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Development of an Affordable Soil Moisture Sensor System with Mini-VNA Tiny and Smartphone

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ABSTRACT

This study attempts to develop a soil moisture measurement system with a monopole antenna sensor, mini-VNA Tiny and a mobile phone respectively. The mini-VNA Tiny is a compact vector network analyzer (VNA) with a USB connection to a smartphone or a tablet. There are 17 sets of data which have been collected from 15 different spots with varying soil moisture content. The actual moisture content on site was collected from TRIME-PICO 64/32 sensor. Upon collection, it was necessary to calibrate the resistance obtained from the mini-VNA between 1 MHz and 3 GHz. The data obtained from the study shows that the resonances of the antenna resistance shift to the left on the frequency spectrum as moisture content increases. A linear model relating the resistance and actual moisture content was developed from this study with coefficient of determination (R^2) value of 0.723 at 13 MHz. This value is much less than the anticipated $R^2 = 0.95$ for accurate measurement of soil moisture with monopole antenna at microwave frequency. This could be due to the 0.60 cm thickness of the monopole antenna which may not be suited for soil moisture measurement. Nonetheless, this study demonstrates the potential application of an inexpensive and portable mini-VNA Tiny and smartphone system for sensing applications.

Keywords: Monopole antenna, resistance, sensor, soil moisture, VNA

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INTRODUCTION

Water is one of the most important components of soil especially for the growth and health of plants. Water content or soil moisture can be regarded as an indicator to determine how much water is present in soil (Kalita et al., 2016). Water content in soil is subject to seasonal changes (Illston et al., 2004) and climate change (Várallyay, 2010). In addition, it is also vulnerable to pollution due to anthropogenic activities such as improper waste disposal (George et al., 2014), among others.

On-going research and general interest in soil science require substantially accurate and quantifiable methods of measuring soil moisture. Presently, one of the most widely-accepted non-destructive methods of measuring soil moisture is by means of electromagnetism, specifically time domain reflectometry (TDR) (Souza et al., 2003; Topp & Davis, 1985; Topp et al., 1980). In fact, various TDR type soil moisture probe sensors are developed and sold under different brands such as the Trime Pico 32 sold by IMKO Micromodultechnik GmbH.

Even though standard professional instruments such as Trime Pico 32 can offer an accurate measurement of soil moisture, they are also quite expensive. McCracken and Yoon (2016) reported that the high cost of scientific instruments was detrimental for effective environmental monitoring and protection in developing countries. To address this problem, Sagasti (2004) recommended replacing expensive conventional scientific instruments with more affordable "virtual" alternatives made possible by advances in computing technology.

Therefore, this study aims to utilize one of the latest miniature technologies in electromagnetics, namely the mini vector network analyzer (miniVNA), for soil moisture measurement in an attempt to minimize costs. MiniVNA is a big leap in electromagnetic technology, having a size that fits into an average human palm at a fraction of the cost of standard table-top VNAs. However, understandably, miniVNA has a limited range of operating frequency compared to table-top VNA due to its small electronics. A past study found that miniVNA functions as effectively as table-top VNA in terms of resonance frequency measurement despite its small size (Rai, 2015). This study could be the first to utilize this technology specifically for soil moisture measurement.

MATERIALS AND METHODS

Fundamental Theory of TDR

TDR measurement deals with the discontinuity in the microwave or radio frequency transmission medium. Consider an example shown in Figure 1 where a wave is propagating through a transmission line with two different impedance characteristics (Z). When the wave reaches the boundary represented by the dashed line, some of its energy will be reflected back to the source and some will propagate through the boundary. The reflected energy can be measured; hence, the term reflection coefficient (Γ) is defined as the ratio of the reflected wave (E^-) and the incident wave (E^+) respectively (Pozar, 2006):

$$\Gamma = \frac{E^-}{E^+} = \frac{Z_S - Z_L}{Z_S + Z_L}$$

$$Z = R + jX$$

Where *Z* is a complex number consisting of resistance, (*R*) as the real component and reactance (*X*) as the imaginary component. A VNA is a device that measures reflection coefficient and impedance of an antenna.

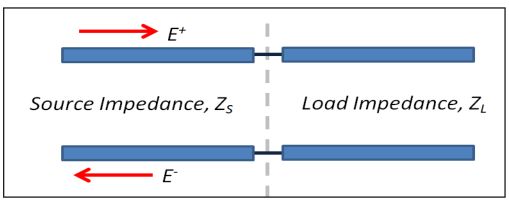

Figure 1. Transmission line theory

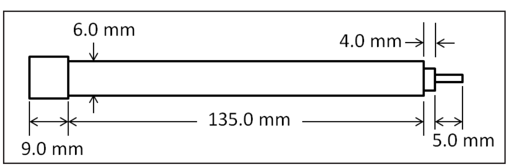

Figure 3. The diagram of the telescopic antenna (not to scale)

Figure 2. Telescopic VHF radio antenna attached to the miniVNA Tiny

Experimental Setup

The miniVNA Tiny used in this study had been developed and sold by Mini Radio Solutions (MRS). This device was developed mainly for the purpose of checking radio and antennas for ham communication from the high frequency (HF) to super high frequency (SHF) range. Indeed, miniVNA Tiny operates between 1 MHz and 3 GHz operating frequency with a step of 10 Hz. It can be used for impedance between 1 and 1000 Ohm. A smartphone was needed to power miniVNA Tiny as well as to obtain the measured data. The application to operate miniVNA Tiny was downloaded from Google Play. The antenna for the sensor probe was a standard 0.60-cm thickness telescopic very high frequency (VHF) radio communication monopole antenna with the tip removed for better soil penetration as depicted in Figures 2 and 3. This antenna can be easily obtained from either physical or online electronic stores. A monopole antenna is an obvious choice since it is simple, inexpensive and can easily penetrate soil. The antenna used in this study is also sufficiently rigid to withstand pressure from dense soil. In addition, a monopole antenna was used in past studies to measure soil moisture (Denoth, 1995; Sagnard et al., 2009). A 50 Ohm cable was used to connect VNA with the antenna probe. The "true" soil moisture was determined with the professional de-facto standard IMKO Trime Pico 32 probe. Figures 4 and 5 show the experimental setup and the standard probe.

MiniVNA Tiny was used to measure the resistance of the antenna probe when inserted into the soil. Figure 6 shows the measurement of the antenna resistance with miniVNA Tiny. For every new measurement, the antenna probe was cleaned of any moist and debris before a new measurement was taken. A total of 18 sets of measurements was collected around the pond near the Faculty of Environmental Studies in the UPM main campus between August and November 2016. The "true" values of soil moisture, obtained from the Trime Pico probe (as mentioned in the preceding section), were needed to calibrate with the

Figure 4. Experimental setup diagram

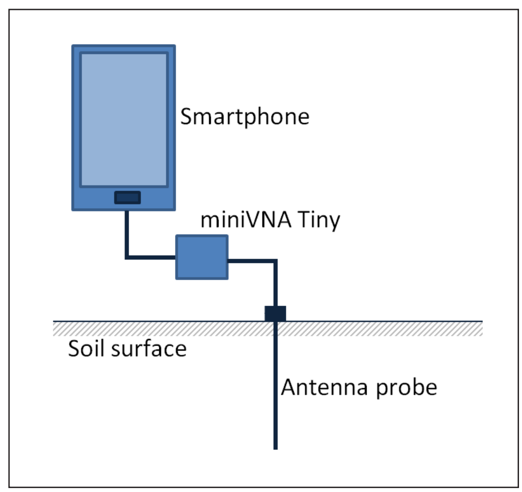

Figure 5. Measuring soil moisture with the standard probe

Figure 6. Measuring antenna resistance

antenna probe resistances. Note that the resistance was calibrated with soil moisture only. The ratio of sand, silt and clay was measured so as to determine the consistency of soil samples in the study area which would be discussed in the results and discussion section. The measurements were taken with the assumption that there was no subsurface metal object or huge cavities in soil or other factors which could significantly impact upon the resistance of the antenna and hinder the accuracy of Trime Pico probe readings.

RESULTS AND DISCUSSIONS

Soil Texture Determination

This step is important in order to determine the extent to which the soil texture in the study area is consistent or not. If the soil texture in the study area is not consistent, it cannot be determined for certain that soil texture does not significantly impact upon the readings of the antenna. Three samples were collected from the area and the compositions of sand, silt and clay of the samples were determined by using the standard hydrometer procedures (Bouyoucos, 1936). It was found that all samples had consistent compositions as tabulated in Table 1, indicating that the type of soil in the area was sandy loam according to the standard United States Department of Agriculture (USDA) soil classification system. Therefore, the antenna resistance would only be calibrated with soil moisture since the composition of soil in the study area is consistent.

Table 1
Composition of sand, silt and clay for all samples

	Sample 1	**Sample 2**	**Sample 3**
Clay	6.10%	4.55%	6.06%
Silt	27.2%	22.75%	19.7%
Sand	66.7%	72.7%	74.24%
Type	Sandy loam	Sandy loam	Sandy loam

Antenna Resistance

Figure 7 shows the variations of antenna resistance for the purposes of measuring soil resistance. Only the resistance of the antenna is considered for analysis in this study. The reactance, impedance, reflection coefficient and phase angle of the monopole antenna were not considered due to time restrictions of the project. The multiple resonance peaks observed in the plot can be attributed to the mismatches between the impedance of the 50 Ohm cable and the impedance of the antenna and the soil combined (Pozar, 2006). It can be observed that, in general, these resonance peaks shift toward the left as soil moisture increases since moisture impacts the impedance of both antenna and soil as explained in (Denoth, 1995; Kupfer, 2005; Sagnard et al., 2009). These shifts can generally be significant at certain frequencies and less significant at other frequencies since the performance of any antenna depends heavily on operating frequencies (Balanis, 2005). Note, however, that the antenna is fabricated for radio communication in the VHF region as stated earlier and not specifically for soil moisture measurement. The plot in Figure 7 is useful in order to study the relationship between monopole probe resistance and soil moisture respectively. A numerical calculation to model the performance of the antenna is outside the scope of this research.

Further analysis reveals that the strongest correlation between resistance and soil moisture was found at the operating frequency of 13 MHz. This could be due to the fact that the dielectric constant and loss factor of water are the highest and the lowest, respectively, at low frequency, $f < 100$ MHz (Kupfer, 2005). This frequency (13MHz) is also well within the range of bound-water relaxation frequency (which is also true for other field and remote soil moisture sensing (Escorihuela et al., 2007). The impact of bound-water is more pronounced in clay since it retains more water compared to sand and clay. Therefore, since the percentage of clay at the study area is low, the impact of bound-water on soil moisture measurement might not be significant (Owe & Van de Griend, 1998).

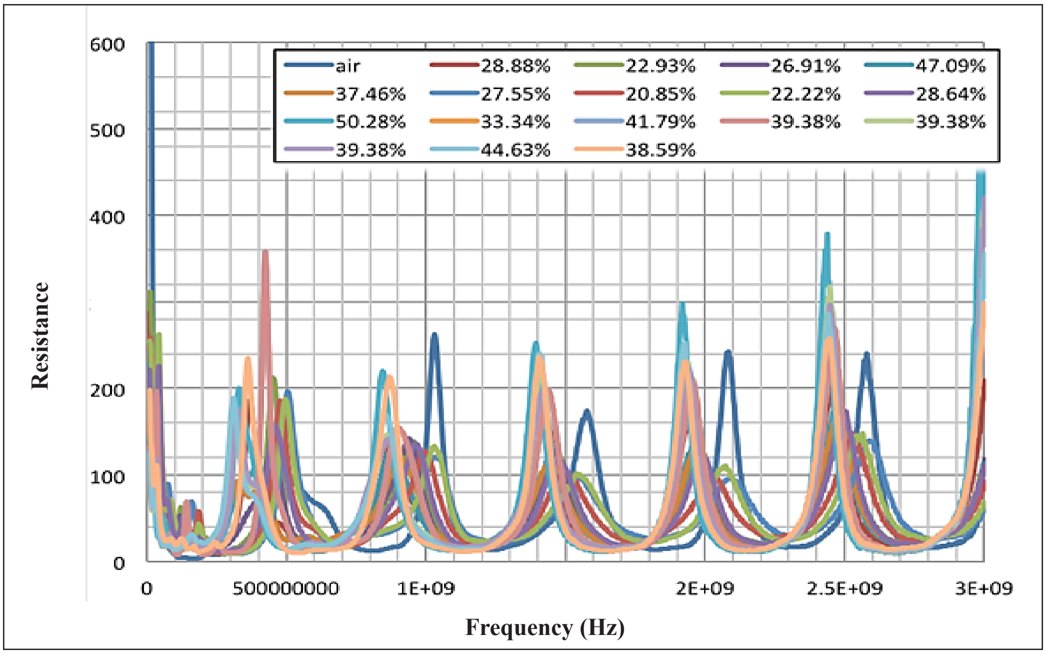

Figure 7. The variations of monopole probe resistance (Ohm) against frequency (Hz) for different soil moisture (%)

A linear calibration model relating resistance and soil moisture was established at 13 MHz as well as shown in Figure 8. Other types of regression models yielded much less value of R^2. The coefficient of determination of the calibration model was found to be

0.723. Unfortunately, this coefficient is much less than the anticipated value of 0.95 and is not sufficiently high for practical soil moisture measurement as has been demonstrated in other studies (Hernandes et al., 2018; Pichorim at al., 2018). This could be due to the fact that the antenna probe used in this study is not specifically designed for measuring soil moisture but for radio communication. Even though the antenna probe can easily penetrate soil and is sufficiently rigid, it is apparent that losses due to the mismatch between the antenna probe and a 50 Ohm cable outweigh any benefits. In order to minimize these losses, a custom-made monopole antenna probe is recommended, having similar dimensions with the standard IMKO Trime Pico 32 probe.

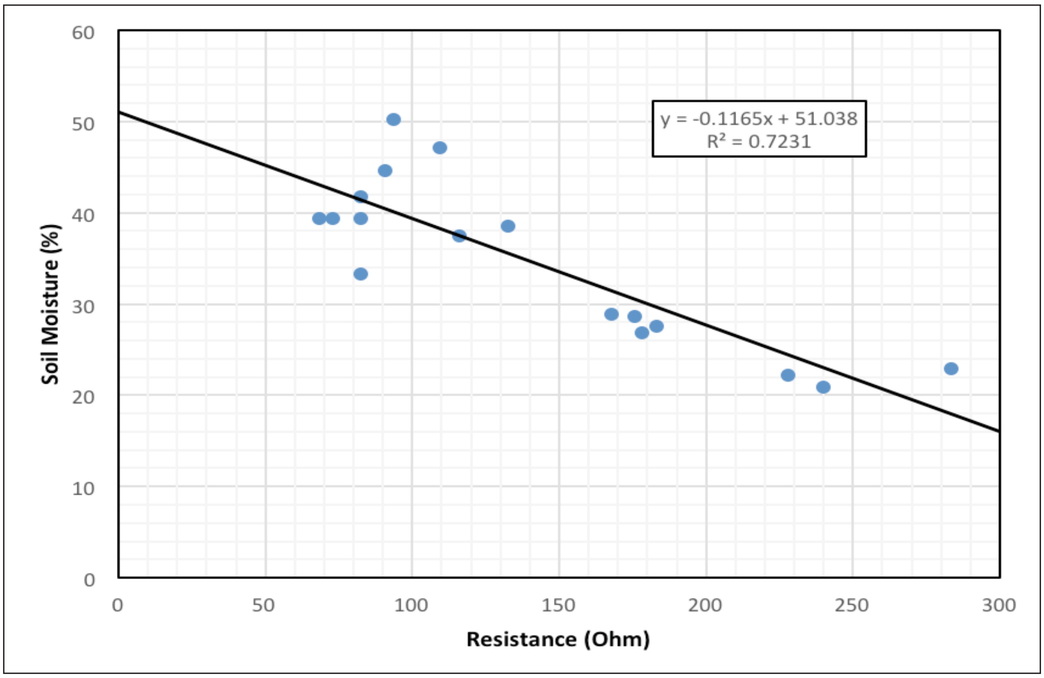

Figure 8. The variation of soil moisture against resistance at 13 MHz and calibration equation relating to soil moisture and resistance

CONCLUSIONS

This study demonstrates the use of MiniVNA Tiny, a smartphone and a monopole antenna probe to determine soil moisture at the specified location. MiniVNA Tiny was considered in this study as an affordable VNA through which to power the antenna probe and measure antenna probe resistance. This device is also substantially small and light and can be carried to the field for measurement. A calibration model relating antenna probe resistance and true soil moisture was developed based on measured data. Even though the accuracy of the model is not sufficiently high for practical measurement of soil moisture, improvement in the antenna probe design could reduce losses in the transmission line; thereby improving the accuracy of the model. Nonetheless, this study has shown that there is great potential for MiniVNA Tiny to be used as an affordable, small, light and portable VNA for determination of moisture content of moist materials such as fruits and latex, among others.

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