

Precise Moisture Monitoring for Various Soil Types Using Handheld Microwave-Sensor Meter

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Abstract—A handheld microwave reflectometer-sensor system is developed to operate from 1.35 to 1.95 GHz and used to measure volumetric and gravimetric moisture content in various types of soils from 0% to 45%. A small monopole driver from coaxial line is buried into the soil, and its reflected voltage is measured and correlated with corresponding soil moisture content obtained from oven drying method. The measured reflected voltage is dependent on the nonlinear change of dielectric properties of the soil with the moisture content.

Index Terms—Frequency domain reflectometry, monopole sensor, reflected voltage, relative permittivity of soil, RF handheld reflectometer, soil moisture.

I. INTRODUCTION

RECENTLY, microwave electronic components are increasingly common with even more affordable price in the market. This situation becomes an advantage for researchers to apply microwave technology to other fields of science, especially in the food industry, medical and agricultural fields. Consequently, adding more microwave technology products into the market and used by consumers. Microwave electronic device has been used in daily life, especially microwave oven, due to the polarization of water molecules contained in the material which is sensitive and showed a significant response when exposed to microwaves. Besides,

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tendency of water to absorb microwave energy, allowing the microwave device to be used as a measuring technique to sense the moisture content, $m.c$ in a material containing water.

Soil Moisture content, $m.c$ is one of the most essential physical characteristics in agriculture, civil engineering, landscaping, irrigation engineering and hydrology, since the consistency and workability of a clayey soil strongly depend on its moisture content, $m.c$. There are two methods of determining moisture content, $m.c$ of soil, which are the direct method and the indirect method. Direct method determine the moisture content, $m.c$ by removing the moisture content, $m.c$ of soil using oven drying method. The direct method is the most accurate method to determine the soil moisture content, $m.c$, but it is time consuming. In contrast, indirect method requires the measurement of the electrical property of the soil using fabricated instrument, so-called moisture meter. The change in electrical properties that can be directly correlated with a change in the actual moisture content, $m.c$ of the soil obtained from oven drying method (direct method). Recently, the indirect methods become more popular than the direct method due to rapid test, high sensitivity and user friendly features.

Since the 1970's, a credible method, so-called Time Domain Reflectometry (TDR) techniques [1] became a popular method for determining the moisture content, $m.c$ in the soil at microwave frequencies. However, the time domain method requires an expensive instrument component in the measurement. Previously, the soil measurement using TDR method is independent of soil types and therefore, no soil calibration is being carried out. In the 1980's, many literatures and information related to TDR techniques have been intensively reported by Topp (1980) Recently, many researchers are still improving the TDR technique [2], [4], [5] and its soil calibration [3]. The time domain measurements are based on the change of the dielectric properties (relative permittivity, ϵ_r) of soil under test, since the volume of moisture in the total volume of soil heavily influences the relative permittivity of the soil. This is due to the relative permittivity of pure water ($\epsilon_r \approx 80$ at very low frequencies) normally being much greater than that of the other constituents in the soil (mineral soil: $\epsilon_r \approx 4$, organic matter: $\epsilon_r \approx 4$, air: $\epsilon_r = 1$). Thus, the travel time of reflected signal that can be directly correlated with changes in moisture content, $m.c$ of the soil using the probe sensor. Recently, most low-cost moisture meters in the market only involve DC circuit by measuring the soil resistance or conductivity. Some of those meters do not require electricity, in which the electricity in the meter is generated from the soil sample

itself. The ionic conductivity, σ in the soil interacts with the probe sensor to create a small amount of voltage in the meter, but, this measurements will cause less sensitivity to the dry soil measurement due to lack of free ionic in the dry soil. Furthermore, those meters can only measure one type of soil for a narrow measurement range of moisture content, $m.c$. Besides that, the sensitivity of measurement towards the water contained in the soil requires extensive interaction between the probe sensor surface and soil samples.

Here, we attempt to introduce a simple and relatively low cost portable microcontroller-based frequency domain reflectometer for soil moisture monitoring at room temperature. Most high-end handheld soil meter on the market only operates at frequencies less than 1 GHz. However, this reflectometer uses Frequency Domain Reflectometry (FDR) technique which operates from 1.4 GHz to 1.5 GHz is designed to improve the sensitivity of measurement. A Small monopole driving from coaxial line was used as a probe sensor, which is connected to the reflectometer via coaxial cable. Similar to TDR, the measurement using this frequency domain reflectometer is dependent on the changes in the soil dielectric properties due to changes in soil moisture content, $m.c$ [8]–[12]. The advantage of this meter is its ability to determine the moisture content, $m.c$ for different soil types. The accuracy of the measurement is equivalent to TDR method and the advantage is that the size of sensor probe is relatively smaller compared to TDR probe. In this work, the reflectometer is calibrated by determining the moisture content, $m.c$ for three types of soil (sand, peat and loam). The reflectometer can give an output reflected voltage, V_r which is linearly proportional to the natural dielectric properties of the soil over the moisture measurement range. In addition, the programmable reflectometer is controlled by a microcontroller and can be used to monitor the water content, $m.c$ in different soil types without applying any soil calibration procedures.

The calibration models for the three types of soil were programmed and allow conversion from measured reflected voltage, V_r to moisture content, $m.c$, display. The specification information (chemical & other physical properties) of the three types of soil was tested using conventional method which will be discussed in Section III [6], [7]. The reflectometer has been programmed so that each type of soil is measured at a specific frequency, respectively (Sand: 1.42 GHz, Peat: 1.47 GHz and Loam: 1.494 GHz). Besides moisture content, $m.c$, the soil dielectric values are also displayed in the LCD meter simultaneously.

II. FABRICATED REFLECTOMETER-SENSOR SYSTEM

A. Reflectometer Specification and Performance

The design of the microwave reflectometer is mainly consist of a microcontroller, a voltage-controlled oscillator (VCO), a directional coupler, a power detector, a 16×2 characters LCD display (in Fig. 1), and a fabricated monopole sensor. The schematic diagram for the reflectometer-sensor system is shown in Fig. 2. The VCO in the reflectometer is able to generate signal frequency from 1.35 GHz to 1.95 GHz when the corresponding voltage supplied is from 1.6 V to 8.7 V as

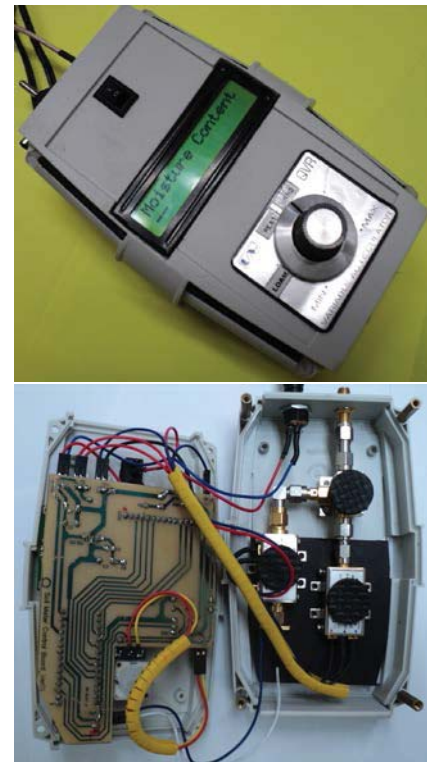


Fig. 1. Configuration of structures and circuits for reflectometer.

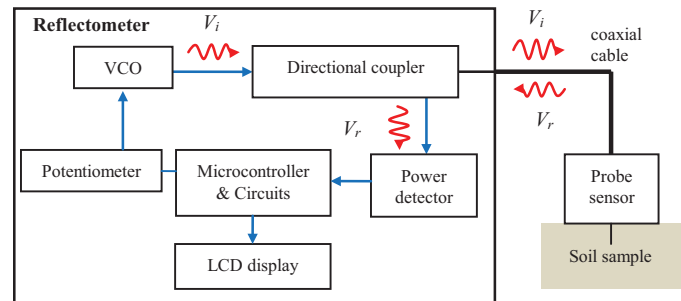


Fig. 2. Variations in generated signal frequency, f with voltage supply, V_{supply} (tuning voltage) at room temperature.

shown in Fig. 3. The reflectometer circuit is designed to provide the measurement range of reflected voltage, V_r from 0 V to 1.70 V with resolution of 1662 mV. The output power, P_{out} from the 30 cm of RD 316 coaxial cable port was measured using PWR-6GHS USB power sensor and the measured power was typically 1.2 ± 0.2 mW as shown in Fig. 4. However, the P_{out} directly supplied from the reflectometer port without going through the cable is typically 1.4 ± 0.2 mW. Therefore, the output power loss in the coaxial cable can be estimated to be ~ 0.2 mW loss.

B. Probe Sensor Specification and Performance

Typically, the sensitivity and repeatability measurement from soil sensor are improved using two or three parallel probe to increase the energy storage density and uniformity distribution energy within the soil sample area. However, only single probe sensor (so-called monopole) was used in this study. The dimensions of the monopole sensor are shown in

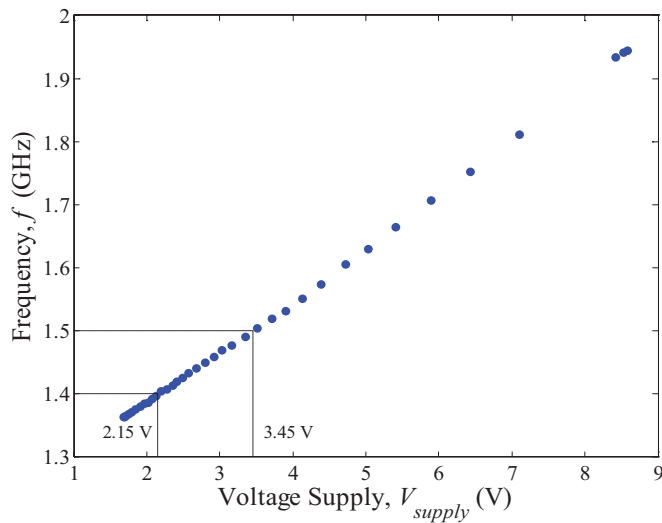


Fig. 3. Variations in generated signal frequency, f with voltage supply, V_{supply} (tuning voltage) at room temperature.

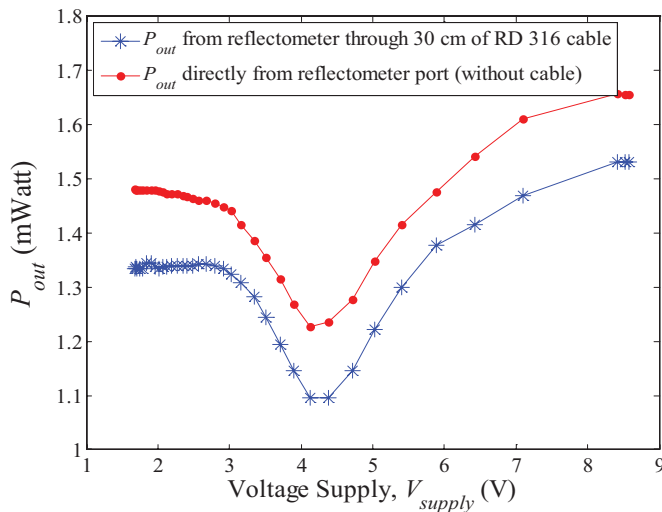


Fig. 4. Variations in output power, P_{out} with voltage supply, V_{supply} (tuning voltage) at room temperature.

Fig. 5, where the length of the monopole driving from the coaxial line is 17.88 mm and this will be buried into the soil for moisture measurement. The advantage of short and small monopole sensor is that less human effort is needed when immersing the sensor into the soil sample. The intensity of the magnetic field distribution generated from the reflectometer through the sensor is simulated to virtual density sensing field surrounding the probe sensor and further determining the probe sensor specification. In the simulation, dry soil and wet soil were assumed to have a value of relative permittivity equal to $\epsilon_r = 2.5 - j0.09$ and $\epsilon_r = 30 - j3.5$, respectively. The simulated magnetic fields, H_θ contour around the half symmetry monopole in the dry soil and the wet soil are shown in Fig. 6 (a) and Fig. 6 (b), respectively. The maximum surrounding magnetic field, H_θ is within 1.9 A/m in the soil when 1.2 m Watt of power, P_{out} is supplied though the coaxial line at 1.45 GHz.

The significant sensing area, d is estimated based on the distance at which the measured reflection coefficient, $|\Gamma|$ at

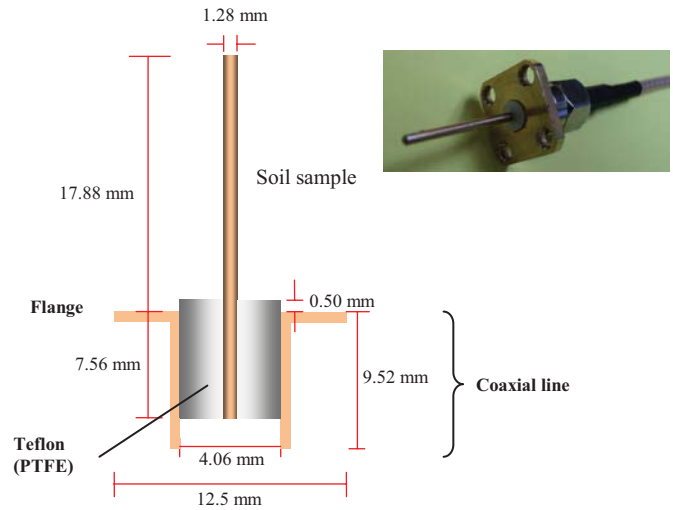


Fig. 5. Dimension and cross-sectional view of monopole sensor.

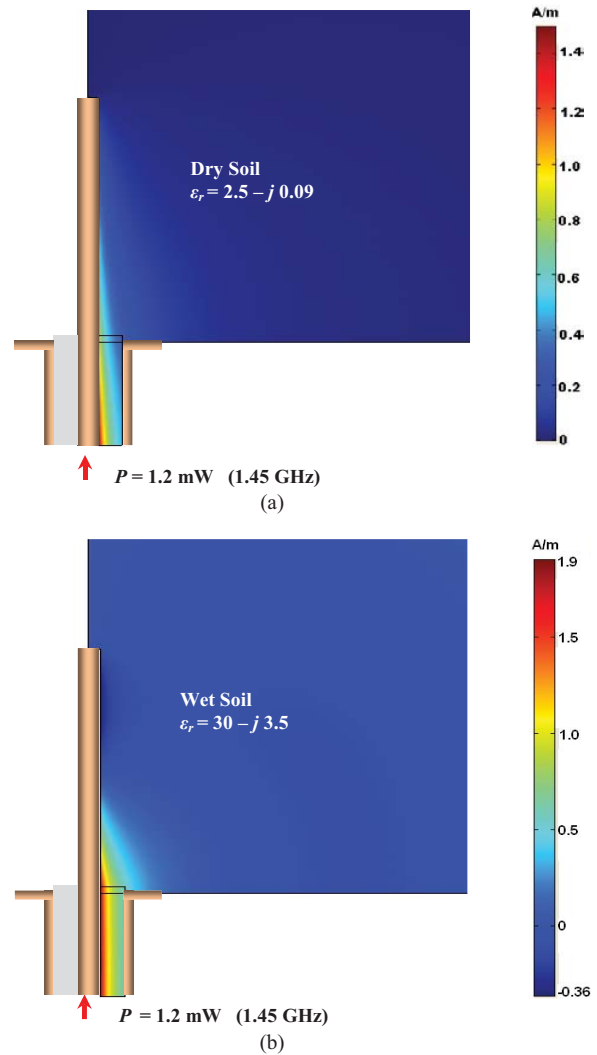


Fig. 6. Distribution of half symmetry magnetic field. (a) H_θ surrounding dry soil. (b) H_θ surrounding wet soil.

1.45 GHz becomes constant when the metal plate is translated away from the top end (case A) and parallel side (case B) of the monopole in the air. The magnitude of the reflection

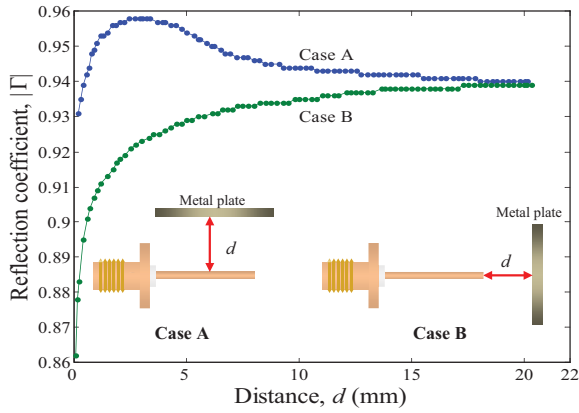


Fig. 7. Variations in reflected signal with distance of metal plate.

coefficient, $|\Gamma|$ at instantaneous distance is measured using E5071C network analyzer and aided with precision translation stage as shown in Fig. 7. We found that the maximum significant sensing area of sample under test is assumed to be 20 mm from the top end and 20 mm from the parallel side of the monopole sensor at 1.45 GHz.

III. CHEMICAL AND PHYSICAL TESTS FOR CALIBRATION SOILS

A. Determination of Metal Elements in Soil

1) *Chemicals and Reagents:* All chemicals and solvents used were of analytical grades. Copper (II) nitrate trihydrate, lead (II) nitrate, nickel(II) sulphate hexahydrate, zinc(II) chloride, magnesium sulphate, aluminium nitrate nonahydrate, iron(II) sulphate heptahydrate, calcium nitrate tetrahydrate, sodium chloride, chromium(III) chloride hexahydrate were purchased from Hamburg Chemical. Potassium nitrate was obtained from Merck. Nitric acid and hydrofluoric acid were purchased from R & M Chemicals. Boric acid, cadmium (II) nitrate tetrahydrate were from Sigma-Aldrich.

2) *Preparation of Standard Solutions:* Stock solution (1000 ppm) of a mixture of metal salt (250 mg), concentrated nitric acid (9 mL), concentrated hydrofluoric acid (3 mL) and boric acid (3 g) was prepared in a 250 mL volumetric flasks. Standard solutions were prepared by diluting from this stock solution and used to obtain the standard calibration curves.

3) *Acid Digestion of Soil Samples:* Soil samples (peat soil, loam soil, sandy soil) were air dried, crushed, and passed through a 2-mm sieve before analysis. 0.2 g of soil sample was dissolved in concentrated nitric acid (9 mL) and concentrated hydrofluoric acid (3 mL) at 180 °C for 15 minutes in a microwave digester (Questron QLAB 8000) as reported in [6]. A reference sample containing concentrated nitric acid (9 mL) and concentrated hydrofluoric acid (3 mL) was prepared as a control.

4) *Preparation of Soil Sample Solutions:* Soil sample solutions were prepared by adding 3 g of boric acid to each of the acid digested soil samples. The solutions were then filtered, and the filtrates were collected in a 100 mL volumetric flask. The final volume of the filtrates was made to 100 mL with

distilled water. The trace metal element concentrations of the soil samples were then determined by using flame atomic absorption spectrometry (Shimadzu AA-6200). Each analysis is conducted in triplicate, and the uncertainty in measurements was less than 10%.

B. Determination of Total Organic Carbon (TOC) in Soil Samples Using Loss-On-Ignition (LOI) Method

5 g of each soil sample was weighed and dried overnight in a hot-oven at 105 °C. The dried soil samples were further heated at 440 °C in a furnace for 24 hours. Afterwards, the soil samples were allowed to cool down in a desiccators and the difference in weight (before and after heating) calculated as the total organic carbon present in the soil samples [7].

C. Determination of Moisture Content in Soil

50 g of each dry soil sample was weighed and mixed with a certain amount of water (1 g, 2 g, 3 g, ...). Then, the relative gravimetric moisture content, $m.c_g$ (gram/gram) in soil sample (dry basis) can be calculated as [14]

$$m.c_g = \frac{m_{\text{water}}}{m_{\text{dry soil}}} \quad (1)$$

From the gravimetric moisture content, $m.c_g$, the volumetric moisture content, $m.c_v$, (cm^3/cm^3) in the soil sample is given as [14]

$$\begin{aligned} m.c_v &= m.c_g \frac{\rho_{\text{dry soil}}}{\rho_{\text{water}}} \\ &= \frac{V_{\text{water}}}{V_{\text{dry soil}}} \end{aligned} \quad (2)$$

where symbols m_{water} and $m_{\text{dry soil}}$ are the weight of water and weight of dry soil sample, respectively. While, symbols V_{water} and $V_{\text{dry soil}}$ are the volume of water and volume of dry soil sample. Symbols $\rho_{\text{dry soil}}$ and ρ_{water} are the dry soil bulk density ($\text{gram}/\text{centimeter}^3$) and density of water ($1 \text{ gram}/\text{centimeter}^3$). The dry soil bulk density, $\rho_{\text{dry soil}}$ was determined using rectangular cavity cube with known mass and cavity volume, $V_{\text{cube}} = 125 \text{ cm}^3$. Dry soil sample was fully filled and compressed in the cavity cube so that the soil is to be compact. The compress dry soil is compact in the cube was weigh and the soil density, $\rho_{\text{dry soil}}$ was calculated as

$$\rho_{\text{dry soil}} = \frac{m_{\text{dry soil}}}{V_{\text{cube}}} \quad (3)$$

D. Measurement for pH and Dielectric Properties of Soil

The pH values for the three calibration soils were measured by burying HI 98127 waterproof pH tester into the soil and record the pH reading from the display LCD tester. The commercial HP85070D dielectric probe was used to determine the relative permittivity, ϵ_r of the calibration soil. The relative complex permittivity, ϵ_r can be expressed as

$$\epsilon_r = \epsilon_r' - j\epsilon_r'' \quad (4)$$

The real part of the relative permittivity, ϵ_r' is called relative dielectric constant. In fact, the imaginary part of the relative

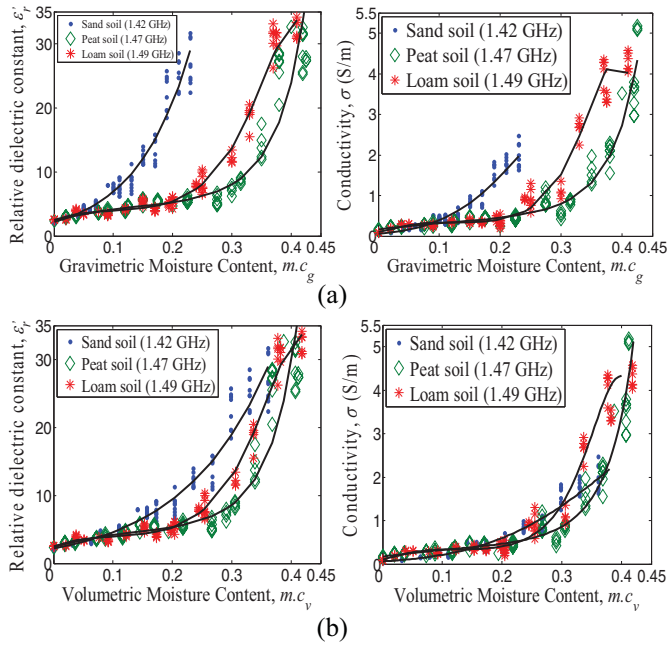


Fig. 8. Variations in relative dielectric constant and loss factor of soil. (a) Gravimetric moisture content, $m.c.g.$, and (b) volumetric moisture content, $m.c.v.$ at $(25 \pm 1)^\circ\text{C}$.

permittivity, ϵ_r'' so-called loss factor, can be used to measure ionic conductivity, σ (in Siemens/meter) of the soil since their relationship can be written as

$$\sigma = \omega \epsilon_r'' \epsilon_0 \quad (5)$$

Symbols ω and ϵ_0 are the angular frequency and permittivity of free space ($8.85419 \times 10^{-12} \text{ Fm}^{-1}$). The variations in relative dielectric constant, ϵ_r' and ionic conductivity, σ of the soil with moisture content ($m.c.g.$ and $m.c.v.$) are plotted in Fig. 8 (a) and (b) including solid fitting line for measurement data. The nonlinear relative dielectric constant and ionic conductivity with respect to the moisture content of the soils are expressed in polynomial forms as listed in Table A1 (Appendix A).

IV. RESULTS AND DISCUSSION

A. Relative Complex Permittivity of Soils

Fig. 8 (a) shows the relative dielectric constant, ϵ_r' and conductivity, σ versus gravimetric moisture content of soils. As expected, the dielectric constant and conductivity for three types of soils increases exponentially with gravimetric water content, $m.c.g.$ [9], [10]. The nonlinear dielectric constant and conductivity for loam and peat soils can be separated into two regions. The first region for loam and peat soils is ranging $0-0.2 m.c.g.$ and $0-0.3 m.c.g.$, while the second region is in the range $0.2-0.4 m.c.g.$ and $0.3-0.42 m.c.g.$, respectively as shown in Fig. 8 (a). In general, the water contained in the soil can either be as bound water (first region) or free water (second region). Particles' shape and density can directly affect the soil's bound water volume

TABLE I
TRACE ELEMENT CONTENT IN SOILS

ELEMENTS (MGKG ⁻¹)	PEAT SOIL	Loam soil	Sandy soil
Cd	n.d.	n.d.	n.d.
Cr	n.d.	n.d.	n.d.
Cu	n.d.	n.d.	n.d.
Pb	n.d.	n.d.	n.d.
Ni	n.d.	n.d.	(0.014%) ^a
Zn	(0.368%) ^a	(0.231%) ^a	(0.207%) ^a
Mg	(0.011%) ^a	(0.017%) ^a	(0.203%) ^a
Ca	(0.146%) ^a	(0.078%) ^a	(0.435%) ^a
Fe	(0.833%) ^a	(1.595%) ^a	(0.174%) ^a
TOC ^b	0.643%	0.335%	0.058%
pH	8.8 ± 0.3	3.7 ± 0.3	6.8 ± 0.2
Compress bulk density $\rho(\text{g/cm}^3)$ (Dry)	0.97 ± 0.05	1.02 ± 0.05	1.57 ± 0.05

n.d. = not detected.

^a Percentage of metal element for 100 mg of soil sample.

^b Total organic carbon content based on 5 g of soil sample.

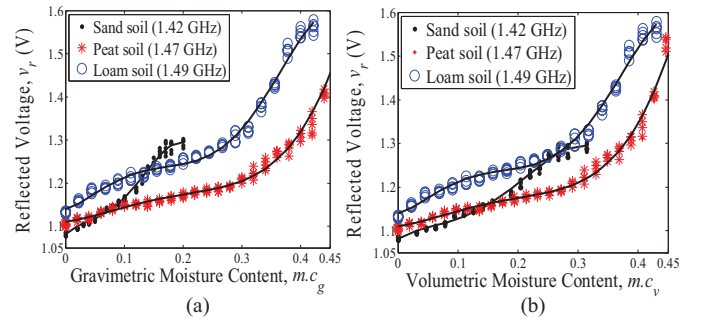


Fig. 9. Variations in reflected voltage, V_r . (a) Gravimetric moisture content, $m.c.g.$, and (b) volumetric moisture content, $m.c.v.$ of three calibration soil at $(25 \pm 1)^\circ\text{C}$.

(fraction). Therefore, the bound water fraction is not the same for different types of soils due to different textures. Since the sand soil has a larger air space in its textures compared to the other types, thus the bound water condition does not exist in sand soil.

From Fig. 8 (b), the relative dielectric constant, ϵ_r' and conductivity, σ for the three types of soils are approximately the same for the equivalent volumetric water content, $m.c.v.$. Thus, the use of volumetric water content is more preferred in most soil meters than gravimetric water content, because it is convenient to measure different types of soils when those soils have approximately the same electrical properties with equivalent volumetric water content. Furthermore, volumetric measurement is also more adaptable to the computation of fluxes and water quantities added to the soil when soil density effects have been resolved. However, in precision practice, the volumetric measurement is not a good choice, because the uncertainty of soil density would contribute to the moisture measurement.

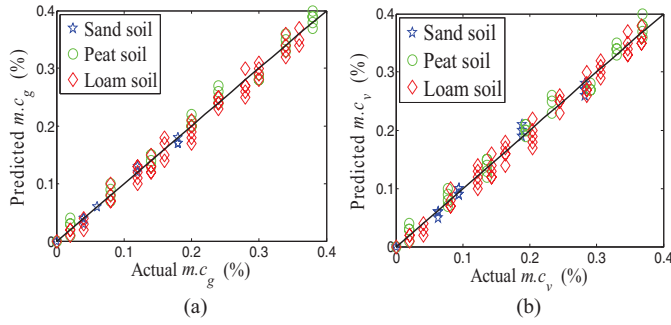


Fig. 10. The comparison between predicted and measure (a) gravimetric moisture content, $m.c_g$ and (b) volumetric moisture content, $m.c_v$ of three calibration soil at $(25 \pm 1) ^\circ\text{C}$.

B. Moisture Content of Soils

The measured reflected voltage, V_r (in volts), of the soils were fitted with corresponding moisture content, $m.c$ obtained from equations (1) and (2), which were based on gravimetric and volumetric methods. The 4th and 5th order polynomial equations for the average moisture content, $m.c$ as a function of reflected voltage, V_r are listed in Table A2 (Appendix A). Later, those polynomial expressions, which were programmed in reflectometer, are used to estimate the gravimetric moisture content, $m.c_g$ and the volumetric moisture content, $m.c_v$ of the soil under measurement in real time. The measured data and calibration curve (solid line) calculated from the polynomial function in the range from 0 $m.c$ to 0.45 $m.c$ are plotted in Fig. 9 (a) and (b). In Fig. 9 (a), peat soil is the soil has a high water holding capacity up to 0.45 $m.c_g$, in fact that it contained a lot of organic matter (0.643%) as compared to loam soil (0.335%) and sand soil (0.058%). The organic matter in peat soil can hold more water than mineral substances [12], [13]. Thus, the sand soil is saturated with water above 0.2 $m.c_g$.

To verify the accuracy and reliability of the equations in the Table 2A (in Appendix A), the predicted of moisture content for the three soil types were repeated. The predicted moisture content of soils using the equations in Table 2A were compared with the actual water content from equations (1) and (2) as shown in Fig. 10 (a) and (b). The mean deviation between the predicted and actual moisture content are within $\pm 0.01 m.c_c$. There are several factors that cause deviations between both predicted and actual moisture content, such as water and soil mixture is not uniform in the preparation of samples, as well as some water content in the soil sample has evaporated into the air during the measurement.

C. Sensitivity of Soil Measurements

This reflectometer is able to detect the changes in soil volumetric water content of 1%, since the reflected voltage changes, resulting from a change of 1% $m.c_v$ in the soil, is more than the value of the resolution voltage (0.001662 V) as shown in Fig. 11. The change of reflected voltage, ΔV_r is

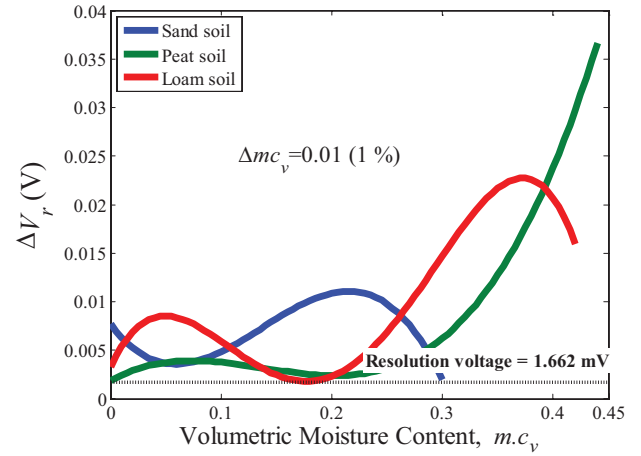


Fig. 11. Sensitivity of reflected voltage, ΔV_r to 1% change in soil volumetric water content, $m.c_v$.

calculated as:

$$\Delta V_r = \left(\frac{\partial V_r}{\partial m.c_v} \right) \Delta m.c_v \quad (6)$$

where the $\partial V_r / \partial m.c_v$ term in (6) is the differentiation of the equations in Table A3. Symbol $\Delta m.c_v$ is the change of volumetric soil moisture content which its value is assumed to be 0.01 in Fig. 11. Typically, soil containing high water content has high sensitivity of reflected voltage measurement.

V. CONCLUSION

This paper discussed a handheld microcontroller-based soil moisture reflectometer based on the principle of frequency domain reflectometry. Three types of soils were used as calibration standards for the reflectometer, which were sand soil, peat soil and loam soil. The physical and chemical properties for the three types of calibration soil were described in detail. Those polynomial calibration equations that are related to the reflected voltage, V_r and actual moisture content, $m.c$ for the three types of soil have been developed and installed in the reflectometer which is able to re-calibrate. From the equations, the moisture content, $m.c$ of soil can be computed from the measured reflected voltage, V_r . Two moisture calculation techniques (gravimetric and volumetric) were used for the reflectometer. In future, the microcontroller-based reflectometer might be able to measure a wider range of soil with different textures, only by applying their calibration equations into the reflectometer. Thus, implementation of this reflectometer may not require specific soil calibration, but only required knowledge of the soil types and particle size distribution. In additional, this reflectometer can also be merged with wireless functions for indoor soil moisture monitoring.

ACKNOWLEDGMENT

The authors would like to thank W. Y. Teoh for technical assistance with the PCB schematic circuit.

APPENDIX A

TABLE A1

RELATIONSHIP BETWEEN MOISTURE CONTENT AND DIELECTRIC PROPERTIES

Gravimetric (0-0.42) $m.c_g$	
Loam (1.49 GHz)	$\ln(\epsilon_r') = -603.35585246 m.c_g^4 + 492.290987588 m.c_g^3$ $- 113.484361735 m.c_g^2 + 11.716720936 m.c_g$ $+ 0.9107948325, R^2=0.982886$
	$\ln(\sigma) = -1381.889544271 m.c_g^4 + 1162.243026553 m.c_g^3$ $-298.538775799 m.c_g^2 + 31.161444909 m.c_g$ $-2.253097662, R^2=0.966523$
Volumetric (0-0.4) $m.c_v$	
Loam (1.49 GHz)	$\ln(\epsilon_r') = -557.407547135 m.c_v^4 + 463.8967927007 m.c_v^3$ $-109.077625659 m.c_v^2 + 11.4869813096 m.c_v$ $+ 0.9107948325, R^2=0.982886$
	$\ln(\sigma) = -1276.652334749 m.c_v^4 + 1095.207562093 m.c_v^3$ $-286.946151287 m.c_v^2 + 30.550436185 m.c_v$ $-2.253097662, R^2=0.966523$
Gravimetric (0-0.44) $m.c_g$	
Peat (1.47 GHz)	$\ln(\epsilon_r') = 79.446013589 m.c_g^3 - 38.131792177 m.c_g^2$ $+ 8.2171311373 m.c_g + 0.9024331333, R^2=0.862293$
	$\ln(\sigma) = 75.87457405 m.c_g^3 - 35.11067381 m.c_g^2$ $+ 8.78269799 m.c_g - 1.74753044309, R^2=0.947642$
Volumetric (0-0.45) $m.c_v$	
Peat (1.47 GHz)	$\ln(\epsilon_r') = 87.047621206 m.c_v^3 - 40.5269339753 m.c_v^2$ $+ 8.4712692137 m.c_v + 0.9024331332, R^2=0.862293$
	$\ln(\sigma) = 83.1344567557 m.c_v^3 - 37.316052513 m.c_v^2$ $+ 9.0543278206 m.c_v - 1.74753044309, R^2=0.947642$
Gravimetric (0-0.2) $m.c_g$	
Sand (1.42 GHz)	$\ln(\epsilon_r') = -1.679293616 m.c_g^2 + 11.564351321 m.c_g$ $+ 0.7942554632, R^2=0.940737$
	$\ln(\sigma) = -27.59684585 m.c_g^2 + 21.458242423 m.c_g$ $- 2.7987339454, R^2=0.939897$
Volumetric (0-0.3) $m.c_v$	
Sand (1.42 GHz)	$\ln(\epsilon_r') = -0.6812826549 m.c_v^2 + 7.3658288669 m.c_v$ $+ 0.7942554632, R^2=0.940737$
	$\ln(\sigma) = -11.1959291859 m.c_v^2 + 13.667670333 m.c_v$ $-2.7987339454, R^2=0.939897$

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TABLE A2
RELATIONSHIP BETWEEN MOISTURE CONTENT AND REFLECTED VOLTAGE

Gravimetric (0-0.4) $m.c_g$	
Loam (1.49 GHz)	$m.c_g = -352.55054959 V_r^5 + 2451.91894804 V_r^4 - 6790.5496279 V_r^3$ $+ 9358.14509487 V_r^2 - 6414.63911622 V_r + 1748.95481667,$ $R^2=0.998032$
	Volumetric (0-0.42) $m.c_v$
Loam (1.49 GHz)	$m.c_v = -359.6015606 V_r^5 + 2500.957327 V_r^4 - 6926.3606205 V_r^3$ $+ 9545.30799676 V_r^2 - 6542.93189854 V_r + 1783.93391301$ $R^2=0.998032$
	Gravimetric (0-0.44) $m.c_g$
Peat (1.47 GHz)	$m.c_g = -4.30549654 V_r^4 + 36.05283306 V_r^3 - 101.7896203 V_r^2$ $+ 120.41759441 V_r - 51.02805743, R^2=0.989909$
	Volumetric (0-0.45) $m.c_v$
Peat (1.47 GHz)	$m.c_v = -4.17633164 V_r^4 + 34.97124807 V_r^3 - 98.7359317 V_r^2$ $+ 116.80506658 V_r - 49.49721571, R^2=0.989909$
	Gravimetric (0-0.2) $m.c_g$
Sand (1.42 GHz)	$m.c_g = 301.80429435 V_r^4 - 1407.8500651 V_r^3 + 2456.61951435 V_r^2$ $-1899.5359176 V_r + 548.97995605, R^2=0.995795$
	Volumetric (0-0.3) $m.c_v$
Sand (1.42 GHz)	$m.c_v = 473.83274214 V_r^4 - 2210.32460221 V_r^3 + 3856.89263754 V_r^2$ $-2982.27139063 V_r + 861.898531, R^2=0.995795$

TABLE A3
DIFFERENTIATION OF THE REFLECTED VOLTAGE RESPECTED TO THE VOLUMETRIC MOISTURE CONTENT

Volumetric (0-0.42) $m.c_v$	
Loam (1.49 GHz)	$\partial V_r / \partial m.c_v = -5.340538304 \times 10^{-7} m.c_v^4 + 3.55048893 \times 10^{-5} m.c_v^3$ $-6.54549437 \times 10^{-4} m.c_v^2 + 3.55634542 \times 10^{-3} m.c_v + 4.29355296 \times 10^{-3}$
	Volumetric (0-0.45) $m.c_v$
Peat (1.47 GHz)	$\partial V_r / \partial m.c_v = 7.90630869 \times 10^{-7} m.c_v^4 - 3.73508075 \times 10^{-5} m.c_v^3$ $+ 5.98554946 \times 10^{-4} m.c_v^2 - 3.59777226 \times 10^{-3} m.c_v + 9.72491403 \times 10^{-3}$
	Volumetric (0-0.3) $m.c_v$
Sand (1.42 GHz)	$\partial V_r / \partial m.c_v = -1.1978312 \times 10^{-6} m.c_v^4 + 5.43969023 \times 10^{-5} m.c_v^3$ $-7.76577077 \times 10^{-4} m.c_v^2 + 4.2202548 \times 10^{-3} m.c_v - 1.37474069 \times 10^{-3}$

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