An Evaluation of the Use of the Acclima Soil Moisture/Temperature Probe for the U.S. Climate Reference Network (USCRN) as a Replacement for the Existing Hydra Soil Probe.

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A reference climate observing system like the USCRN is predicated on it providing a reference standard platform for the provision of long-term climate quality data. As such, the USCRN fully subscribes to the Global Climate Observing System (GCOS) Climate Monitoring Principles as outlined in Appendix A. However, the purest aspects of any climate observing system are at times mitigated by issues of cost, logistics, and the overall sustainability and practicality of operating an autonomous system in the field 24/7 and 365 days a year that requires changes in sensors and algorithms throughout its lifecycle. As stewards of such a reference quality system as noted in Diamond et al (2013), we take our responsibilities here very seriously. Unfortunately, sometimes sensor changes need to be made to ensure the long-term sustainability of the network. Additionally, manufacturers of sensors that are used in the network may go out of business, and as time progresses, new sensors with greater capabilities may be produced. However, when we contemplate such a change, we do so carefully and with the utmost of scientific integrity to ensure that we do not introduce a discontinuity into the climate record. This Technical Memorandum addresses the suitability of adding a new soil sensor to the suite of USCRN sensors. This evaluation takes into account the data continuity of the historical climate record as well as the nature of having for some time a mixed set of soil sensor types in the ground and its impact upon that record.

The USCRN network began using the Hydra soil probe (Stevens Water Monitoring Systems, Inc.) when soil measurements began in 2009. This was done primarily in an effort to match the soil sensors used in the U.S. Department of Agriculture’s (USDA) Soil Climate Analysis Network (SCAN) program. Additionally, at that time there were not many sensor
options available to choose from for soil measurements. After nearly 10 years of deployment of the Hydra sensors at USCRN stations, two primary issues have arisen which now requires us to procure a substantial number of additional probes. First, there has been a high failure rate of the Hydra probes in the network, and second, a large number of probes simply do not function very well in soils that are much different than a standard loam soil. Sites with high clay fractions comprise about 30% of the total network sites. As noted earlier, the long-term sustainability of the USCRN in budget constrained times is also a significant consideration, and with the need to replace such a high-number of sensors, cost is a practical and unavoidable consideration. The TDR-315L sensors (from Acclima, Inc.) evaluated in this Tech Memo are at least 40% less in overall cost over the Hydra; while the TDR-315s are less expensive than the Hydras, the analysis shows that the TDR-315Ls are well within the statistical uncertainty ($\approx 0.10$ fractional water content) with regards to soil sampling (see section 3.5). In a recent intercomparison of soil sensors at Oklahoma State University, Datta et al (2017) found that in high clay fraction soils, the TDR-315L had the lowest rmse ($\approx 5\%$) and had the lowest mean bias of all the sensors compared.

With over 1,500 sensors installed in the field (15 per station at 91 sites and 6 per station at an additional 24 sites), and in today’s resource constrained times, cost is not an insignificant issue. After already selecting a soil moisture sensor through a fairly rigorous selection process, the National Ecological Observing Network (NEON) is also considering switching to the Acclima TDR-315L given its superior performance. NEON currently has Acclima sensors under evaluation at one of their sites. One of the risks with any research climate network is the loss of availability of a particular sensor or any component of the data acquisition system; while we try
to avoid this, practical considerations regarding cost, performance, and sustainability take precedence. In addition, as a reference network, we want the ability to be able to take advantage of new and improved technologies while also being sensitive to the long-term climate record.

The long-term climate record is an important consideration in evaluating any sensor change. Maintaining these records is relatively straightforward for parameters like air temperature and precipitation. However, for soil moisture, there is added uncertainty due to the spatial variability of soil properties and its related structure that preclude maintaining any climate record, especially when the records are short. For example, the high clay content nature of soils at about 30% of the stations can bias the observed soil moisture measurements. Out of the 70 USCRN stations where soil samples were analyzed, about 20 sites had high clay content values of 25-40%, compared with the percent of sand and silt, which can be scaled to about 30% for the 114 USCRN stations.

As demonstrated from studies cited in this report, sites that do not exhibit high clay fractions show very good agreement between the Hydra and the TDR-315L. For these cases, the use of the “loam” equation is appropriate for the Hydra probe resulting in no significant changes in the data record. For those sites with high clay fractions, a mitigating strategy that was examined in this study to minimize abrupt changes in the site record is to employ a more “soil appropriate” equation for the Hydra. Our analysis showed that the use of a “clay equation” from Seyfried et al (2005) minimized the difference in fractional water contents between the Hydra and TDR-315L. These observed differences were on the same order as those observed for sites having Hydra probes only. Unfortunately, the Hydra probe manufacturer cautions that because different clays can have widely different electrical properties, the silt and clay calibration
equation can only be used where a calibration validation has been performed (Stevens Water Monitoring Systems, Inc., 2015), which the USCRN soil measurements currently lack.

Finally, from a long-term sustainability standpoint, the Hydra sensors seem to experience a much higher failure rate than the Acclimas and this has been experienced both within the USCRN and USDA SCAN systems (per. Communication. Deborah Harms, USDA-NRCS). Over the 3-year period from 2014-17, the USCRN has experienced a failure rate of 15-18 Hydra probes per 100 installed; and this is comparable to a failure rate of 14-19 Hydra probes per 100 installed in the Oklahoma Mesonet program. Conversely, from information from our colleagues at the SCAN program, their experience with failure rates of the Acclima sensor during the same time period has been less than 2 probe failures per 100 installed.

Therefore, taking all of this into account, the scientific and technical staffs at OAR’s Atmospheric Turbulence and Diffusion Division, in partnership with NESDIS’ National Centers for Environmental Information, offer this Technical Memorandum and a formal and well-researched documentation to justify the addition of a new sensor to the USCRN suite of instrumentation. This analysis has been conducted from the standpoint of long-term sustainability, cost, technical performance, performance in high clay soils, and comparative data from both probes which we will show will have essentially no impact on the long-term climate record. These areas are all well-documented in the body of this document, and therefore, the overall recommendation of this analysis will be to allow for an eventual transition from the Hydra to Acclima TDR-315L with no negative impacts on the long-term USCRN climate record and this will be well-documented in the body of this Technical Memorandum. On the contrary, we believe that this replacement probe will not only improve the overall climate record particular
in its operation in clay soil stations, but will be far more affordable and sustainable in the future allowing for a continued and improved overall climate record.

Abstract

Many climate networks deploy electromagnetic sensors to monitor soil moisture conditions. The Stevens Hydra probe which operates at 50 MHz has been deployed since 2009 to measure volumetric water content at 113 United States Climate Reference Network (USCRN) stations in the conterminous United States and one in Alaska. Because of the difficulty with site-specific calibrations to convert measured dielectric permittivity to volumetric soil water content, Hydra probe operations across the USCRN rely upon factory-supplied calibrations. In particular, the loam equation is used throughout the entire network.

Overall performance of Hydra probes at most USCRN stations have been acceptable; however, they have performed poorly at many sites and have failed consistently at others. Of the 1383 Hydra probes deployed across the USCRN stations from 2009 to 2015, 337 failed. Moreover, 20 stations have accounted for about 80% of all the failures, compelling USCRN to reconsider the use of the Hydra probe. This study evaluated the more advanced TDR-315 and the TDR-315L Acclima probes’ electromagnetic sensor, which operates at 3 GHz. Unlike the Hydra probe, the Acclima TDR-315Ls are a true time domain reflectometer based sensor which means that it has the potential to overcome problems of high electrical conduction of soil some high clay content soils at many USCRN stations.

Given that the USCRN operates as a high-quality reference climate network, it adheres to the Global Climate Observing System (GCOS) Monitoring Principles (see Appendix A); first among these states that, “The impact of new systems or changes to existing systems should be
assessed prior to implementation.” As such, this NOAA Technical Memorandum documents the appropriate assessment required in order to be able to incorporate a replacement sensor into the network.

Hydra probes and the more advanced TDR-315 (TDR-315L) Acclima probe were evaluated in a customized uniform loamy soil testbed at the USCRN station in Oak Ridge, TN. Unlike the Hydra probe, the Acclima TDR-315Ls are a true time domain reflectometer based sensor. Soil dielectric permittivity and soil temperature were measured by both probes buried at 10-cm depth. In spite of the use of the factory-supplied calibration for loam soils, an excellent regression line correlation of determination ($r^2 = 0.99$) was obtained for the volumetric soil water content and soil temperature measurements by the Hydra probe and the Acclima probe in the testbed. The Acclima probe measurements within the testbed were slightly higher than those of the Hydra probe by 2-5%. Measurements of volumetric soil water content indicated that the differences among the individual Hydra probes were much higher than differences among individual Acclima probes, with the standard deviation of about 2.5%, compared with about 1.5% among the four Acclima. Mean differences of the Hydra probe minus the Acclima probe in terms of hourly volumetric soil water content averaged about -3.0% during 2016, 1.0% during 2017, and 3% during 2018. For the soil temperature in the testbed, the mean difference of Hydra probe minus the Acclima probe was about -0.3° C during 2017, but during most of 2018 when only two Hydra probes were working, the difference dramatically increased to about -4.0° C, while the difference among the four Acclima probes remained small with a standard deviation of the about 0.1°C.
When three Acclima TDR-315L probes were tested at 5 cm and 10 cm in the natural ground at the USCRN station next to the testbed where three sets of Hydra probes are buried at 5, 10, 20, 50, and 100 cm, the difference of Hydra minus Acclima probe in terms of volumetric soil water content ranged from -1.0 to 10%, which was much larger than it was in the testbed. Unlike in the testbed, the Hydra probe exceeded the Acclima probe in terms of volumetric soil water content at the USCRN station by 0-10%. There was a larger difference among the three Hydra probes than was among the Acclima probes in the ground of the USCRN station, with calculated standard deviation of 0-10% for the three Hydra Probes in term of volumetric soil water constant, compared to 0-2.0% for the three Acclima Probes. An example of a major difference between the Hydra and Acclima probes was in the measurements of the soil water content at the USCRN station in Selma, AL during 2018; with the soil dominated by high clay content of 52-66% throughout the measurement depths, Hydra probe consistently measured higher volumetric soil water content than the Acclima probe by 10-15%, depending on rain events. Improved measurements of soil volumetric water content were obtained at the Selma station during 2018, with the daily volumetric soil water content of 40-50% measured by the Acclima probe, which is realistic for the station; compared with the measurement by the Hydra probe that consistently exceeded 50%, which was much larger than expected for the station. This arose because of the relatively high electrical conductivity of the clay type of the soil, which interferes with the measurements of the Hydra probe. Clearly, outside the ideal soil testbed, measurements of soil moisture often consist of a considerable scatter, and depending on site landscape and soil characteristics, the scatter among individual Hydra probes may even exceed the difference between the Hydra and the Acclima probes.
Despite the large scatter recognized among the Hydra probes in field settings, current replacement of failed Hydra probes across the USCRN stations do not or cannot explicitly include a transfer function to consider data continuity in the network. This omission is largely because required probe validations are not available at the individual soil measurement depths. Along the same vein, developing a realistic transfer function to consider data continuity related to adopting the Acclima probes across the USCRN stations is challenging. The role of local probe measurement variations at individual soil depths must be understood, however, to formulate transfer functions for providing depth- and point-specific soil data continuity formulations across USCRN stations.

Another motivation for the understanding of soil measurement variations at individual soil depths is related to the fact that different soil depths may have different soil properties. As soil depth and landscape location change in the field, soil characteristics can change. This change in soil characteristics alters various soil properties, including bulk density, organic matter, structure, pH, texture, and the hydraulic conductivity. Since soil probes sensors are often influenced by the local soil depths in which they are buried, which can differ greatly from the soil conditions at another depth or location in the field, this change in spatial soil properties has serious implication for developing realistic transfer functions for determining soil data continuity for soil probe measurements. The testbed at ATDD provides the best case scenario for probe intercomparisons. The 2016 time series of the difference between the average Hydra and Acclima probes shows an overall difference of 3%, and is well within the 5% manufacturer uncertainty (Figure 31). In 2017, after a year of equilibration and a more uniform grass cover over the testbed, the overall difference is about 1% (Figure 32). Investigations of the Acclima
TDR-315Ls at the USCRN station in the immediate vicinity of the testbed also indicated excellent agreement between the Acclima and Hydra probes at the 5- and 10-cm depths (Figure 34). Improved measurements of soil volumetric water content were also obtained at the USCRN station in Selma, AL during 2018 when Acclima TDR-315Ls were used to replace failed Hydra probes.

1. Introduction

The United States Climate Reference Network (USCRN) currently comprises 114 stations in the continental United States, 22 stations in Alaska (29 stations by 2022), and 2 stations in Hawaii. From 2009-11, the USCRN Program, at the behest of the National Integrated Drought Information System (NIDIS) Program, deployed the commercial Hydra Probe II soil sensors (Stevens Water Monitoring Systems, Inc) at 113 of the 114 USCRN stations in the continental United States\(^1\), plus one station (Kenai in Alaska) to provide automated measurements of soil moisture and soil temperature. Hydra probes have been used successfully in many different applications (RoTimi Ojo et al., 2014; Logsdon et al., 2010; Robinson et al., 2008; Cosh et al., 2016). The Hydra probe is promoted for its reliability, durability, low power use, and the factory-supplied calibration equations. Financial support to add soil moisture and temperature sensors to the existing climate monitoring instrumentations at USCRN stations was provided by the National Integrated Drought Information System (NIDIS) program (Diamond, et al., 2013).

This development represented a dramatic expansion of the USCRN program which was established in 2000 and began fielding systems in 2004, in order to provide automated and

\(^1\) The ground at the station in Torrey, UT was too rocky to be able to feasibly install any probes.
continuous measurements of air temperature and precipitation in its mission to document the long-term climate variability across the United States. Because the original focus of the USCRN program was on air temperature and precipitation and other supporting meteorological observations, USCRN station sites were selected without much consideration to measurements below-ground. The continuous measurement of soil moisture and temperature across the USCRN stations was expected to enhance the public benefit of the USCRN program, as soil moisture is an important parameter for a wide range of studies, including agriculture, ecology, hydrology, weather, and climate. At the majority of stations (~90), soil moisture and soil temperature are measured by 15 Hydra probes. Three separate holes are used at each station. In each hole, sensors are buried at 5-, 10-, 20- 50-, and 100-cm depth. At the remaining number of stations, where bedrock at shallow depths hinder deep excavation, probes are buried at 5- and 10-cm. Because of the lack of site-specific soil physical property data to calibrate the Hydra Probe at the individual USCRN stations, a default manufacturer-supplied calibration equation is used to convert the Hydra Probe dielectric permittivity measurements to volumetric soil water content. Various manufacturer-supplied calibration equations based on soil types (loam, sand, silt, and clay) have been reported for operating the Hydra Probe in different soil environments (Stevens Water Monitoring Systems, Inc., 2015). While the Hydra Probe has performed acceptably at USCRN stations with coarse textured soils, it has been unreliable at sites with high clay content, fine textured soils which indicate the need for soil-specific calibration equations. Zamora et al. (2011) reported differences as high as 25% between site-specific calibration using gravimetric measurements and manufacturer-supplied calibrations in the evaluations of soil moisture observing networks in Arizona, California, and Colorado. Other studies have shown that soil
dielectric permittivity depends not only on the soil physical texture but also on soil chemical properties (Blonquist Jr. et al., 2005). The cation exchange capacity in soils and the related impact of soil ions on the soil dielectric permittivity vary considerably, from low in loamy soils to much higher values in saline and certain clay soils. High ion concentration in the soil increases the soil electrical conductivity that can influence soil electrical properties and responses. The Hydra Probe uses a relatively low frequency signal. This makes it sensitive to energy losses from high electrical absorption and conductivity (Stevens Water Monitoring Systems, Inc., 2015), and even though the Probe will continue to operate in some instances, the determination of soil water content can be unreliable.

Accurate determination of dielectric permittivity-soil moisture content calibration equations is required to convert soil dielectric permittivity measurements to volumetric soil moisture content. Thus, a serious challenge in adopting the Hydra probe to measure soil moisture is accurately determining how various factors—including soil texture, soil chemical properties, bulk density, temperature, and organic matter—can affect the dielectric permittivity at a given soil depth and site. Topp et al. (1980) reported the formulation of dielectric permittivity–soil moisture content calibration equations that are the basis for nearly all TDR probes, albeit with some minor modifications. Several studies have reported evaluations of the Hydra probe and other dielectric permittivity sensors in field settings using gravimetric soil sampling measurements (considered the true measurement) to validate the volumetric soil water estimated based on probe calibration equations (Kelleners et al., 2009; Cosh et al., 2016). These field evaluations are laborious and require observations over a wide range of water contents and can take months to years to obtain a full range. Many laboratory studies have reported successful
evaluations of dielectric permittivity sensors in liquids and uniform soil media (Vaz et. al, 2013; Burns et al., 2014; Blonquist Jr. et al., 2005).

Determining the correct calibration of dielectric permittivity sensors is a process that challenges their application across a wide variety of heterogeneous field sites. To simplify the application of soil dielectric permittivity sensors, factory-supplied calibration equations have been developed for determining soil moisture in various soil types, including loam, silt, and clay (Seyfried et al, 2005). Factory-supplied calibration equations have been supporting operations of dielectric permittivity sensors in soil moisture measurements for many years (Cosh et al., 2005; Zamora et al., 2011). These operations are fostered by using the soil textural classification as the basis for adopting factory-supplied calibration equations for use by dielectric permittivity sensors, thus avoiding the burden of in situ calibrations (Cosh et al., 2005; Zamora et al., 2011; Scott et al., 2013). This opportunity has promoted evaluation of dielectric permittivity sensor performance using factory-supplied calibration equations in both field and laboratory settings (Vaz et al., 2013; Cosh et al., 2005; Zamora et al., 2011).

Cosh et al. (2005) evaluated routine operations of soil dielectric permittivity sensors to measure the top surface soil moisture for hydrological modeling and remote sensing applications based on factor-supplied calibration equations in croplands in Iowa and Oklahoma. Site-specific correction of the factory-supplied calibration equation did improve the dielectric permittivity performance (using gravimetric soil moisture sampling). Zamora et al. (2011) reported a difference between factory-supplied calibration and site-specific calibration for dielectric permittivity sensor using infield gravimetric soil sampling. Scott et al. (2013) used in situ gravimetric soil sampling to conduct site-specific evaluations of heat dissipation sensors for
measuring soil moisture across 115 Oklahoma Mesonet stations. Overall, sensors overestimated soil moisture by over 0.15 cm$^3$ cm$^{-3}$ for dry soil conditions without in situ corrections for water retention curve parameters. The difference between the sensor soil moisture estimates and those obtained by gravimetric soil sampling was reduced from 0.078 to 0.053 cm$^3$ cm$^{-3}$ by use of in situ water retention curve parameters.

Notwithstanding the widespread use of the Hydra probe, site and depth gravimetric soil sampling evaluations of soil dielectric permittivity sensors remain a relatively difficult process to implement in individual fields. The deeper soil dielectric permittivity is measured, the more difficult the field evaluation becomes. The USCRN soil moisture depths are from 5- to 100-cm, therefore, depth and site-specific evaluations are inhibited by the cost, time, and labor required for implementing the *in-situ* calibration of dielectric permittivity sensors at individual USCRN stations. Current operation of the Hydra probe across the USCRN stations is not based on in situ-derived calibration equations or local evaluations of the Hydra probe to convert dielectric permittivity measurement to soil moisture. Instead dielectric permittivity is converted to volumetric soil moisture content using factory calibration equation supplied for loamy soils. An understanding of the impact of local soil factors on soil dielectric permittivity and hence the spatial variability is needed. Though Wilson et al. (2016) described the large variability of soil properties across 70 of the 114 USCRN stations in the continental U.S., their effort did not include the evaluation of the impact of soil properties on soil dielectric permittivity. In addition, evaluations of the USCRN station soil instrumentation methodology, data quality control strategies, and potential applications of the soil moisture data have not included the impact of soil properties on the dielectric permittivity sensor performance (Bell et al, 2013).
While the Hydra probe has performed well across majority of the USCRN sites, it has performed poorly at a number of stations with relatively high clay content soils. In addition to the high clay content, these soils generally have a higher organic matter fraction and are consistently wet due to frequent rains. The Hydra probe operates at a low frequency of 50 MHz, and effects of high clay electrical activities on dielectric permittivity values may inhibit its ability to measure the dielectric permittivity (Blonquist Jr. et al., 2005). Clays with large specific clay surface area and high CEC are known to affect sensors using a lower frequency. Adopting a more robust dielectric permittivity sensor that can accurately determine volumetric water content on a wide range of soils is a priority for the USCRN. Soil clays often differ greatly in structure and properties from those of silt and sand minerals. Clays which are usually smaller in size than both silt and sand minerals have surface area and cation exchange capacities (CEC) that are greater than those of silt and sand. Moreover, clays vary widely in terms of their structures, clay particle size and mineralogy and ultimately in surface area and CEC. Bohn et al. (1985) reported that coarse clays such as micas of about 70 to 120 x 10³ m² kg⁻¹ in surface area often have low CEC (200 to 400 mmoles (+) kg⁻¹) compared with fine clays such as smectites of 600 to 800 x 10³ m² kg⁻¹ in surface area which have high CEC (800 to 1200 mmoles (+) kg⁻¹).

Fine clays are therefore colloidal. At issue is the assumption with dielectric permittivity sensors that the dielectric constant of pure water content (80) must be significantly greater than that of the soil materials (4-15) holding the water in order to determine the volumetric water content. The impact of clay on dielectric permittivity is more evident from the clay mineralogy than from the percent of clay content of total soil. Moreover, current calibration equations of dielectric permittivity sensors deal mostly with the general soil descriptions consisting of loam, silt, clay,
and organic matter, and largely ignore the quantification of the interactions of the mineralogy and content of the various soil components. Several studies have indicated that clay electrical activity can increase the soil electrical conductivity due to proton hopping (Saarenketo, 1998). Proton hopping consists of large charge transfer through soil water mixture in high CEC soils such as smectite clays when alternating current is applied during the operation of permittivity based sensors. The high electrical conductivity and increased soil water content contribute to the elevated soil dielectric permittivity values far above the expected accurate range for low frequency permittivity sensors. In addition, the soil freeze–thaw is a typical process across many of the USCRN stations. This process influences the soil water and soil temperature and the operation of the Hydra probe. The Hydra probe lacks the ability to measure water content in frozen soils so no effort has been made by the USCRN to evaluate the Hydra probe performance regarding frozen soils.

In order to overcome the difficulties high electrical conductivity of clay soils impose on the measurement of soil moisture at many USCRN stations, the Acclima TDR-315L probe was selected for evaluation. The TDR-315L probe is a widely used high frequency dielectric permittivity sensor. Being a true time domain reflectometer, the TDR-315L probe determines the soil dielectric permittivity by measuring the reflection travel time of a high frequency waveform (around 3.5 GHz). Successful field measurements have been made with the TDR-315L in several settings and laboratory evaluations have been made using various liquids and soil types (Blonquist Jr. et al., 2005; Kelleners, 2009). In addition the probes performance was comparable to a conventional TDR with root mean square errors ranging from 0.017 – 0.020 m$^3$ m$^{-3}$ (Schwartz et al, 2016) The objectives of this study were to use factory-supplied calibration
equations to evaluate the performance of the TDR-315L to measure soil moisture in field conditions relevant to USCRN and quantify any potential difference between the TDR-315L and the Hydra probe. The loam calibration is the default, which currently forms the basis for soil measurements at the USCRN stations. However, the measured dielectric from each probe is also recorded and archived for each site, and more soil appropriate relationships could be used to compute volumetric water content. The silt and clay calibrations could be used where a calibration validation has been performed.

1.2 Background on the need to investigate the use of Acclima Sensors

The first two GCOS monitoring principles state that the impact of new systems or changes to existing systems should be assessed prior to implementation and comparisons between old and new observing systems should be made over a suitable period. One of the risks with any research climate network is the loss of availability of a particular sensor or any component of the data acquisition system. Scientists supporting research climate networks are continuously looking at ways to improve the quality and robustness of the observations. New sensors are continuously being sought after and occasionally evaluated in the event that one of the sensors in the existing system is no longer commercially available and alternative replacements are needed. There have been many advances in environmental sensors over the last decade, especially those with soil related observations. Many of these newer technologies may provide equal or better accuracy and performance at a lesser cost. A research component of any climate observing network evaluates new technologies with the overall goal of improving the accuracy of the climate record.
As a result of the mounting issues the USCRN was having with the Hydra probes, USCRN scientists contacted Dr. Steve Evett, a research soil scientist with the USDA Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, Texas. Evett also serves as the ARS research coordinator for the Middle East Regional Irrigation Management Information Systems Project, which has research and extension partners in Israel, Jordan and the Palestinian Authority; and he co-leads the Water Saving Technologies Flagship Project – a USDA-China cooperative effort in advanced irrigation technologies. Dr. Evett is a leading expert in soil moisture sensing technology and is very familiar with the pros and cons of each of the methodologies that are used to monitor soil moisture.

He made us aware of the new advanced sensor from Acclima that seemed to overcome many of the shortcomings associated with other sensor technologies. In addition, the new sensors were also at a lower cost. The impact of new systems or changes to existing systems should be assessed prior to implementation and comparisons between old and new observing systems should be made over a suitable period. In addition, given that the new sensors are at a lower cost with improved performance in clay soils, prompted an exploratory investigation to see if this new sensor technology could be seamlessly integrated into the USCRN sensor suite.

2. Materials and Methods

2.1. The Application of Dielectric Theory to Soil Moisture Measurement

Currently, the basis for all new soil moisture measurement technologies is based on the application of determining the dielectric of the soil media and relating that to volumetric water content. There are various methods used to determine the dielectric nature of a material. A
A detailed description of the dielectric properties of a material is reported in the literature (Robinson et al, 2003a; b). Here we provide a brief description of the dielectric theory focusing on the important aspects related to the measurement of soil dielectric permittivity and soil water content determination. The dielectric permittivity of the soil is a diagnostic physical property which characterizes the degree of electrical polarization a material experiences under the influence of an external electric field and is the primary diagnostic physical property in ground penetrating radar (GPR) and advanced sensors for soil moisture.

The permittivity can be described by a complex number with both real and imaginary components and is dependent on frequency, temperature, and the properties of the soil. The frequency-dependent relative complex permittivity $\varepsilon_r^*(\omega)$ is described by

$$\varepsilon_r^*(\omega) = \varepsilon_r(\omega) - j \varepsilon_{ri}(\omega)$$

(1)

where $\varepsilon_r(\omega)$ is the frequency-dependent relative real permittivity, $j$ is the imaginary number, $\varepsilon_{ri}(\omega)$ is the frequency-dependent relative imaginary permittivity, and $\omega$ is the angular frequency $2\pi f$, and $f$ is the frequency. The imaginary permittivity is described by

$$\varepsilon_{ri}(\omega) = \left(\frac{\sigma_{dc}}{\omega \varepsilon_0}\right) + \varepsilon_{r,rel}(\omega)$$

(2)

where $\sigma_{dc}$ the direct current bulk electrical conductivity, $\varepsilon_0$ is the permittivity in a vacuum ($= 8.8542 \times 10^{-12}$ F m$^{-1}$) and $\varepsilon_{r,rel}(\omega)$ is the frequency-dependent relative dielectric loss due to relaxation. The relative permittivity $\varepsilon_r$ is ratio of the permittivity of the soil material $\varepsilon$ (F m$^{-1}$) to that of the vacuum $\varepsilon_0$ ($\varepsilon_r = \varepsilon/\varepsilon_0$).
Due to the fact that the Hydra probe operates at a low frequency of 50 MHz, effects of high clay electrical activities on dielectric permittivity values may inhibit its ability to measure the dielectric permittivity of clay soils (Blonquist Jr. et al., 2005). Clays with large specific clay surface area and high CEC are known to hinder low frequency permittivity sensors. Thus finding a way to adopt a more robust dielectric permittivity sensor that can accurately determine the effect of clays on dielectric permittivity is important for observing soil moisture across the USCRN stations. Soil clays often differ greatly in structure and properties from those of silt and sand minerals, as total soils vary widely in clay, silt, sand, and organic matter contents, respectively. The impact of clay on dielectric permittivity is more evident from the clay mineralogy than from the percent of clay content of total soil. Moreover, current calibration equations of dielectric permittivity sensors deal mostly with the soil qualitative descriptions consisting of loam, silt, clay, and organic matter, and largely ignore the quantification of the interactions of the mineralogy and content of the various soil components. Several studies have indicated that clay electrical activity can increase the soil electrical conductivity due to proton hopping (Saarenketo, 1998.). Proton hopping process consists of large charge transfer through soil water mixture in high CEC soils such as smectite clays when alternating current is applied during the operation of permittivity sensors. The high electrical conductivity and increased soil water content contribute the elevated soil dielectric permittivity values far above the expected accurate range for low frequency permittivity sensors. In addition, the soil freeze–thaw is a typical process across many of the USCRN stations. This process influences the soil water and soil temperature and the operation of the Hydra probe. The Hydra probe lacks the ability to
measure frozen soil water content so no effort has been made by the USCRN to evaluate the Hydra probe performance regarding frozen soils.

2.2. TDR-315L Probe

The Time Domain Reflectometry (TDR) 315L probe essentially measures the travel time of a step voltage pulse across a transmission line. To measure the soil water content, the transmission line which consist of three metal rods are embedded in the soil. The travel time $t$ of the voltage pulse can be determined in term of the relative real permittivity $\varepsilon_r$ and the relative apparent permittivity $\varepsilon_a$ of non-electrically conductive soil through (Von Hippel, 1954; Topp et al., 1980):

$$ t = \frac{2L}{c} \sqrt{\frac{\varepsilon_r}{2} \left[1 + (1 + \tan^2 \delta)^{0.5}\right]} = \frac{2L \sqrt{\varepsilon_a}}{c} \tag{3} $$

where $L$ is the length of the metal rods, $c$ is the velocity of light in a vacuum ($= 2.9979 \times 10^8$ m s$^{-1}$), and $\tan \delta$ is the loss tangent. The factor 2 is included in the above equation to account for the fact that the pulse has to travel back along the rods before it is detected. The loss tangent is defined as (Topp et al., 2000):

$$ \tan \delta = \frac{\varepsilon_{ri}}{\varepsilon_r} = \frac{\sigma_{dc}/\omega \varepsilon_0 + \varepsilon_{r, rel}}{\varepsilon_r} \tag{4} $$
The $\sigma_{dc}$ is determined from the steady-state reflection coefficient $\rho_\infty$, i.e., the constant reflection coefficient that can be observed after multiple reflections have died down (Lin et al., 2007):

$$\sigma_{dc} = \frac{K_p}{R_s} \left( \frac{1 - \rho_\infty}{1 + \rho_\infty} \right) \left[ \frac{1}{1 - \left( \frac{R_{\text{cable}}}{R_s} \frac{1 - \rho_\infty}{1 + \rho_\infty} \right)} \right]$$

(5)

where $K_p$ is a geometric factor relating the sample resistance $R$ to $\sigma_{dc}$ ($R = K_p/\sigma_{dc}$), $R_s$ is the resistance associated with the source impedance (generally 50 $\Omega$), and $R_{\text{cable}}$ is the resistance of the cable that connects the voltage source to the sample rods. To determine $\sigma_{dc}$, both $K_p$ and $R_{\text{cable}}$ should be known.

The TDR-315L probe consists of three 15-cm long stainless steel rods of about 3.5 mm diameter and about 2-cm rod spacing attached to 5.9- x 5.3- x 1.5-cm probe head. Like the Hydra probe, electronics to operate the TDR-315L are also embedded in a miniaturized circuit with the probe head, and resulting data are sent digitally via SDI-12 communication protocol with a 10-m long waterproof cable. The TDR-315L and Hydra probe both provide the same measurements which include dielectric permittivity, electrical conductivity, and soil temperature, respectively. A less expensive version of the TDR-315, is the TDR-315L. The difference is that the TDR-315L uses all silicon chips (CMOS) whereas the TDR-315 uses Si-Ge chips, which are faster but more expensive and power hungry than CMOS. The tradeoff is that the rise time of the TDR pulse is not as short in the CMOS sensor as in the Si-Ge sensor. Preliminary data indicate that the CMOS version will work as well as the Si-Ge version.

2.3. The Hydra Probe
Campbell (1990) and Seyfried et al. (2005) described in great detail the design and measurement techniques of the Hydra probe soil water sensor. From Campbell (1990), when a voltage is applied to a Hydra probe metal rod inserted in the soil, the reflected voltage signal related to the probe impedance ($Z_p$) is described as

$$\frac{Z_p}{Z_c} = \frac{1 + \Gamma}{1 - \Gamma}$$  \hspace{1cm} (6)$$

where $Z_c$ is the characteristic impedance of the metal rod and $\Gamma$ is the complex ratio of the reflected voltage to the incident voltage. The probe impedance ($Z_p$) is determined by the electrical properties of the probe itself ($Z_0$) and the $\varepsilon_r^*$ of the media in the sensing volume (e.g., soil). The relationship between $Z_0$ and $\varepsilon_r^*$ is described as

$$Z_p = \frac{Z_0}{\sqrt{\varepsilon_r^*}} \cotanh \frac{\omega L \sqrt{\varepsilon_r^*}}{c} j$$  \hspace{1cm} (7)$$

where $L$ is the electric length of the probe and $c$ is the speed of light. By inverting Eq. (7), $\varepsilon_r^*$ (and therefore $\varepsilon_r$ and $\varepsilon_{ri}$) can be solved for given the measured reflected voltages. Note that the value of $\varepsilon_{ri}$ obtained in this way does not distinguish between $\varepsilon_{r,rel}$ and $\sigma_{dc}$.

The Hydra probe sensor consists of four 5.7-cm-long stainless steel tines of 0.3-cm diameter extending out from a 4-cm diameter cylindrical head. The four tines are configured so one centrally located tine is surrounded by the other three times that form an equilateral triangle with 2.2-cm sides. Electronics to operate the probe consists of a wave signal generator, thermistor, microprocessor, and communication protocol are embedded in a print circuit assemble within the cylindrical head. The thermistor is used to measure temperature. The Hydra
The complex ratio of the reflected voltage to applied voltage is used to determine probe impedance which is related to the soil dielectric permittivity. These calculations are done using a manufacturer-supplied conversion software. The calculated soil dielectric permittivity is a complex number containing both real and imaginary components. Output data from the Hydra probe consist of four values: real dielectric permittivity, imaginary dielectric permittivity, bulk electrical conductivity, and temperature.

2.4. Field Measurement

Field measurements to evaluate the Acclima TDR-315L probe alongside the Hydra probe were initiated since June 8, 2016, and are ongoing at the USCRN research testbed in Oak Ridge, TN. A homogeneously packed coarse loamy soil testbed was built in the immediate vicinity of the USCRN station as the primary field study site. The testbed is located in a relatively flat low lying open grassy area. The surrounding landscape to the west and north of the testbed location is elevated about 2m high, while to west, the landscape slopes gently upward toward the west with about 15-20% slope for about 30m. A line of trees with thick bushes runs north-south about 20 m eastward from the testbed. The low lying measurement site receives rainfall runoff from the elevated east-west city street about 100 m away and the elevated landscape about 30 m westward with driveways, grassy fields, parking a parking lot, and the NOAA-ATDD building. The
testbed is made of a wooden plank (24-cm wide and 6-cm thick) that covers a rectangular ground area about 130 cm x 245 cm and about 20-cm high above the natural ground about 4 m from the base of the USCRN station. Uniform grass cover is maintained over the surface of the testbed to minimize spatial variability of soil moisture and soil temperature in the testbed. The average bulk density of the soil in the testbed during 2017 was about 1.17 gm cm$^{-3}$. Four Hydra probes and four TDR-315L Acclima probes along with four Decagon GS1 probes$^2$ are buried in the testbed at 10-cm depth about 25-cm horizontal distance apart (Figures 1 and 2). Two of the Acclima TDR-315Ls malfunctioned in August 2016 and were not replaced until April 2017 when the testbed was also cleared of weeds and reseeded with grass.

Three soil samples collected on a weekly basis, depending on rain conditions, at 10-cm depth in the testbed were used to determine the gravimetric soil water. Three Acclima TDR-315Ls and three Hydra probes were also buried at 5- and 10-cm depths, respectively, in the natural soil in the immediate vicinity of USCRN station. The USCRN station at the testbed also provides data on the local microclimate including solar radiation, precipitation, wind speed, air temperature and relative humidity at 2-m above the ground. The power supply to operate the instruments is obtained from the A/C power of the City of Oak Ridge, TN. A Campbell Scientific Inc. datalogger is used to record all of the probe measurements at 5-sec intervals and calculated 3600-sec means.

From May 2017 to March 2018, Acclima TDR-315Ls were used to replace malfunctioning Hydra probes at 10 USCRN stations (Kenai, AK; Fairhope, AL; Selma, AL;  

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$^2$ Please note that the Decagon probes were used as an additional check on the range of soil moisture – these are soil moisture only probes and are not under consideration as a replacement.
3. Results

3.1. Comparison of soil volumetric water content in testbed and local USCRN location in Oak Ridge, TN

Measurements of soil volumetric water content and soil temperature from the Hydra probes and Acclima TDR-315L probes buried at 10-cm in the soil testbed located in the immediate vicinity of USCRN station in Oak Ridge, TN were obtained during 2016 and 2017. Excellent comparisons of soil volumetric water content collected on 5-minute basis from the Hydra and Acclima TDR-315Ls are presented in Figures 3 and 4, and Figures 31-33 and 37-38 document a series of difference plots to document this. The slope and $R^2$ of the regression line are close to 1, and the root mean square error (rmse) is less than 2% of mean values of soil volumetric water (23-30%) during both years. The excellent agreement between the Hydra and the Acclima TDR-315L in the testbed demonstrates that there is no statistical difference between the probes when they are used in the same uniform layer of coarse loamy soils. Both probes were operated with the factory-supplied calibration equations for loamy soils. The y-intercept of the regression line during 2016 is about 3.55% higher compared with the value during 2017 (about 0.27%). The most likely reason is there were only two working Acclima TDR-315L probes during 2016, which suggests the need for comparable number of soil sampling even for measurements conducted in uniform soils. A closer examination of the differences between the Acclima and Hydra probes in the testbed are shown in Figures 31 and 32. In 2016, the mean

Williams, AZ; Newton, GA; Arco, ID; Champaign, IL; Millbrook, NY; Coos Bay, OR; and McClellanville, SC).
difference was on the order of 3% and in 2017, the difference was less than 1%. In 2017, there was more time for the probes and soil to become settled. In addition in 2017, there was a more concerted effort to have a more uniform grass cover over the testbed.

For the same time period, the mean difference of Hydra probe minus the Acclima probe for the soil temperature was about -0.3 C during 2017 (Figure 37). In 2018, only two Hydra probes were working. The mean difference dramatically increased to about -4.0 C. The difference among the four Acclima probes remained small with a standard deviation of the about 0.1 C (Figure 38).

Figures 34 and 35 show results of three Acclima TDR-315L probes buried at 5 cm and 10 cm in the natural ground at the USCRN station next to the testbed where three sets of Hydra probes are buried at 5, 10, 20, 50, and 100 cm. The difference of Hydra minus Acclima probe in terms of volumetric soil water content at the 5 and 10 cm depths ranged from -1.0 to 10%, much larger than in the testbed. More often, the Hydra probe exceeded the Acclima probe in terms of volumetric soil water content, with the difference ranging from 0-10%. The difference among the three Hydra probes was larger than among the three Acclima probes in the natural ground of the USCRN station, where calculated standard deviation was 0-10% for the three Hydra Probes in term of volumetric soil water content, compared to 0-2.0% for the three Acclima Probes. The offset between the probe types was also observed at other USCRN sites. There was a major difference between the Hydra and Acclima probes in the measurements of the soil water content at the USCRN station in Selma, AL during 2018 (Figure 36); with the soil dominated by high clay content of 52-66% throughout the measurement depths, Hydra probe consistently measured higher volumetric soil water content than the Acclima probe by 10-15%. The difference between
the Hydra and Acclima probes for soil temperature was smaller than for soil moisture (Figure 39-41). Daily volumetric soil water content of 40-50% was measured by the Acclima probe at the Selma station during 2018. By contrast, unrealistically high soil moisture was measured by the Hydra probe at Selma, with values that consistently exceeded 50%. The bias in the Hydra probe can be explained as a result of the relatively high electrical conductivity of the clay type of the soil, which interferes with the determination of the permittivity from the Hydra probe.

The performance of the Hydra and Acclima TDR-315L probes was comparable when compared against gravimetric soil moisture measurements. For 2016, the average difference was -0.91 +/- 0.99% and 1.78 +/- 1.03% for the Hydra and Acclima, respectively. In 2017, the average difference was -1.06 +/- 2.47% and -0.02 +/- 2.73%, for the Hydra and Acclima, respectively. Both sensors were on average within 3% of the observed volumetric water content for both years.

Figure 7 presents the volumetric water content measurements by the Acclima TDR-315L probes at depths of 5- and 10-cm outside but close to the testbed and in the immediate vicinity of the three local locations of the Hydra probes for measuring the soil moisture and soil temperature at the USCRN station in Oak Ridge, TN during 2016. The correlation between the Acclima TDR-315L and the Hydra probes is significant, with a slope of about 0.92. There is some scatter between the two probes with rmse of about 1.5%. At the 10-cm depth, the y-intercept was about 7.62%, and was larger than at the 5-cm depth, where the y-intercept was about 2.84%.

The daily averages of the Hydra and Acclima at 10 cm in the tested show very good agreement overall with slope of 1.03, $r^2 = 0.98$ and offset less than 1% (Figure 8). When both the Hydra and Acclima 10 cm daily testbed data were compared to the CRN Hydra at 10 cm in
the yard, the correlations and slope were comparable, but the offset was nearly 5% for both probes. The side yard was probably a bit moister than the testbed because of a higher clay fraction and the area where the side yard probes were buried was shaded for a longer period of time during the day.

3.2. Comparison of soil temperature in testbed and local USCRN location in Oak Ridge, TN

The soil temperature exhibits less scatter than the soil volumetric water content between the Hydra and Acclima TDR-315L probes in both the testbed and in the local USCRN location (Figures 10 and 11). From the results in the testbed, the temperature readings from the Acclima and Hydra probes showed no discernable difference. The Acclima TDR-315L was also operated next to a platinum resistance thermometer, the exact type that is used for air temperature in the USCRN. Over the extreme temperature range, the temperature from the Acclima showed good agreement with the PRT. From the testbed results, the measured temperatures agreed to within 0.1°C, but the Hydra probes responded more slowly to sudden changes in temperature.

3.3. Time series of soil volumetric water content in testbed and local USCRN location in Oak Ridge, TN

Figures 12 to 15 show the time series of 5-minute soil volumetric water content measurements by the Hydra and Acclima TDR-315Ls and gravimetric values at 10-cm in testbed with hourly precipitation at the site during 2016 and 2017. Gravimetric values closely follow probe measurements, while the soil water shows temporal variation clearly related to
precipitation, evapotranspiration, and soil drainage conditions. Soil water tends to increase rapidly with precipitation amount, reached maximum values during precipitation events, and decreased gradually between precipitation events.

For each probe type, the difference among the four Hydra probes versus the four Acclima TDR-315Ls is reasonably estimated by the time series of the standard deviation and the mean percent difference during the 2016 and 2017. In particular, values of the standard deviation and mean percent difference approximate the spatial variation of volumetric water content across the testbed as measured by the four Hydra and Acclima TDR-315Ls. As expected, the approximated spatial variation of the volumetric water content cross the testbed is much larger during precipitation events than during non-precipitation periods. For the intra-probe variation, the volumetric water content by the four Hydra probes exhibited greater variation than the measurements by the four Acclima TDR-315Ls. For the inter-probe variation, the root mean square error (rmse) between volumetric water content measured by the Hydra and Acclima TDR-315Ls (Figures 3 and 4) was smaller than the standard deviation of either the four Hydra or the four Acclima TDR-315Ls across the testbed.

Figures 16 to 17 show the time series of the daily soil volumetric water content measurements by the Hydra and Acclima TDR-315Ls values at 10-cm in testbed and at 5- and 10-cm at the local USCRN location and its immediate vicinity, with the precipitation during 2016 and 2017. As expected, the daily variation of the soil volumetric water content is consistent with the 5-minute measurements (Figures 12-15). Values of the soil volumetric water content were consistently greater at the local USCRN location and its immediate vicinity than in soil testbed nearby. This difference is attributed to the coarse loamy soil in the testbed compared
with the relatively fine clay soil that likely accumulates at the local USCRN location due to precipitation water runoff from the adjoining elevated landscape toward the west.

3.4. Time series of soil temperature in testbed and local USCRN location in Oak Ridge, TN

Figures 18 and 19 show the soil temperature measured by the Hydra and Acclima TDR-315Ls during 2017 with 5-minute variation at 10-cm depth and across the soil testbed. Unlike the gravimetric soil water measurements to evaluate the soil moisture measured by the probes, no such direct measurement was made to evaluate the soil temperature measured by the probes. However, the temporal pattern of the soil temperature is acceptably consistent with the hourly and annual variation of the solar radiation, with maximum values of soil temperature during the summer. For the intra-probe variation, the soil temperature measured by the four Hydra probes exhibited equal variation as the measurements by the four Acclima TDR-315Ls. For the inter-probe variation, the root mean square error (rmse) between the soil temperature measured by the Hydra and Acclima TDR-315Ls (Figure 11) was smaller than the standard deviation of either the four Hydra or the four Acclima TDR-315Ls across the testbed. The temporal variation of the soil temperature shows slightly greater scatter during late spring and early summer because of sparse green grass cover than it did during late summer and fall, but compared with the soil water content, the soil temperature measurements by the probes show less scatter. In general, the soil temperature values in the testbed were similar to those at 5- and 10-cm at the local USCRN location and its immediate vicinity, but the soil temperature measured by the Acclima TDR-315Ls in testbed was much greater during 2016 than during 2017 (Figures 20 and 21).
3.5. Time series of soil volumetric water content at the USCRN station in Selma, AL during 2018

The primary motivation for this study was to evaluate the suitability of using the Acclima TDR-315L probes at USCRN locations in which soil clay fractions are high. An example of the deployment of TDR-315L probes alongside the Hydra probes at the USCRN station in Selma, Alabama, is presented in Figures 22 to 26, with individual Hydra and TDR-315L, probes buried at 5-, 10-, 20-, 50-, and 100-cm depths at three different holes. Hydra probes were first deployed at the Selma station at three hole locations in June 2009, TDR-315L probes replaced malfunctioned Hydra probes in one hole location in November 2017, and TDR 315 probes replaced malfunctioned Hydra probes in another hole location in March 2018. Since May 2017, TDR-315L probes have been used to replace malfunctioning Hydra probes at 10 USCRN stations. These stations comprise soils high in clays and soil water dynamics that seem to have extra apparent electrical conductivity that makes the use of the Hydra probe more problematic in measuring soil moisture.

The deployment of TDR probes shows clear improvement in the measurements of the soil volumetric water content at the Selma, AL station during 2018, although the “noisiness” of the signal clearly shows how soils with high electrical conductivities can affect the Acclima TDR-315Ls as well as the Hydra. The Acclima TDR-315Ls provide a realistic measurement of maximum saturated soil volumetric water content values of about 50%. However, the computed volumetric water content from the Hydra probes using the standard loam equation from Seyfried (2005) in converting the apparent dielectric to volumetric water fraction resulted in offsets of more than 15%. The use of a more appropriate equation than the loam equation was explored by
using the relationship for the soil with the highest clay fraction from Seyfried (2005). This relationship was applied to the observed dielectric from the Hydra probe at Selma for the 5- and 50-cm layers, respectively (Figures 21a, 21b). At the 5-cm level, which is usually the most dynamic time series of all the soil moisture levels, the Hydra and Acclima TDR-315Ls have nearly identical signatures over the 60 day period (Figure 21a), although the Hydra probe clearly shows an offset that on average is about 0.15 +/- 0.021. This offset is above the normal expected deviation for expected spatial uncertainty. The average difference between the TDR-315 and TDR-315L at the 5-cm and 50-cm level is 0.071 +/- 0.026 and 0.0006 +/- 0.017, respectively. These differences are well within the expected field uncertainty of soil moisture values. Field studies conducted to examine the spatial variability of soil moisture have used the standard deviation of volumetric water content as the measure of uncertainty, which is approximately 0.10 m$^3$/m$^{-3}$ (Garnaud et al., 2017, Choi et al., 2007). This implies a coefficient of variation on 40%, which additionally is used as a measure of spatial variability.

Of particular interest for both the Hydra and Acclima TDR-315Ls at the Selma station is related to the removal of spurious data from the hourly data output. On March 27, 2018, a filter was added to the data logger data processing program to remove spurious data in the calculation of the hourly averages of the soil volumetric water content data. This modification in data processing has greatly reduced the scatter in the hourly measurement of the soil volumetric water content. Before that time, only a single value was used in the computation of the hourly value.

With the new algorithm, 12 of the 5-minute values are averaged to generate an hourly value. From statistical sampling theory, the reduction in the noise or variance should be proportional to the ratio of the square root of the sample sizes. In this case, the sample size was
increased by 12, so the reduction in the hour to hour variability as depicted by the standard deviation of water content over a stationary period, should be on the order of 3.5. To evaluate this noise reduction as affected by the new averaging algorithm, two stationary time periods were selected from the 60 day period from April 1 to May 30. Days 97 - 105 were used for the “before” period and days 114 - 122 were used to evaluate the standard deviation of hourly values with the new algorithm. The data from the 50-cm level were used for this evaluation. Indeed, on average, for both the Hydra and Acclima TDR-315Ls, the reduction in noise is by a factor of 4.06, which is close to that expected from a statistical sampling level of 3.46. Since the probe communication protocol influences also improves the probe susceptibility to spurious dielectric permittivity data, this program modification has implications for observations of soil volumetric water content across all the USCRN stations.

3.6 NCEI Network Analysis of Soil Sensors

The analysis of soil volumetric water content & soil temperature measurements is important for determination of the accuracy, consistency, robustness, and durability of how the Hydra and Acclima TDR-315Ls perform across the USCRN stations. In the analysis of the probes at individual soil depths and local USCRN stations, soil data are assessed and spurious values are manually flagged to identify the probe inconsistent behavior & malfunction. Overall, out of 335 Hydra probes flagged for faulty performance in measuring volumetric soil moisture, 232 were listed as bad sensors. Similarly, 228 Hydra probes were flagged for faulty measurements of soil temperature with 97 listed as bad sensors. In addition, a total of 49 Acclima TDR-315Ls have been deployed across the USCRN stations. All the deployed Acclima TDR-315Ls are flagged on the bad sensor list (BSL) because the Acclima TDR-315Ls are being
evaluated in the USCRN program. Because the analysis of the USCRN soil sensors is a routine process, probes are consistently being removed & added to the BSL across the USCRN stations. During the April 2018 analysis of the probes across the USCRN, probes at various depths were removed from the BSL at USCRN stations in six states (CA, CO, MO, MS, NE, and RI), while problematic probes were added to the BSL at USCRN stations in six other states (FL, GA, NC, SC, TN, and TX).

3.6.1 Using Alternative Equations for the Hydra Probe.

The computed volumetric water content from the Stevens Water Hydra probe is computed using a pre-defined relationship between the apparent dielectric and water content. These functional relationships were presented and discussed by Seyfried et al (2005). Approximately 19 different soil types were examined to evaluate and determine the functional relationship between the soil dielectric and water content. It was decided early on the in lieu of an exact site calibrated relationship, the coefficients from the loam equation would be used. For most of the soils in the USCRN, this relationship is appropriate. However, for soil that are comprised of mostly clay or sand, such as those in the Southeastern U.S., this may not be the case.

Applying the equation from Seyfried (2005) with the coefficients from the soil with the clay contents similar to that of Selma, the average difference is reduced by roughly 50% to 0.078 +/- 0.021 for the same period. At the 50-cm level, similar results are observed with both the Hydra and Acclima showing similar day to day trends over the 60 day period, with an the average difference between the Hydra and the average of the Acclima TDR-315Ls using the loam equation on the order 0.1284 +/-0.009. Using the same coefficients used for the 5-cm level,
the average difference between the Hydra and Acclima was again reduced by about 50% to 0.0535 +/- 0.009. The soils at Selma represent an extreme environment in order to adequately obtain meaningful observations of soil moisture. However, even given these conditions, the Hydra probes and Acclima TDR-315Ls both showed similar day to day trends during the 60 day period used in this analysis. The major difference was mainly in the offset between the Hydra and Acclima, which was reduced significantly (Table 1) when a more soil specific equation was applied to the raw Hydra data. The observed difference using the soil specific coefficients (clay), are no more than what is typically observed using like sensors at the same level (Cosh et al, 2016). These findings strongly suggest that at sites where the soil characteristics can be either measured or estimated (sand, silt, and clay fractions), soil appropriate coefficients from Seyfried (2005) can be applied to the Hydra raw data (dielectric) in order to mitigate any significant step changes that could be introduced by adding Acclima TDR-315Ls to a particular site that may also have Hydra probes installed.

3.7 Implications of Mixing Hydras and Acclima Sensors at an Individual USCRN Station

In order to address concerns of mixing Hydra and Acclima TDR-315Ls at the same sites, the comparison between the Acclima and Hydra probes in the ATDD testbed and side yard, show there is no statistical difference between the computed volumetric water contents. In this instance, the loam equation was used for the Hydra to produce a volumetric fraction of water. From the results from Selma, which represent a worst case scenario, because that site has a high clay content with high electric conductivity, the absolute differences between the computed volumetric fractions are significant. However, once again, for this initial analysis, the loam equation was used for the Hydra probe to compute the volumetric water content. The hour to
hour trends tracked very closely, so the differences result mainly from a baseline shift or offset. However, when more “soil appropriate” coefficients are used (high clay); the average difference is reduced by a factor of 2 for both the 5- and 50-cm layer. The observed differences between all three probes at the same level at Selma are no more different than what is typically observed at other USCRN sites with like sensors in each hole. These results also strongly suggest that for sites with mixed sensors, the physical properties of the soil could be used to select the most appropriate equation for the Hydra to match the baseline values of the Acclima TDR-315Ls.

The “soil appropriate” coefficients, selected from Seyfried (2005), and applied to the Hydra probe, would then serve as the transfer function between the Hydra and Acclima TDR-315Ls. This would minimize the introduction of any step changes in the data record and also accommodate the use of mixed sensors at all the sites. The “soil appropriate” coefficients, selected from Seyfried (2005), and applied to the Hydra probe, would then serve as the transfer function between the Hydra and Acclima TDR-315Ls.

As an alternative to transfer functions, soil-specific equations can be tested and developed for the Hydra probe. To pursue this approach, soil property measurements will be needed from all USCRN sites. The evaluation of the Acclima and Hydra probes in the soil testbed so far deals with a homogeneous soil horizon. The testbed study is useful for investigating the performance of both probes in changing conditions of soil water and temperature within a uniform soil horizon. Results of the soil testbed indicate excellent agreement between the Acclima and the Hydra probes with a slope of about 1 at a soil depth of 10-cm. However, the testbed study gives no information about the soil moisture below the 10-cm depth, but perhaps both probes would remain equal to say the 100-cm depth if the uniform testbed extended that deep.
In order to further evaluate the Acclima TDR-315L alongside the Hydra probe at USCRN stations, the Acclima TDR-315Ls are being slowly added at a small number of select USCRN stations. At these stations the Acclima TDR-315Ls are being used to replace bad or failed Hydra probes. Figures 27-30 show the volumetric soil water at three locations at 10- and 50-cm, respectively, at two of these select stations: Selma, AL and McClellanville, SC for the month of April 2018. The Selma station is dominated by 52-66% clay content and 29-43% silt content with only small sand of about 5%. At McClellanville, the soil is dominated by 89-94% sand, with only 2-8% clay and 3-5% silt. In general, with increasing depth, the clay content increases and both silt and sand decrease. Results clearly illustrate the challenge of measuring soil moisture across a wide variety of individual field sites with different soil, vegetation, and climate conditions.

The magnitude of soil dielectric permittivity (volumetric water content) demonstrates the relative influence of the soil at both sites. For the Selma station with high clay/silt content soils, soil water content tends to be high. Soil water contents tend to be quite low for the McClellanville station with the high sand content soil. In addition to the difference in soil water between the two sites, soil water shows spatial variations in the vertical and in the horizontal, with soil water content the lowest near the soil surface and increase with depth. The hourly change in soil water content tends to be smaller with increasing soil depth. This vertical profile soil water is because, on hourly basis, more stored soil water is lost to evaporation and transpiration than lost to drainage.

From the examples presented for Selma and McClellanville, it is quite obvious that micro-soil environments are a critical factor that can affect the soil water at a given depth at a
given point in the field. It is the micro-soil environment in which the probe rod is buried that is important for the probe measurement, but description of the soil at the exact point of the probe is complicated since the probe directly interacts with the soil and because soil and site factors can vary even across short distances in a given field. These factors include land topography, soil texture, soil bulk density, rocks, borrowing animals, and vegetation cover, plant root distribution. Therefore it will take knowledge of these factors at individual probe locations and depths at the various USCRN sites to formulate, develop, and implement any useful transfer functions to interrelate the Hydra and Acclima TDR-315L measurements among depths and locations across the various USCRN sites.

4. Conclusions

The continuous 5-minute averages of soil volumetric water content and soil temperature measurements by four Hydra probes and four Acclima TDR-315L probes at 10-cm depths across a uniform coarse loamy soil testbed at the USCRN station in Oak Ridge, Tennessee, reliably produced the variation of the soil water under field conditions during 2016 and 2017. Over the course of the year soil volumetric water content measured by both probes in the testbed ranged from 10 to 35% while the soil temperature ranged from 5 to 30 degrees C. A linear regression was completed on the dataset from the Hydra and Acclima TDR-315Ls. The regression equations and regression statistics of the soil volumetric water content and soil temperature provided excellent agreement between the Hydra and Acclima TDR-315Ls with a slope nearly 1.0, indicating that measurements of the Hydra probes are essentially interchangeable with those of Acclima TDR-315Ls in the testbed. The root mean square error between both probes was
way less than the difference among each type of probe. The soil temperature data exhibited less
scatter than the soil volumetric water content.

Investigations of the Acclima TDR-315Ls at the USCRN station in the immediate
vicinity of the testbed also indicated great agreement between Acclima and Hydra probes at the
5- and 10-cm depths. However, the range in magnitude of the scatter of the soil volumetric
water content and soil temperature was much greater at the USCRN station and its immediate
vicinity than it was in the testbed. This explains the important sensitivity exhibited by both
probe types to the spatial heterogeneity of the soil characteristics at the local USCRN station. It
also indicates that the probes will experience highly variable soil effects among different natural
field sites.

The measurement of the soil moisture at the USCRN station in Selma, AL was improved
when Acclima TDR-315Ls replaced the malfunctioned Hydra probes. The volumetric water
content measured by the Acclima was lower than that measured by the Hydra probes at the
station; however, both probe types use the factory-supplied calibration equation for loamy soils.
A limitation for the Hydra probe sensor is the assumption that at 50 MHz the variation of soil
dielectric permittivity is due to water content, ignoring the soil electrical conduction depending
on clay types and salinity conditions, and this incorrect assumption was the main source of error
at the Selma station. This issue was not a problem for the Acclima TDR-315L. The effect of the
clay electric activities cannot be neglected for the soils at the Selma station.

5. Way Forward

Given the need for the USCRN to adhere to the GCOS Monitoring Principles and as a
high-quality reference system great care must be exercised in sensor changes which could
change the long-term record. The current Hydra sensors, while not perfect have been operating at about a third of stations for nearly 9 years now. Great care must be taken to justify the move to the Acclima TDR-315L noted in this Tech Memo.

Therefore, using the test results documented here, the following deliberative steps are proposed to allow the USCRN Program to properly document the steps required in order to allow for this change to a new sensor. Therefore, in order to do these, we propose the following two primary steps that justify this change from a reference observing standpoint be undertaken as Acclima TDR-315Ls are installed across the network.

1. At sites where the loam equation (Seyfried et al 2005) is appropriate, and where Acclima TDR-315Ls have been installed in at least one hole, compare the coefficients of variation using the Acclima with periods when all of sensors at the site were Hydra probes to demonstrate compatibility and interchangeability.

2. At sites where the loam equation is not applicable because of high clay fractions, do the same comparison above except for the use of the most appropriate equation and coefficients from Seyfried et al (2005) based on the soil characteristics of the site.

3. Incorporate the use of these steps in the soil moisture metadata portion of the USCRN record to document sensor changes.

The statistics from this analysis can be used justify the mixing of soil probe types and to mitigate the possibility of any step changes resulting of introducing a new sensor into the suite of USCRN system sensors.
6. References


Appendix A - GCOS Monitoring Principles for the Effective Monitoring of Climate

1. The impact of new systems or changes to existing systems should be assessed prior to implementation.

2. A suitable period of overlap for new and old observing systems is required.

3. The details and history of local conditions, instruments, operating procedures, data processing algorithms and other factors pertinent to interpreting data (i.e., metadata) should be documented and treated with the same care as the data themselves.

4. The quality and homogeneity of data should be regularly assessed as a part of routine operations.

5. Consideration of the needs for environmental and climate-monitoring products and assessments, such as IPCC assessments, should be integrated into national, regional and global observing priorities.

6. Operation of historically-uninterrupted stations and observing systems should be maintained.

7. High priority for additional observations should be focused on data-poor regions, poorly observed parameters, regions sensitive to change, and key measurements with inadequate temporal resolution.

8. Long-term requirements, including appropriate sampling frequencies, should be specified to network designers, operators and instrument engineers at the outset of system design and implementation.

9. The conversion of research observing systems to long-term operations in a carefully-planned manner should be promoted.

10. Data management systems that facilitate access, use and interpretation of data and products should be included as essential elements of climate monitoring systems.
Figure 1. The soil testbed located alongside the USCRN station in Oak Ridge, TN.
**Figure 2.** The TDR-315L Acclima Probe ([https://acclima.com](https://acclima.com)) and the Stevens Hydra Probe ([www.stevenswater.com](http://www.stevenswater.com)).
Figure 3. The regression of hourly values of averaged percent soil volumetric water (VWC) of four Acclima Probe measurements against four Hydra Probe measurements in the testbed during 2016.
Figure 4. The regression of hourly values of averaged percent soil volumetric water (VWC) of four Acclima Probe measurements against four Hydra Probe measurements in the testbed during 2017.
Figure 5. The regression of percent soil volumetric water (VWC) of probe measurements against gravimetric sample measurements in the testbed during 2016; and probe measurements consist of the average of four Hydra Probes (Hydr) and four Acclima Probes (Acclima), respectively.
Figure 6. The regression of percent soil volumetric water (VWC) of probe measurements against gravimetric sample measurements in the testbed during 2017; and probe measurements consist of the average of four Hydra Probes (Hydr) and four Acclima Probes (Acclima), respectively.
Figure 7. The regression of daily percent soil volumetric water content (VWC) measurements at 5 and 10 cm, respectively, and the average of three Acclima Probes in vicinity of the USCRN against three Hydra Probes each buried three individual holes at the USCRN ATDD station during 2016.
Figure 8. The regression of daily percent soil volumetric water content (VWC) measurements, and the average of four Acclima Probes/Hydra Probes at 10 cm in the testbed against four Hydra Probes at 10 cm in the testbed as well as three Hydra Probes buried at 5 and 10 cm, respectively, in three individual holes at the USCRN ATDD station during 2016.
Figure 9. The regression of daily soil moisture measurements, and the average of four Acclima Probes/Hydra Probes at 10 cm in the testbed against four Hydra Probes at 10 cm in the testbed as well as three Hydra Probes buried at 5 and 10 cm, respectively, in three individual holes at the USCRN ATDD station during 2016.
Figure 10. The regression of daily soil temperature measurements at 5 and 10 cm, respectively, and the average of three Acclima Probes in vicinity of the USCRN against three Hydra Probes each buried three individual holes at the USCRN ATDD station during 2016.
Figure 11. The regression of hourly soil temperature measurements consisting of the average of four Acclima Probes against four Hydra Probes buried at 10 cm in the testbed during 2017.
Figure 12. Hourly time series of percent soil volumetric water of four Hydra Probes buried at 10 cm in the soil testbed along with gravimetric measurements and precipitation (bottom), and standard deviations of the four Hydra Probes and mean percent difference among the four Hydra Probes (standard deviations divided by the mean) (top) during 2016.
Figure 13. Hourly time series of percent soil volumetric water of four Acclima Probes buried at 10 cm in the soil testbed along with gravimetric measurements and precipitation (bottom), and standard deviations of the four Hydra Probes and mean percent difference among the four Hydra Probes (standard deviations divided by the mean) (top) during 2016.
Figure 14. Hourly time series of percent soil volumetric water of four Hydra Probes buried at 10 cm in the soil testbed along with gravimetric measurements and precipitation (bottom), and standard deviations of the four Hydra Probes and mean percent difference among the four Hydra Probes (standard deviations divided by the mean) (top) during 2017.
Figure 15. Hourly time series of percent soil volumetric water of four Acclima Probes buried at 10 cm in the soil testbed along with gravimetric measurements and precipitation (bottom), and standard deviations of the four Hydra Probes and mean percent difference among the four Hydra Probes (standard deviations divided by the mean) (top) during 2017.
Figure 16. Daily time series of percent soil volumetric water content (VWC) at 5 and 10 cm, respectively, of the average of four Hydra Probes and four Acclima Probes buried at 10 cm in the testbed, three Acclima Probes buried at 5 and 10 cm, respectively, in the vicinity of the three USCRN holes each with Hydra Probes at 5 and 10 cm, respectively, during 2016.
Figure 17. Daily time series of percent soil volumetric water content (VWC) at 5 and 10 cm, respectively, of the average of four Hydra Probes and four Acclima Probes buried at 10 cm in the testbed, and the three USCRN holes each with Hydra Probes at 5 and 10 cm, respectively, during 2017.
**Figure 18.** Hourly time series of soil temperature of four Hydra Probes buried at 10 cm in the soil testbed and precipitation (bottom), and standard deviations of the four Hydra Probes and mean percent difference among the four Hydra Probes (standard deviations divided by the mean) (top) during 2017.
Figure 19. Hourly time series of soil temperature of four Acclima Probes buried at 10 cm in the soil testbed, and precipitation (bottom), with standard deviations of the four Acclima Probes and mean percent difference among the four Acclima Probes (standard deviations divided by the mean) (top) during 2017.
Figure 20. Daily time series of soil temperature at 5 and 10 cm, respectively, of the average of four Hydra Probes and four Acclima Probes buried at 10 cm in the testbed, three Acclima Probes buried at 5 and 10 cm, respectively, in the vicinity of the three USCRN holes each with Hydra Probes at 5 and 10 cm, respectively, during 2016.
Daily time series of soil temperature at 5 and 10 cm, respectively, of the average of four Hydra Probes and four Acclima Probes buried at 10 cm in the testbed, and the three USCRN holes each with Hydra Probes at 5 and 10 cm, respectively, during 2017.
Figure 22. Hourly time series of **percent soil volumetric water content (VWC)** at 5 cm and precipitation at the USCRN station in Selma, AL during 2018 with **one Hydra Probe is buried in hole #1**, **one Acclima TDR315L Probes** is buried in hole #2, and **one Acclima TDR315 Probe** is buried in hole #3.
Figure 23. Hourly time series of percent soil volumetric water content (VWC) at 10 cm and precipitation at the USCRN station in Selma, AL during 2018 with one Hydra Probe is buried in hole #1, one Acclima TDR315L Probes is buried in hole #2, and one Acclima TDR315 Probe is buried in hole #3.
Figure 24. Hourly time series of percent soil volumetric water content (VWC) at 20 cm and precipitation at the USCRN station in Selma, AL during 2018 with one Hydra Probe is buried in hole #1, one Acclima TDR315L Probes is buried in hole #2, and one Acclima TDR315 Probe is buried in hole #3.
Figure 25. Hourly time series of percent soil volumetric water content (VWC) at 50 cm and precipitation at the USCRN station in Selma, AL during 2018 with one Hydra Probe is buried in hole #1, one Acclima TDR315L Probes is buried in hole #2, and one Acclima TDR315 Probe is buried in hole #3.
Figure 26. Hourly time series of percent soil volumetric water content (VWC) at 100 cm and precipitation at the USCRN station in Selma, AL during 2018 with one Hydra Probe is buried in hole #1, one Acclima TDR315L Probes is buried in hole #2, and one Acclima TDR315 Probe is buried in hole #3.
Figure 27. Hourly time series of soil dielectric permittivity (top), precipitation in mm (middle), and percent soil volumetric water content (bottom) at 10-cm depth at the USCRN station in Selma, AL during April 2018 with one Hydra Probe buried in hole #1 (SM1010 & SW1010), one Acclima TDR315L Probe buried in hole #2 (SM2010 & SW2010), and one Acclima TDR315 Probe buried in hole #3 (SM3010 and SW3010); and the one Hydra Probe volumetric soil water is presented in the bottom plot (SMV010).
Figure 28. Hourly time series of soil dielectric permittivity (top), precipitation in mm (middle), and percent soil volumetric water content (bottom) at 50-cm depth at the USCRN station in Selma, AL during April 2018 with one Hydra Probe buried in hole #1 (SM1050 & SW1050), one Acclima TDR315L Probe buried in hole #2 (SM2050 & SW2050), and one Acclima TDR315 Probe buried in hole #3 (SM3050 and SW3050); and the one Hydra Probe volumetric soil water is presented in the bottom plot (SMV050).
Figure 29. Hourly time series of soil dielectric permittivity (top), precipitation in mm (middle), and percent soil volumetric water content (bottom) at 10-cm depth at the USCRN station in McClellanville, SC during April 2018 with one Acclima TDR315L Probe is buried in hole #1 (SM1010 & SW1010), one Hydra Probe is buried in hole #2 (SM2010 & SW2010), and one Hydra Probe is buried in hole #3 (SM3010 & SW3010); the average of the two Hydra Probes is presented in the bottom plot (SMV010).
Figure 30. Hourly time series of soil dielectric permittivity (top), precipitation in mm (middle), and percent soil volumetric water content (bottom) at 50-cm depth at the USCRN station in McClellanville, SC during April 2018 with one Acclima TDR315L Probe is buried in hole #1 (SM1050 & SW1050), one Hydra Probe is buried in hole #2 (SM2050 & SW2050), and one Hydra Probe is buried in hole #3 (SM3050 & SW3050); the average of the two Hydra Probes is presented in the bottom plot (SMV050).
Figure 31. Hourly time series of percent soil volumetric water of four Hydra Probes buried at 10 cm in the soil testbed along with gravimetric measurements (Top), the standard deviations and mean percent difference of the Hydra Probes minus Acclima Probes (Bottom) during 2016.
Figure 32. Hourly time series of percent soil volumetric water of four Hydra Probes buried at 10 cm in the soil testbed along with gravimetric measurements (Top), the standard deviations and mean percent difference of the Hydra Probes minus Acclima Probes (Bottom) during 2017.
Figure 33. Hourly time series of percent soil volumetric water of four Hydra Probes buried at 10 cm in the soil testbed along with gravimetric measurements (Top), the standard deviations and mean percent difference of the Hydra Probes minus Acclima Probes (Bottom) during 2018.
Figure 34. Daily time series of percent soil volumetric water of three Acclima Probes buried at 5 cm in the vicinity of the three USCRN Hydra Probes (Top), the standard deviations and mean percent difference of the Hydra Probes minus Acclima Probes (Bottom) during 2016.
Figure 35. Daily time series of percent soil volumetric water of three Acclima Probes buried at 10 cm in the vicinity of the three USCRN Hydra Probes (Top), the standard deviations and mean percent difference of the Hydra Probes minus Acclima Probes (Bottom) during 2016.
Figure 36. Daily time series of percent soil volumetric water content (VWC) averaged in terms of Hydra and Acclima Probes at 5 depths (Top), the difference of Hydra Probe minus Acclima Probe and precipitation (Bottom) at the USCRN station in Selma, AL during 2018.
Figure 37. Hourly time series of soil temperature of four Hydra Probes buried at 10 cm in the soil testbed along with gravimetric measurements (Top), the standard deviations and mean percent difference of the Hydra Probes minus Acclima Probes (Bottom) during 2017.
Figure 38. Hourly time series of soil temperature of four Hydra Probes buried at 10 cm in the soil testbed along with gravimetric measurements (Top), the standard deviations and mean percent difference of the Hydra Probes minus Acclima Probes (Bottom) during 2018.
Figure 39. Daily time series of soil temperature of three Acclima Probes buried at 5 cm in the vicinity of the three USCRN Hydra Probes (Top), the standard deviations and mean percent difference of the Hydra Probes minus Acclima Probes (Bottom) during 2016.
Figure 40. Daily time series of soil temperature of three Acclima Probes buried at 10 cm in the vicinity of the three USCRN Hydra Probes (Top), the standard deviations and mean percent difference of the Hydra Probes minus Acclima Probes (Bottom) during 2016.
Figure 41. Daily time series of soil temperature averaged in terms of Hydra and Acclima Probes at 5 depths (Top), the difference of Hydra Probe minus Acclima Probe and precipitation (Bottom) at the USCRN station in Selma, AL during 2018.