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Validation of Wireless Volumetric Soil Water Content Sensor Based on Soil Temperature and Impedance Measurements

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***Abstract*— The rational use of water resources requires accurate assessment of soil moisture content. During the last three decades, electromagnetic measurement techniques have evolved into versatile, cost- effective solutions for conducting in situ soil moisture measurements. However, it is still necessary to further continue developing technological solutions that can yield soil moisture measurements close to the real content, stressing ease of use and can be adjusted to operate under different site conditions. Here the authors describe a volumetric soil moisture measurement instrument based on soil impedance measurements. The soil temperature is used as an additional parameter to implement a measurement compensation method. The measurement compensation process uses a feedforward artificial neural network. 10 measurements were obtained in situ in three test fields (maize, wheat, pastureland), over a period of 10 weeks (october-december 2017). The results were compared to measurements obtained using a commercial soil moisture instrument (6050X1 Trase System) and the gravimetic method. The results indicate that the prototype developed for this application can yield information close to gravimetric data for the three test sites (Maize SSE [sum of squared error]: 5.97, Wheat SSE: 19.81, Pastureland SSE: 12.71) in agreement with TDR data.**

***Index Terms*—Soil moisture measurement, soil electrical impedance, artificial neural network, wireless sensor.**

I. Introduction

The importance of sustainable development in the global context, is widely recognized [1] as a key factor to mitigate climate change, favour economic growth and social development while preserving the environment. In particular Mexico has shown great commitment to take environmental policy seriously by introducing regulatory environmental laws with clear actionable goals; Mexico is a signatory of the Kyoto protocol and was the first developing country to submit a climate action plan ahead of the 2015 Paris Agreement. In addition Mexico's, National Strategy on Climate Change: Vision 10-20-40 (*Spanish: Estrategia Nacional de Cambio Climático: Vision 10-20-40* [2]) recognizes the vulnerability of Mexico to climate change and establishes actionable guidelines towards sustainable development. Despite the Mexican efforts to introduce domestic legislation and planning, as well as efforts to comply with international environmental policies, a recent report [3] highlights the challenges Mexico faces to attain sustained development.

One particular aspect of strategic interest for Mexico is adequate management of water resources since it plays an essential role towards achieving sustainable development. The United Nations (UN) Sustainable Development Goal (SDG) 6, identifies water-use efficiency and water resources management as a key component of the sustainable development agenda. In accordance with the Bellagio Principles on valuing water" the Mexican Strategy on Climate Change (*Spanish: Estrategia Nacional de Cambio Climático* [4]) highlights the significance of research, development for improving water resources management; therefore, it is necessary to conduct development, adoption and adaptation of ad hoc technology according to regional needs and conditions, to generate knowledge that can be translated into feasible solutions to increase the efficiency of water usage.

In turn, soil moisture measurements plays an important role in elucidating important information about the synergistic relationship between multiple natural and anthropogenic processes in agricultural management systems. In addition, soil moisture is a critical component of the continental land system that influences geomorphologic [5], atmospheric [6]-[7] hydrologic [8] and biological processes [9]-[11]. On the other hand, it is also important that research and development efforts are conducted considering the end user.

There is a wide variety of soil moisture sensing technologies commercially available [12]. However, in developing countries, it is necessary to raise awareness and educate farmers about the benefits of adopting advanced technologies to increase crop yield [13]. Therefore, it necessary to conduct research and development, cantered on the end user in order to facilitate promotion and adoption of new technological developments. In addition commercially available equipment may not be suitable for measuring water content in some types of soils, and could be difficult to

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integrate the resulting measurements into existing, publically available, information data bases. Thus there are incentives to develop versatile ad hoc soil moisture sensing technology considering regional soil and characteristics, in coherence with current development policies.

In this work, the authors present the performance evaluation of a volumetric soil moisture sensor. The design stresses ease of use and versatility to include the ability to measure other soil parameters as well as atmospheric variables. The measurement principle is based on the use of a set of cylindrical electrodes inserted into the soil sample to measure the soil impedance. One of the variables that have been show to influence electromagnetically-derived soil moisture measurements is soil temperature [14-[15]. In [16] the authors presented a soil moisture sensor with temperature compensation using a Backpropagation Artificial Neural Networks (ANN) to adjust the measurements for the soil temperature influence on the impedance measurements. In this work the authors use a similar approach, based on ANN to compensate the impedance measurements for soil temperature values. One of the main difference relies in the manner in which the soil impedance is measured. In [16] the soil impedance is measured using a self-balanced impedance bridge. Here, the authors use a four point measurement strategy (V+, I+; V-, I-) and an analogue demodulation process to obtain the real and imaginary components of the measured signals that translates into complex impedance values. In addition, the performance of the soil measurement device is compared with data obtained using a Time domain Reflectometry measurement system on three different test sites: maize, wheat and Pastureland. The manner in which the sensor stores the information is of great importance to allow storing records of long term measurements.

A. *Time Domain Reflectometry measurement methods*

The recent advances in satellite-based soil moisture measurements have resulted in cost-effective mapping of wide areas [17]-[18]. However, it is still necessary to validate remote sensed data with in situ data [19]. Amongst the techniques that have gained wide world amongst researchers and producers to obtain in situ soil moisture data are electromagnetic sensing methods [20].

In particular, since Topp [21] reported the use of Time Domain Reflectometry (TDR), TDR measurements have gained international acceptance due to its ability to provide quick in situ data. The TDR method is an indirect measurement technique that measures the propagation time and reflection of a high frequency pulse along a waveguide. The waveguide is composed of a set of electrodes; the electrodes are inserted into the soil in the test site. The measurement principle relies on the influence of the dielectric constant of the material surrounding the electrode set. In principle, the propagation time of the electromagnetic pulse travelling along the waveguide can be obtained from (1):

$$t = \frac{2L\sqrt{k}}{c} \quad (1)$$

where L is the length of the waveguide (m), c is the speed of light in free space ($m\ s^{-1}$), k is the relative permittivity of the medium where the waveguide resides, and t is the propagation time (forth and back) of the signal (s) along the waveguide.

Thus, the bulk dielectric constant of the material surrounding the waveguide can be obtained from (2):

$$k = \left(\frac{t\,c}{2L}\right)^2 \quad (2)$$

Since the dielectric constant of water (~80) is larger to that of the soil constituents (air: ~ 1, minerals: ~2-4) the propagation time of the electromagnetic wave along the waveguide depends greatly on the volumetric water content [22]: the propagation speed decreases as the dielectric constant increases. Several methods have been proposed to estimate the volumetric electric conductivity, σ, by examining the morphology of the reflected TDR wave. For instance, Nadler et al investigate the use of TDR to measure volumetric water content using TDR and suggest that the propagation time of the reflected wave should be measured at the least inflection point [23]. Although TDR is considerably immune to variables other than moisture content, other reports consider additional factors the influence TDR measurements [24]. For instance, Castiglione and Shouse [25] investigate the effect of cable losses and suggest a compensation method and modifications to the model of the waveguide. Another parameter that influences TDR measurements is soil texture. Ponizovsky et al. [26] suggest the need to include soil texture as a parameter to fit data pertaining to both fine- and coarse-texture soil. Zanetti et al. [27] use an Artificial Neural Network (ANN) for calibration in order to include further soil parameters, of which organic matter content appeared to yield the smallest Root Mean Square Error (RMSE). In addition, from the early reports of TDR measurements to infer soil moisture content, temperature stands out as a prevailing factor that influences TDR measurements. For example, Kahimba and Ranjan [28] report a method for calibrating TRD field data at low temperatures; Skierucha [15] considers the effects of temperature over a wide range (~5 ^{o}C - 55 ^{o}C).

B. *Electrical impedance measurements.*

Dielectric sensors are a low cost alternative to TDR sensors [14] [29] and new measurement devices are continuously proposed [30]. In particular, electrical conductivity sensors [31] are an alternative to TDR since they are safe (use a low power electrical signal) low cost and allow easy integrations into commercial or dedicated data acquisition systems for continuous recording of in situ data. In a similar manner to TDR and capacitance measurements, electrical impedance measurements require a set of electrodes inserted into the soil sample. In general, a voltage controlled current source is used as the soil sample excitation signal. A data acquisition signal conditioning and acquisition system is used to measure the potential that develops in the sensing field. The advantage is that the procedure allows to measure both the resistive and capacitive properties of the soil sample by means of a modulation-demodulation signal processing circuit. Thus the real and imaginary components of the measured signal can be used to quantify the soil water content based on a priori calibration procedure.

Previous results of using electrical impedance measurements indicate that they are suitable for measuring soil moisture. In addition, there are indications that a soil temperature compensation scheme should be sought. The work described in this document focuses on the validation of the sensing technique based on demodulation of the measured signals obtained in situ in comparison with TDR measurements.

II. Materials and Methods

Recalling Mexico's current development needs, the development of new sensing technology has to stress ease of use and integration into knowledge based information systems. In addition the data acquisition system has to be flexible so as to be able to measure other environmental variables. Therefore, the system should be capable of accepting signals derived from sensors with different output protocols (analogue and digital). In order to test the measurement and data gathering strategy a prototype was developed corresponding to NASA's TRL 4: "prototype proof-of-concept" tested under field conditions. The soil parameters chosen to be included in the prototype are soil temperature and soil moisture content. The soil moisture sensing technique chosen for this application is soil electrical impedance. Since the aim of the work is to validate the soil moistures measurements in a test site, the communications configuration will be restricted to operate in a short distance as a local area sensing device.

A. *Electrode array*

Fig. 1 shows the geometry of the electrode array. The electrode array is set of two electrodes mounted in isolation base (Nylamid). The sensing array is a set of two 30cm long, stainless steel electrodes mounted on an isolating (Nylamid) base. In open air, the impedance can be approximated to (3) [16]:

$$C_{electrodes} = \frac{\pi \, \varepsilon_0 \, l}{ln\left(\frac{d-a}{a}\right) k} \qquad (3)$$

where l is the electrode length, a is the diameter of the electrode, d is the distance between electrodes, k is the dielectric of the material between electrodes (kair≈1 and k water≈80).

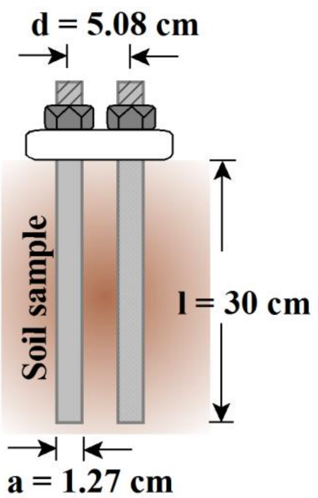

Fig. 1. Electrode array (stainless steel electrodes) for soil moisture measurements.

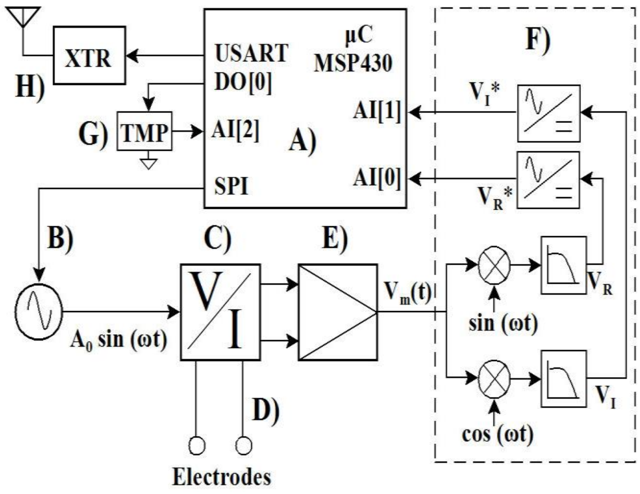

Fig. 2. Schematic diagram of the soil moisture instrumentation system. A) A microcontroller. B) Sinewave generator. C) Voltage controlled current source (VCCS). D) Electrode array connector. E) Differential amplifier. F) Demodulation module. G) Temperature Sensor. H) Radio transceiver

Equation (3) is used to determine the appropriate geometric values of the sensor array.

B. *Data acquisition system*

Fig. 2 depicts the data acquisition system schematic diagram. The core of the design is a low power 16-bit RISC microcontroller (MSP 430FRxx, Texas Instruments) with 2 kB of RAM, 64 kB of non-volatile memory, 8 12-bit analogue-to-digital converter channels, 52 general-purpose input/output pin, 2 I^2C ports, 4, SPI ports and 2 USART ports. The non-volatile memory available allows storing the sampled data, functioning as a data logger. The signal excitation is controlled using a 2 V, 20 MHz, voltage signal. The number of input/output ports available allows interfacing with the transceiver module and sensing electronics. The voltage signal is measured using an array of high-speed operational amplifiers configured as an instrumentation amplifier. A demodulation circuit is used for obtaining both the magnitude and phase components of the measured voltage.

The microcontroller measures the voltages corresponding to the real and imaginary components and calculates the resulting impedance. The microcontroller device also activates the temperature sensor and measures the resulting voltage through an analogue-to-digital port. When the instrument operates as a data logger, the microcontroller switches on the soil humidity and temperature measurement sections, awaits 1 second to get stable measurements before acquiring the data. The data is stored in the non-volatile memory and then enters into sleep mode to save power. When the radio transceiver senses a data request command issued by the host computer, activates the microcontroller which in turn reports the data, either continuously or that stored in non-volatile memory.

The measurement scheme is power efficient, since the sensing electronics are active only during the measuring time.

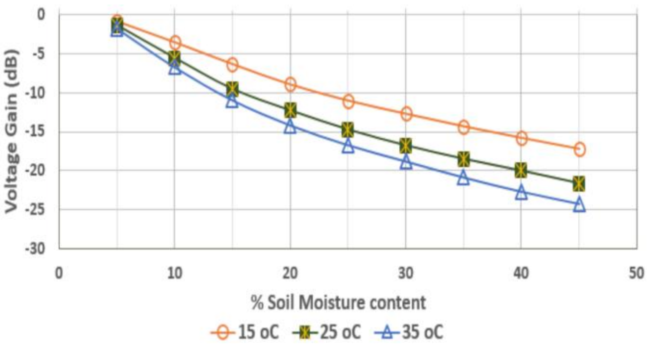

Fig. 3. Attenuation of the applied voltage (20 log $\Re\{V_m(t) /(A0 \sin(\omega t))\}$. Sensor response shown for different soil moisture concentration (5% to 45%) and different temperatures (15 °C, 25 °C and 35 °C).

C. Soil temperature

A semiconductor temperature sensor (TMP 36, Analog Devices) is used for measuring soil temperature. The TMP 36 is a low power compensated sensor, and thus can be powered directly from a digital output port of the microcontroller. The sensor is mounted in a cylindrical rod, leaving only the sensing tip of the sensor exposed. The temperature sensor is inserted into the soil sample locating the sensing area of the TMP36 at 15 cm depth, half the length of the electrodes.

D. Soil moisture measurements

The soil moisture sensor is dedicated for measuring soil moisture in high clay contents soils, which are characteristic soils in the Purepecha Plateau (Michoacán México). In order to determine the sensor response to different soil moisture contents and translate soil impedance measurements into soil moisture content, the response of the sensor array was tested in laboratory. A test phantom was filled with soil samples from the intended test site (68% Clay, 12% Sand, 20% loam). Impedance measurements where obtained at different soil moisture concentrations (by wt.) and different temperatures. Fig. 3 shows the results of laboratory tests of measuring the soil temperature and soil impedance simultaneously.

The sensor output is similar to that of the excitation signal for low soil moisture concentrations. When the soil moisture content increases, the signal attenuation (and thus the soil impedance) increases due to the increased conductivity of the medium. In addition, Fig. 3 shows that the temperature has a noticeable effect on the sensor response. The signal attenuation increases as a function of temperature, probably due to increased ion mobility of the soil-water mixture. Thus it is necessary to compensate for temperature variations.

E. Temperature compensation

One of the signal compensation methods that have been proposed for correcting electromagnetically-derived soil moisture measurements is the use of Artificial Neural Networks (ANN) [32]. In order to compensate the soil moisture measurements for soil temperature variations, a Back Propagation Artificial Neural Network was used as described elsewhere [33]. The neural network is a feedforward, 2 layer network (tanh sigmoide, linear) commonly used for regression analysis.

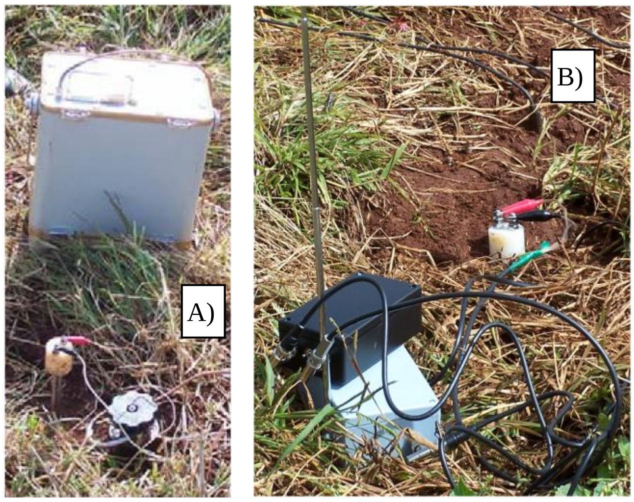

Fig. 4. A) Location of the electrode sets for soil impedance and TDR measurements. B) Soil moisture measurement system.

F. Experimental setup

The prototype performance was investigated in a test site located in the Purepecha Plateau (Michoacán, Mexico). Ten measurements were obtained weekly (October 2017-December 2017) using the prototype described in this manuscript. A commercial soil moisture measurement equipment was used (*6050X1 Trase System*), to obtain measurements 15 cm from the prototype electrode set. A soil sample from the test site was obtained after both electromagnetic measurements were conducted, for comparing the performance of both instruments (Fig. 4).

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III. Results and Discussion

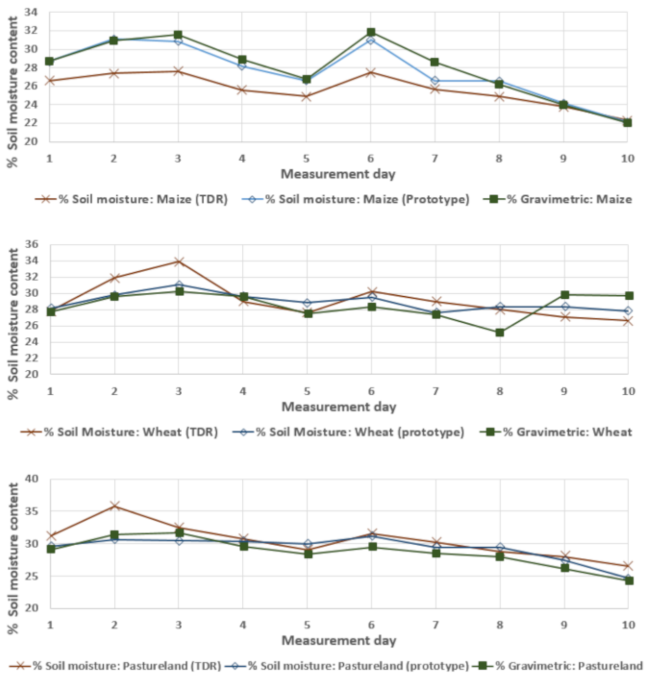

Fig. 5. Comparison of the soil moisture content measurements for three test sites (maize, wheat and pastureland) using Soil impedance, TDR and gravimetric measurements,

Fig. 5 shows a comparison of soil moisture content measurements obtained from the soil impedance (e. g. the prototype described in this work), TDR and gravimetric measurements as reference.

The results shown in Fig. 5 correspond to the average of ten measurements taken each week, from the maize, wheat and pastureland fields. There is a close relationship between TDR and soil impedance measurements with reference with gravimetric data. However, by examining the average error (Fig. 6), the results show a closer relationship between the soil impedance measurements with the gravimetric data than that of the TDR.

In fairness to the TDR measurement method, the smaller error obtained from soil impedance measurements, may be due to the fact that soil samples from the test site where used for deriving the compensation method. In addition, it has been reported that TDR measurements may tend to overestimate the soils water content in high-clay soils [34]. The measurements on wheat and pastureland agree with this assumption. However, the TDR measurements in the maize crop appear to underestimate the soil water content. This may be due to other variables such as soil compactness, biological, mineral content and salinity; these effects were not investigated in this work and suggest further examination of the test sites in future works. In any case, the soil impedance measurements yielded a close approximation to gravimetric data (Table 1) and suggest that the proposed method is suitable for use in high clay soils and can yield information close to TDR data.

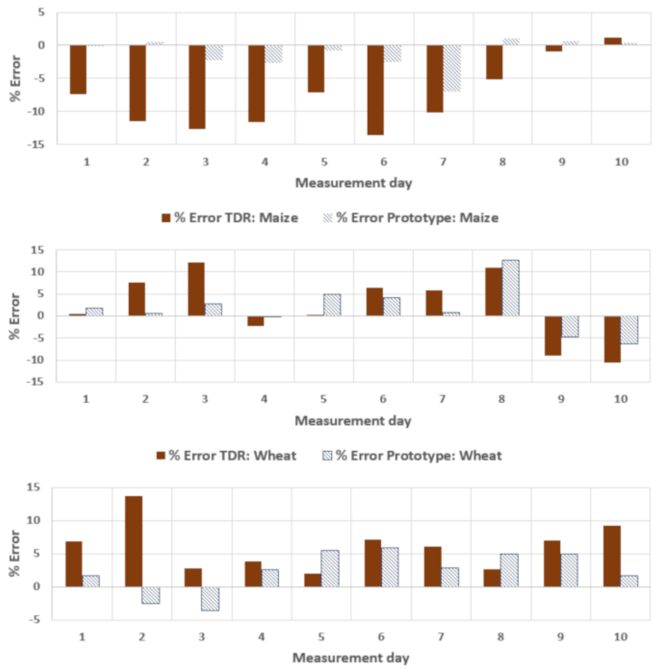

Fig. 6. Comparison of errors (result of averaging ten in situ measurements each sample date) of the electromagnetic measurements (TDR and soil impedance) with reference to gravimetric data.

Table 1. Summary of sum of squared Error (SSE) and error standard deviation

	Maize		Wheat		Pastureland	
	TDR	Soil Impedance	TDR	Soil Impedance	TDR	Soil Impedance
SSE	76.72	5.97	49.87	19.81	41.58	12.71
STD DEV	6.35	1.18	4.33	2.90	5.12	0.92

IV. Conclusions

This work examines the performance of a soil moisture measurement system based on soil impedance measurements. The measurement strategy uses a signal demodulation procedure to obtain the soil impedance real and imaginary components. Laboratory tests show the temperature dependence of the soil impedance measurements over a wide soil moisture content, typically encountered in rain fed soils. In particular for high-clay content soils, the results suggest that the proposed measurement scheme is suitable for in situ measurements. In addition, the ANN-based temperature compensation method appears to be a suitable technique to yield a close measurement to the real soil moisture content. The method requires using direct gravimetric measurement to calibration. However, it is no different from other electromagnetic measurement methods that require calibration to adjust for particular site conditions. The architecture of the prototype in intended to facilitate including further environmental measurements. The ANN-based compensation scheme is versatile since it can then be extended to accommodate those other measurements to improve. Therefore, the results suggest that the instrumentation method and apparatus is suitable for obtaining soil moisture information for high-clay type soils, commonly found and can be a cost-effective alternative to its TDR counterpart.

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