Discussion of "Soil Moisture Measurements: Comparison of Instrumentation Performances" by Ventura Francesca, Facini Osvaldo, Piana Stefano, and Rossi Pisa Paola

February 2010, Vol. 136, No. 2, pp. 81–89.

DOI: 10.1061/(ASCE)0733-9437(2010)136:2(81)

Steven R. Evett[1] and Robert C. Schwartz[2]

[1]Member, EWRI (corresponding author). E-mail: steve.evett@ars.usda.gov

[2]USDA-ARS Conservation and Production Research Laboratory, Bushland, TX.

Discussion of "Soil Moisture Measurements: Comparison of Instrumentation Performances" by Ventura Francesca, Facini Osvaldo, Piana Stefano, and Rossi Pisa Paola

February 2010, Vol. 136, No. 2, pp. 81–89.

DOI: 10.1061/(ASCE)0733-9437(2010)136:2(81)

Steven R. Evett[1] and Robert C. Schwartz[2]

[1]Member, EWRI (corresponding author). E-mail: steve.evett@ars.usda.gov

[2]USDA-ARS Conservation and Production Research Laboratory, Bushland, TX.

Ventura et al. document the comparison of electromagnetic sensors during wetting-drying cycles in two soils, a clay loam and a loam. The sensors included in the study were two capacitance type sensors, the models EC-20[1] and EC-5 (Decagon Devices, Pullman, WA), and the model CS616 water content reflectometer (Campbell Scientific, Logan, UT), which is incorrectly described as a time domain reflectometry (TDR) device. (Mention of trade names or commercial products in this report is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture). If followed, the conclusions reached by Ventura et al. will lead to poor engineering practice to determine volumetric soil water content (θ_v, $m^3\ m^3$). The purpose of this discussion is to document errors in theory, experimental design, statistical analysis, and critical thinking that led Ventura et al. to conclude that "the tested probes give acceptable results after being calibrated in the field."

Field estimation of volumetric soil water content using electromagnetic (EM) sensors not only requires an accurate estimate of the real permittivity (ε'), but also entails the determination of the functional relationship between water content and ε' and how this varies with ambient environmental conditions and soil properties. A further complication is that all EM sensors measure an apparent permittivity (ε_a) rather than ε'. For lossy, microscopically inhomogeneous dielectrics such as soils, ε_a is influenced by the soil bulk electrical conductivity (σ_a, $S\ m^{-1}$), dielectric relaxation losses such as those related to bound water (θ_{bw}, $m^3\ m^{-3}$), and the effective measurement frequency f_{eff} (Schwartz et al. 2009; Evett et al. 2005). Both σ_a and θ_{bw} are highly dependent on soil temperature and typically result in a positive response of ε_a with respect to temperature at a magnitude depending on f_{eff}. In contrast, the real dielectric permittivity of bulk water declines with increasing temperature. Consequently, the soil thermodielectric response to changing θ_v results from the interplay of several mechanisms and is tied to the effective measurement frequency. Existing sensors may accurately estimate ε_a, but an accurate estimation of θ_v requires consideration of these mechanisms in the calibration and the permittivity model, particularly if θ_v is to be free of temperature bias.

Although the authors acknowledge some of these physical effects, they do not correctly include them in the analyses and discussion of their results. This led them to incorrectly conclude that diurnal oscillations in phase with soil temperature (up to 0.07 $m^3\ m^3$ at 0.06 m) resulted from real fluctuations in soil water content brought about by vapor transport, citing Jackson (1973) and Cahill and Parlange (1998). Contrary to the authors' statement, the data of Jackson (1973) show diurnally varying θ_v at a depth of 0.5 cm that peaks at 7 a.m., out of phase with soil temperature. Moreover, diurnal temperature cycling of soil water content rapidly decays with depth and should not be evident at a depth of 17 cm (Grifoll et al. 2005), the deepest probe at the authors' Cadriano site. The conclusions of Cahill and Parlange (1998) based on TDR measurements have been credibly challenged by Or and Wraith (2000) because of the strong dependence of ε_a on temperature in the presence of significant amounts of θ_{bw}.

The temperature sensitivity of the EC-20 sensor has been shown to range from 0.0043 $m^3\ m^3 °C^{-1}$ at $\theta_v = 0.15$ to 0.005 $m^3\ m^3 °C^{-1}$ for sandy loams (McMichael and Lascano 2003; Campbell 2006) and loams (Saito et al. 2009). Ventura et al. show similar temperature sensitivities of up to 0.0054 $m^3\ m^3 °C^{-1}$ for the EC-20 sensor in the loam at 0.06 m depth (Fig. 7). A temperature sensitivity of 0.003 $m^3\ m^3 °C^{-1}$ was documented for the CS616 sensors by Benson and Wang (2006). The discussers found the temperature sensitivity of the CS616 to increase linearly with water content in a silty clay loam, ranging from 0.0012 to 0.0113 $m^3\ m^3 °C^{-1}$

Downloaded 06 Jul 2011 to 165.91.74.118. Redistribution subject to ASCE license or copyright. Visit http://www.ascelibrary.org

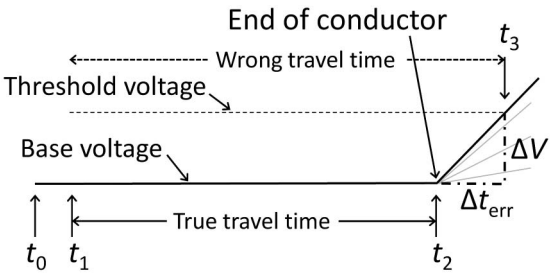

Fig. 1. In TDR, the waveform is analyzed graphically to determine the true time, t_2, at which the electronic pulse reaches the end of the conductor; in contrast, the CS616 measures the time at which the pulse reaches a threshold voltage, t_3; because the slope ($\Delta V/\Delta t_{\mathrm{err}}$) of the reflected pulse decreases (shown by gray lines) as σ_a and θ_{bw} increase, the error in travel time, Δt_{err}, increases as these temperature-dependent quantities increase; in this graphic, t_0 is the time at which the pulse generator emits a pulse, and t_1 is the time at which the pulse enters the electrodes that are embedded in the soil

as water content ranged from 0.10 to 0.40 $\mathrm{m^3\,m^3}$. This can be attributed to the temperature sensitivity of ε_a and an added error resulting from the manner in which travel time is evaluated. The CS616 is not equivalent to TDR because it does not find the true travel time of the fast rise time electronic pulse that it emits. Rather, it finds the time at which the reflected pulse reaches a threshold voltage value (Fig. 1), and this time includes an error that increases as θ_{bw} and σ_a increase. Because θ_{bw} and σ_a are temperature-dependent, the magnitude of this error changes with temperature. The "empirical correction method … to temperature-compensate" the CS616 is not universal and must be determined for each soil. In soils with nonnegligible θ_{bw} and σ_a, this compensation method results in incorrect values at some water contents because the effects of θ_{bw} and σ_a are mutually nonlinear.

Based on the preceding lines of reasoning, Occam's razor favors the more direct and physically realistic explanation that diurnal oscillations of apparent water content in phase with temperature are caused by temperature effects on σ_a and θ_{bw} and thus on the observed values of ε_a. The discussers recommend that the writers recalibrate the sensor response to temperature over a range of water contents before drawing conclusions regarding potential effects of vapor transport. Owing to the documented temperature sensitivity of the three sensors used in this study, none can be used to provide evidence for vapor transport unless they are calibrated for the temperature effects on θ_{bw} and σ_a. Such a calibration (e.g., Schwartz et al. 2009) goes beyond the simple temperature correction algorithms suggested by the sensor manufacturers. Although application of temperature corrections under field conditions obviously requires the measurement of temperature at the time and place of sensor readings, more sophisticated EM sensor calibration methods also employ σ_a and f_{eff} (e.g., Evett et al. 2005; Schwartz et al. 2009), again measured at the time and place of sensor readings. Unfortunately, it appears that the authors did not measure soil temperature and σ_a colocated with the soil water sensors and at the times of sensor readings. In addition, knowing f_{eff} for all these sensors may not be possible.

The experimental method used in this study will almost certainly result in misleading data. Soil samples used in the calibration procedure were procured at a distance of 0.5 m and, hence, outside the EM field of the soil water sensor (e.g., Hignett and Evett 2008). Moreover, in the first experiment, the sensors were placed at 20 and 40-cm depths, whereas the nearest soil samples were taken over the depth ranges 0–20 and 20–40 cm, not centered on the depths of the sensors, and thus biasing the sample values to water contents existing up to 20 cm above the sensors. As a consequence, the calibration results depend on the particular water content gradient at the time of sampling. Further degrading the data quality, volumetric soil samples were not taken, so water content data were determined on a mass per mass basis ($\mathrm{g\,g^{-1}}$). Separate bulk density samples were taken (where and how were not specified), and apparently the bulk density values were used to convert water content data from mass basis to volumetric, θ_v (the authors do not describe this). In the second experiment, sensors were placed at 6 and 17-cm depth, and the nearest soil samples were taken over the depth ranges of 0–10 and 10–20 cm, more accurately corresponding to the sensing depths, but still too far away at 50 cm laterally. Because the spatial variability of θ_v increases as sampling volume decreases, the number of samples needed to obtain an accurate mean value is large for the small sample volumes involved in this study, and the likelihood is great that samples taken 50 cm away from the sensors were not highly related to what was sensed (Evett et al. 2009). Therefore, the basis for accurate calibration did not exist, something that is evident in the large confidence intervals ($> 0.10\ \mathrm{m^3\,m^{-3}}$) for a given value of sensor output (mV) shown in Fig. 4 of Ventura et al.

Data analysis was by linear regression of sensor output versus θ_v, not in itself incorrect. However, the logic behind concluding for the capacitance sensors that "results from the calibration process did not differ greatly with depth" is specious when r^2 values ranged as low as 0.09, and slope and intercept values varied by factors of up to two for given depths and soils. Contrary to the authors' claim, this is not "an important result because it allows a single calibration equation to be used … at different depths." With only two replicates per depth and such small r^2 values and large confidence intervals (0.06 to 0.09 $\mathrm{m^3\,m^{-3}}$; Fig. 4), there was not enough statistical power to come to such a conclusion even if a test for significant differences between slopes had found no significant differences. The authors do not report such a statistical test. The calibration results for the CS616 were more accurate, but the slope and intercept values differed across the two depths by factors of 5 and 16, respectively (only calibrated on the loam soil), a result that is difficult to understand because the authors did not describe a texture contrast between those depths, and the reported bulk density values were not greatly different at 1.40 and 1.47 $\mathrm{Mg\,m^3}$. The authors give no explanation for this large change in calibration over a 20-cm depth range.

There are other important shortcomings in this study. The authors did give a single soil electrical conductivity value for each soil, but they did not specify a method of measurement or whether the values were of bulk electrical conductivity, which directly affects ε_a, or the conductivity of a solution extract of some kind. Solution extract conductivity can easily be 10 times the value of σ_a (Rhoades et al. 1999); or conversely, in soils with large quantities of high charge clays (superactive), the value of σ_a can be much larger than the solution extract conductivity (Logsdon and Laird 2004). Therefore, the reader has no way to gauge the possible effects of the conductivity values. At any rate, unless measured continuously at the time and place of sensor readings, σ_a is of little use in sensor calibration. The authors appear to justify their use of an auger for soil water content sampling (with subsequent conversion from mass basis to volumetric basis using bulk densities measured elsewhere) by writing "Gravimetric soil moisture is considered by scientists as a standard for calibrating sensors [as an example, see Merlin et al. (2007), Walker et al. (2004), and Eller and Denoth (1996)]." However, Eller and Denoth (1996) used volumetric soil sampling equipment (cylinders with known volume) and calculated

Downloaded 06 Jul 2011 to 165.91.74.118. Redistribution subject to ASCE license or copyright. Visit http://www.ascelibrary.org

volumetric water content directly. Similarly, Walker et al. (2004) and Merlin et al. (2007) used volumetric samples.

On the basis of inadequate experimental and statistical methods, and given the likelihood that the reported θ_v variation in phase with the temperature variation was attributable to temperature effects on ε_a (via θ_{bw} and σ_a) rather than vapor transport, the discussers judge this study to be inconclusive and its conclusions misleading.

Acknowledgments

Research discussed in this article was funded in part by the USDA-ARS Ogallala Aquifer Program, a consortium between USDA-Agricultural Research Service, Kansas State University, Texas AgriLife Research, Texas AgriLife Extension Service, Texas Tech University, and West Texas A&M University.

References

Benson, C. H., and Wang, X. (2006). "Temperature-compensating calibration procedure for water content reflectometers." *Proc., TDR 2006*, Purdue Univ., West Lafayette, IN.

Cahill, A. T., and Parlange, M. B. (1998). "On water vapour transport in field soils." *Water Resour. Res.*, 34(4), 731–739.

Campbell, C. S. (2006). "Response of the ECH2O soil moisture sensors to temperature variation." *Application note No. 13394-00*, Decagon Devices, Pullman, WA.

Eller, H., and Denoth, A. (1996). "A capacitive soil moisture sensor." *J. Hydrol. (Amsterdam)*, 185, 137–146.

Evett, S. R., Tolk, J. A., and Howell, T. A. (2005). "time domain reflectometry laboratory calibration in travel time, bulk electrical conductivity, and effective frequency." *Vadose Zone J.*, 4, 1020–1029.

Evett, S. R., Schwartz, R. C., Tolk, J. A., and Howell, T. A. (2009). "Soil profile water content determination: Spatiotemporal variability of electromagnetic and neutron probe sensors in access tubes." *Vadose Zone J.*, 8(4), 926–941.

Grifoll, J., Gastó, J. M., and Cohen, Y. (2005). "Non-isothermal soil water transport and evaporation." *Adv. Water Resour.*, 28(11), 1254–1266.

Hignett, C., and Evett, S. R. (2008). "Direct and surrogate measures of soil water content." Chapter 1, *Field estimation of soil water content: A practical guide to methods, instrumentation, and sensor technology*, S. R. Evett, L. K. Heng, P. Moutonnet, and M. L. Nguyen, eds., International Atomic Energy Agency, Vienna, Austria, 1–21.

Jackson, R. D. (1973). "Diurnal changes in soil water content during drying, in field soil water regime." *Field soil water regime: SSSA special publication 5*, R. R. Bruce, ed., SSSA, Madison, WI, 37–55.

Logsdon, S. D., and Laird, D. A. (2004). "Electrical conductivity spectra of smectites as influenced by saturating cation and humidity." *Clays Clay Miner.*, 52(4), 411–420.

McMichael, B., and Lascano, R. J. (2003). "Laboratory evaluation of a commercial dielectric soil water sensor." *Vadose Zone J.*, 2, 650–654.

Merlin, O., Walker, J. P., Panciera, R., Young, R., Kalma, J. D., and Kim, E. J. (2007). "Soil moisture measurement in heterogeneous terrain." *MODSIM 2007 Int. Congress on Modelling and Simulation*, L. Oxley and D. Kulasiri, eds., Modelling and Simulation Society of Australia and New Zealand, Canberra, Australia, 2604–2610.

Or, D., and Wraith, J. M. (2000). "Comment on 'On water vapor transport in field soils.'" *Water Resour. Res.*, 36(10), 3103–3105.

Rhoades, J. D., Chanduvi, F., and Lesch, S. (1999). "Soil salinity assessment: Methods and interpretation of electrical conductivity measurements)." *FAO Irrigation and Drainage Paper 57*, Food and Agriculture Organization of the United Nations, Rome.

Saito, T., Fujimaki, H., Yasuda, H., and Inoue, M. (2009). "Empirical temperature calibration of capacitance probes to measure soil water." *Soil Sci. Soc. Am. J.*, 73, 1931–1937.

Schwartz, R. C., Evett, S. R., Pelletier, M. G., and Bell, J. M. (2009). "Complex permittivity model for time domain reflectometry soil water content sensing: I. Theory." *Soil Sci. Soc. Am. J.*, 73(3), 886–897.

Walker, J. P., Willgoose, G. R., and Kalma, J. D. (2004). "In situ measurements of soil moisture: A comparison of techniques." *J. Hydrol. (Amsterdam)*, 293, 85–99.

Downloaded 06 Jul 2011 to 165.91.74.118. Redistribution subject to ASCE license or copyright. Visit http://www.ascelibrary.org