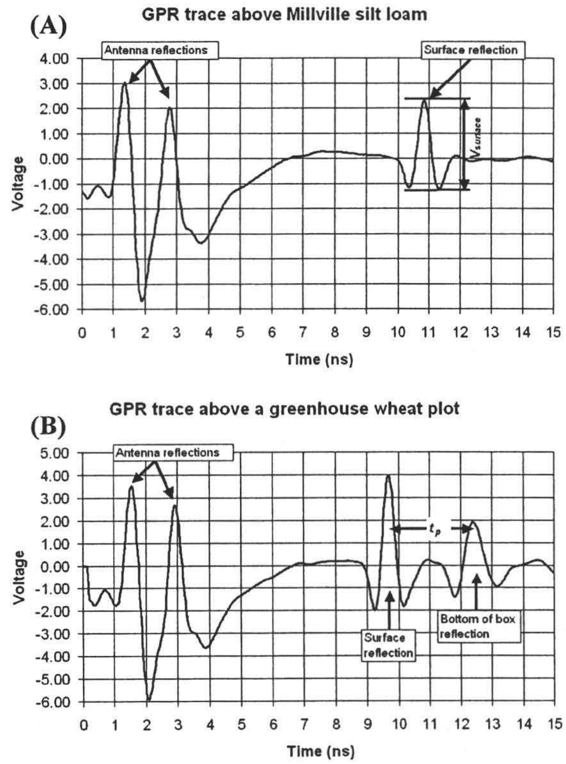
where $E^i_{0,n}$ and $E^r_{0,n}$ denote the incident and reflected electric field amplitudes, respectively, *0* denotes normal incidence, ε denotes the relative dielectric permittivity and *n* is an integer denoting the medium.

Acquisition of soil dielectric properties via GPR

GPR units provide time domain reflectivity measurements that are analogous to that of commonly used in-situ time domain reflectometry (TDR) techniques, albeit that GPR measures reflections that were transmitted from an antenna and TDR measures reflections along a transmission line. However, unlike TDR, both the surface reflectivity and the propagation time between reflections can be used to determine soil dielectric properties.

Two GPR waveforms may be viewed in Figures 1A-B, the first (Figure 1A) from a flat soil surface in a field and the second from a soil layer terminated by a flat layer of aluminum foil (Figure 1B). In both Figures the antenna reflection pattern is also visible.

Figures 1A-B. Acquired GPR waveforms from A. Millville silt loam. B. Measurements over USU-Perigee dwarf wheat.



Dielectric properties via surface reflectivity

Surface reflectivity properties can be used to determine the surface dielectric properties via determination of the time domain reflection coefficient.

From these measurements the time domain reflection coefficient of the surface $\Gamma(t)$ is related to Equation (2) via the ratio of the surface reflection voltage to that of a flat metal plate (which approximates a perfectly conducting surface):

$$\Gamma(t) = -\frac{V_{surface}}{V_{fmp}} = \frac{\dfrac{E^r_{0,surface}}{E^i_0}}{\dfrac{E^r_{0,fmp}}{E^i_0}} = \frac{E^r_{0,surface}}{E^r_{0,fmp}} \qquad (3)$$

where V denotes the magnitudes of the surface reflections in volts and the *surface* and *fmp* subscripts denote surface and flat metal plate values for E and V for the surface and flat metal plate, respectively. Furthermore, $V_{surface} < V_{fmp}$ and the normal incidence reflection coefficient of metal (or any perfectly conducting medium) equals -1. It should be noted that $V_{surface}$ and V_{fmp} may measured by the heights in Figures 1A-B. From this the apparent bulk dielectric constant of the soil surface ε_b may then determined via (Ulaby, 1999):

$$\varepsilon_b = \left(-\frac{\Gamma(t)-1}{\Gamma(t)+1} \right)^2 . \qquad \textbf{(4)}$$

From this the volumetric water content as a function of ε_b may then be determined via the Topp et al. (1980) equation.

Dielectric properties via propagation time

When the depth to a subsurface feature is known, the propagation time may be used to calculate soil dielectric properties, via:

$$\varepsilon_b = \left(\frac{c}{v_p} \right)^2 = \left(\frac{ct_p}{2L} \right)^2 \qquad \textbf{(5)}$$

where

$$v_p = \frac{2L}{t_p} \qquad \text{[m/s]} \qquad \textbf{(6)}$$

where c is the speed of light in a vacuum, v_p and t_p are the propagation velocity and the propagation time along the length of the TDR probe, respectively and L is the thickness of the medium. t_p may be measured via the time difference between the maxima of the surface and bottom of the box reflections as seen in Figure 1B.

Diurnal changes in near surface soil water content and temperature

In diurnal cycles soils heat up and cool down due to the existence or lack of solar radiation during the day and nighttime, as well as additional micrometeorological factors such as wind speed, vegetation cover and ambient air temperature (Hillel, 1998; Or and Wraith, 2000). Within the soil depth the temperature regime is a function of the soil type, water content and organic matter content.

Surface temperature minima and maxima occur before dusk and at about 2:00 PM due to solar radiation patterns. As depth in the soil increases, these minima and maxima show a time lag and decreasing amplitude from the mean soil temperature until constant temperature below a certain depth is reached.

Or and Wraith (1999), Serbin et al. (2001) and Serbin (2001) showed that the dielectric properties of soils can show a strong dependence on soil temperature, particularly at lower water contents. Thus, variations in soil temperature in the profile can cause changes in dielectric properties even if all other conditions throughout the profile (such as water content, texture, bulk density, etc.) are identical.

These soil temperature changes then induce water vapor transport in the soil profile. During the day water vapor is transported either downwards or evaporates to the air above. At night vapor condenses at the surface from dew and from transport for depths in the soil profile (Jackson, 1973).

Materials and methods

Ground penetrating radar setup, data acquisition and ground truthing

Field studies

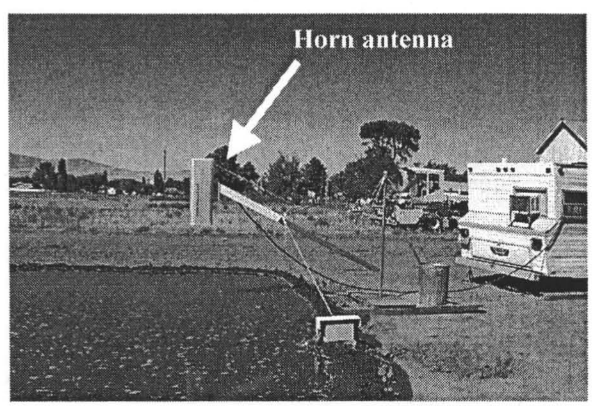
Remote measurements of the soil surface utilized a Penetradar IRIS GPR unit and a 30 AGC horn antenna (Penetradar Corp., Niagara Falls, NY) that operates at a center frequency of 1.025 GHz. The antenna was pointed normal to the ground surface. The GPR unit was housed in a 14-foot trailer or a tent. 110 VAC was supplied extension cord from a nearby building, and all power to the GPR unit was regulated via UPS. The antenna was mounted on a custom manufactured mast structure and connected to the GPR unit via a 25 foot cable (Figure 2). Except for the free-space calibration, all measurements were taken with the antenna pointing downwards.

Measurements were collected every 10 minutes with each measurement consisting of 30 waveforms.

Greenville Farm, North Logan, UT measurements

The first set of measurements with the GPR unit was conducted at Utah State University's Greenville Farm located in North Logan, UT. The soil type is Millville Silt Loam with a specific surface area of 73 m^2/g (Or and Wraith, 1999). Prior to measurement, an artificial pond with earthen barriers was constructed. Thermocouples were installed for soil temperature measurement but all data were lost due to a data logger error. Soil water content was ground

Figure 2: The 30 AGC GPR antenna mounted on the supporting structure above the ponded surface and the trailer housing the control unit.



truthed daily using gravimetric methods. Addition air temperature data were provided by the USU Climate Center.

The soil surface was ponded with water for 24 hours after which the earthen barriers were broken and the pond was drained. The ponding of the surface served to generate theoretically uniform water contents in the soil profile and to slake the surface, reducing surface roughness.

The antenna was oriented such that the electric field was pointed toward azimuth 169° (uncorrected) as measured via compass, with an incidence angle of $\theta = 2.5 \sim 3°$ toward the north and a height from the base of the antenna of about 105 cm above the soil surface. The soil surface directly beneath the antenna appeared to be flat and level, though inadequate instrumentation was available for measurement of this.

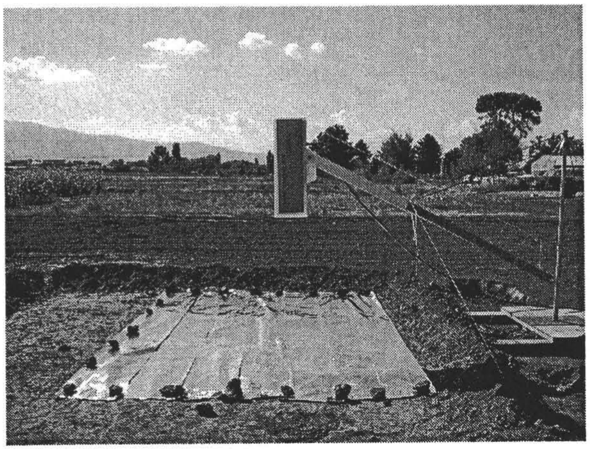
Measurements were collected starting at 16:40 on 7 September 2001 and ending at 15:40 at 17 September 2001. Free space and flat metal plate calibrations were collected on the afternoon of 18 September 2001 using aluminum foil instead of a flat metal plate (see Figure 3).

Tucson, AZ measurements

GPR measurements of surface reflectivity were carried out in Tucson, AZ at the University of Arizona West Campus Agricultural Center that bordered the Santa Cruz River. The site consisted of a sandy soil with some clay in it and a slight undulating surface.

Measurements were carried out in a similar manner to that of the measurements at the Greenville Farm, albeit that due to space considerations the antenna was pointed southeast. The base of the antenna was placed about 57 cm above the soil surface.

Figure 3: Flat plate calibration utilizing aluminum foil.



GPR measurements were started at 12:50 on 9 November 2001 until 06:40 on 15 November 2001. Flat plate (using aluminum foil over the soil surface) and free space calibrations were acquired at approximately 7:00 AM on that same day.

Irrigation of the site spanned for 48 hours using porous hose starting at midday 9 November. During this time about half the surface was ponded. After then end of irrigation the hoses were removed and the drying pattern measured.

Antenna incidence angles were also measured and adjusted to normal when necessary due to problems with antenna mast rope stretching.

Ground truthing consisted of gravimetric measurements of soil water content. Soil bulk density was determined by coring a known volume of soil. Soil temperature data at a depth of 1" (2.5 cm) were provided courtesy of Dale Rucker of the Department of Hydrology and Water Resources at the University of Arizona.

Greenhouse studies

The GPR unit was deployed at the Utah State University Research Greenhouse in Logan, UT for the purpose of measurement of soil water drying patters under a wheat canopy. The wheat cultivar planted was USU 3-2-3 (USU Perigee wheat) that was developed at the USU Crop Physiology Lab. This specific cultivar was chosen as it would attain a maximal canopy height of around 25 cm such that the antenna could be placed a meter above the soil surface and still hopefully see a "uniform" canopy.

Wheat was planted in a 1.44 m^2 square planter at a density of 1160 plants/ m^2 in a peat-perlite soilous mixture with a bulk density estimated at about 100 kg/m^3. The planter had a total depth of 14 cm, the bottom of which was terminated with aluminum foil to prevent radiation from penetrating beneath it and also to act as a clear marker of the bottom. Above the aluminum foil a thin layer of gravel was spread to allow for adequate drainage and airflow to the root zone. After planting the soil surface settled to a total thickness (including gravel) of about 12 cm.

Measurements of soil water content beneath the canopy occurred between 15:20 on 6 February 2002 and 15:50 on 14 February 2002. 4 gravimetric samples and TDR with a 15 cm long 3-rod probe were used to ground truth soil water content and dielectric properties. The experiment was ended prior to anthesis and after which the wheat plants were destructively sampled for leaf area index determination.

GPR data processing

Acquired GPR data were either processed in Mathcad or Matlab. These data then had either had hourly measurements extracted from total data sets or had the entire set corrected for time variations in the waveform and averaging of the 30 waveforms collected per measurement. These data were then exported to Microsoft Excel for reflectivity and water content determination, and these data charted.

Results and discussion

Field studies

Greenville Farm, UT

Prior to the draining of the pond reflectivity measurements were conducted over the pond surface. The estimated value of ε_b for water as measured from the pond prior to draining was calculated at 79.4. As will be stated in the next section, it should be noted that the water surface was about 15 cm closer to the antenna than the ground surface, such that this may have biased readings.

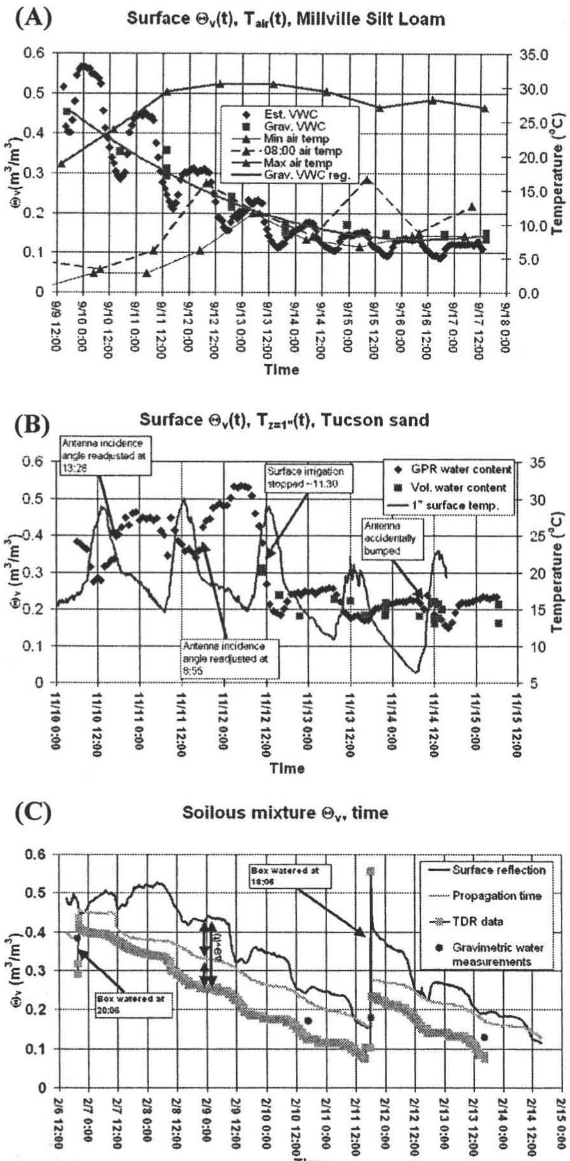
Results from this data set (Figure 4a) show diurnal variations in surface reflectivity that appear to follow the diurnal patterns reported in Jackson (1973). Unfortunately, as the temperature data were lost, we cannot analyze these data fully to see if any thermodielectric bound water release effects occurred. Since no midday water content maxima appear to occur (albeit that it there does appear to be a mid-day slowing in drying processes, which may be indicative of bound water desorption), it can be assumed that either soil temperature or water content conditions were not conducive to thermodielectric bound water release effects.

It should be noted that air temperature maxima during this day period did not exceed 30.6°C and after September 13 air temperature maxima remained below 30°C. A minor precipitation event of ~1 mm was recorded on Sept. 13 but this did not seem to affect measurements. Temperature minima and maxima were assumed to occur at 05:00 and 14:00, respectively. Air temperatures were routinely sampled at 08:00. Air temperature data were provided courtesy of the USU Climate Center.

Tucson, AZ

These measurements also appeared to follow a similar pattern to those reported by Jackson (1973). From Figure 4B it can be shown that soil temperature never made it above 30°C while the soil was drying such that it may not be possible to see soil water bound water desorption effects (Serbin, 2001; Jones and Or, 2002). Surface reflectivity derived water

Figures 4A-C. Diurnal GPR, TDR and gravimetric measurements of volumetric soil water content from A. Millville silt loam. B. Tucson sand. C. Measurements over USU-Perigee dwarf wheat.



contents do appear to be inversely related to the temperature at a depth of 2.5 cm (1") in the soil. However, both reflectivity and gravimetric data show that there was a good deal of spatial variability not only in the irrigated plot as a whole but also specifically underneath the antenna. Events such as simple antenna angle adjustments (due to stretching of antenna support ropes) or movements by wind or people tripping over antenna guy wires resulted in changes in measured surface reflectivity and thus water contents. In some cases gravimetrically measured volumetric water contents varied by almost 0.1 m^3/m^3 for similar times.

Greenhouse studies

Greenhouse measurements of soil water content (Figure 4C) showed different measured permittivities via surface reflection and propagation time between irrigation events. It should be noted that the GPR managed to successfully measure soil water drying patterns even though the surface was covered with a dense wheat plot (Leaf Area Index = 7.5 m^2/m^2).

Little canopy interference/ reflections should be expected due to the antenna's center frequency, which should have pretty good canopy penetration, in particular at normal incidence (Elachi, 1988). Furthermore the geometry of wheat plants, with primarily vertical leaves and stalks, allows the antenna to "see" the surface relatively well in comparison to a plant with flat, horizontal leaves that would effectively cause aboveground reflections. This issue is currently being researched.

The surface reflection data show a diurnal pattern of water content that is consistent with Jackson (1973) observations, namely, the condensation of vapor near the surface (0-1 cm) during the night (low temperature) and surface drying during the day. In contrast, TDR measurements, and to a lesser degree, GPR propagation time (GPR-PT) analysis, show a diurnal pattern that is in antiphase to GPR reflection data. This suggests that surface reflection measurement is strongly influenced by changes in water content at the top few millimeters of the soil surface, whereas TDR and GPR-PT sample larger soil volume and thus could be influenced by thermodielectric phenomena.

Surface water contents were seen to show increases primarily in the evening after sundown but with a few local maxima occurring between 14:00 and 16:00 as well. The afternoon may possibly be due to bound water desorption or possibly cloud cover whereas the nighttime maxima appear to be due to a redistribution if water within the planter at night in accordance with patterns reported by Jackson (1973). It should be noted that during this time the wheat plants were transpiring water and this should account for some of the constant water content loss in the soil.

The difference between surface reflection and GPR-PT data is up to $\Delta\Theta_v(t)$ = 0.14 m^3/m^3 at night but during the day GPR-PT $\Theta_v(t)$ can meet or exceed surface reflection $\Theta_v(t)$. Comparison between the surface reflection and TDR data shows measurement discrepancies of up to $\Delta\Theta_v(t)$ = 0.19 at night and as low as $\Delta\Theta_v(t)$ = 0.05 m^3/m^3 during the day.

TDR and GPR-PT measurements show similar diurnal trends but at times have different values by up to $\Delta\Theta_v(t)$ = 0.1 m^3/m^3. Differences in these two measurements are probably attributable to the fact that the TDR probe was not sampling the same area that the GPR antenna was (albeit that they were subjected to similar watering regimes), that the TDR probe was placed diagonally in the soil (due to soil thickness considerations and probe geometry, with a soil thickness of about 12 cm and a probe length of 15 cm) and frequency issues as well. The thin gravel layer, which was placed to ensure excellent drainage and air flow, may also be a source for error in the propagation time readings as well. Another issue here is the applicability of the Topp et al. (1980) equation which is primarily applicable for loamy soils.

The four gravimetric samples acquired appear to follow the TDR derived water contents the best although they are between those of the TDR and GPR-PT data.

Accuracy of the GPR antenna

It should be noted that there were also some measured diurnal variations in the antenna reflection pattern and possibly the sampling time. We have reason to suspect that this may have biased readings and are currently awaiting a response from the manufacturer as to whether or not this is a problem.

Implications for large scale studies

The diurnal variations noticed in the three experiments illustrate the need for constant monitoring of water content, meteorological data and temperature for large-scale radar water content measurement from air- and spaceborne.

Due to diurnal variations in soil water content, any gravimetric soil samples collected will have to either be concurrently collected with data acquisition or water content corrected against other data such as TDR (after a temperature correction, assuming that soil temperature requires such) based upon the time discrepancy between sample collection and radar data acquisition.

This is necessary as large-scale sampling of gravimetric water contents is both manpower and time intensive, and such studies, such as those by Blumberg et al. (2000) often sampled water content a few hours or more before or after the site had been sampled via scatterometer. Additional ground truthing previously conducted in Israel by the primary author often occurred over 12 hours prior to or after ERS-2 SAR data acquisition as part of research conducted by Blumberg and Freilikher (2001).

Such diurnal variations could have affected the accuracy of the research and subsequent modeling of Blumberg et al. (2000) and Blumberg and Freilikher (2001).

Conclusions

GPR using a horn antenna is a useful tool for measurement of diurnal soil surface reflectivity characteristics. When soil temperatures do not exceed 30°C or conditions are sufficiently wet bound water desorption effects should not adversely affect water content measurement inferences from microwave methods.

Irrigation methods can adversely affect measurements as non-ponding methods of irrigation can cause local differences in water content on the centimeter scale.

The surface reflectivity water content measurement was found to vary the most, with positive and negative changes in water content during drying even though the overall water content in the planter box was shown to decrease. Furthermore significant differences between TDR and GPR-PT derived Θ_v were found to exist, suggesting that further research is needed to determine the source of these differences.

Vegetation canopies with vertical leaves have minimal effects upon surface reflectivity for microwave radiation at around 1 GHz.

Any large-scale ground truthing of soil water content for SAR and scatterometer measurements will require constant monitoring of soil dielectric properties. Furthermore, gravimetric samples may have to be corrected for in-situ water content changes that occurred between gravimetric sample acquisition and radar data acquisition to improve the accuracy of the fit between ground-truth data and remotely sensed radar signatures.

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