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Soil Water Content Estimation over Plantation Area Using FMCW Radar

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Abstract—In plantation areas, soil conditions affect the crop's quality. One of the crucial elements in the soil for plant survival is soil water content (SWC). Radar system has advantages that can be implemented for measuring SWC in plantation areas. A radar system operates by utilizing electromagnetic waves to obtain the dielectric characteristics of the soil. However, the presence of tea plants has become an obstacle to the radar wave propagation toward the soil layer. Reflected signal, which is influenced by the presence of vegetation, makes the estimation of SWC inaccurate. Consequently, the estimation of SWC needs to consider the vegetation's effect. This study uses an FMCW radar system, which operates at a frequency of 24 GHz. A layer medium propagation model is proposed in this study to prove the relationship between the reflected signal and the SWC. The reflection coefficient extracted from the radar signal is used to estimate the SWC. The vegetation propagation constant was obtained from the average field measurement results. The gravimetric method is used to validate the SWC estimation in vegetation's presence using the radar system. The results of the field experiments showed that the proposed method succeeded in estimating the SWC by considering the presence of vegetation with an average error of 3.57%. The proposed method has the potential to be applied to plantation areas.

1. INTRODUCTION

In plantation areas, soil is the primary medium for plant's growth. Soil conditions affect the quality of the crops produced. One of the crucial elements in the soil for plant survival is soil water content (SWC). Plants can respond to soil conditions in terms of the ability of roots to absorb water and nutrients [1, 2]. Aside from being a raw material for photosynthesis, water also acts as a solvent, reagent in various reactions and as a turgor maintainer in vegetation [3]. Vegetation requires sufficient water, meaning not too much and not too little. Soils with excess water content can reduce vegetation quality due to waterlogged vegetation roots (e.g., reduced root respiration due to oxygen depletion), and soils containing little water can also cause permanent damage to vegetation due to drought [4].

One method for measuring SWC with a high accuracy is the gravimeter [5]. This method compares the weight of a soil sample in the initial conditions with the weight in dry conditions to measure SWC. The gravimetric method is challenging to apply in large areas because we have to take soil samples from many points in the area, so that it will take a lot of time and effort [6]. SWC measurement using remote sensing is a solution to this problem by utilizing electromagnetic waves [7]. Remote sensing methods in [4, 8–13] have been studied to measure soil characteristics.

Radar system for measuring SWC is one of the most promising and widely used methods because it performs detection with a wide coverage area [14]. Ground Penetrating Radar (GPR) is a widely used radar system for estimating SWC. GPR uses electromagnetic waves to detect objects buried below

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the ground's surface. SWC can be obtained from the soil dielectric characteristics extracted from the reflected signal. Based on the transmitted signal, the GPR system is divided into several methods, namely Pulse Radar, Continuous Wave (CW), Stepped Frequency Continuous Wave (SFCW), and Frequency Modulated Continuous Wave (FMCW) [15].

Several studies have successfully examined applying GPR system methods in measuring SWC. The GPR-UWB pulse radar system in [16] classified soil layers with a depth of 10–50 cm based on SWC with an accuracy of 71%. The UWB-GPR system in this study works at a center frequency of 900 MHz. UWB radar has advantages in terms of accuracy and resolution in detecting the ground's surface [17, 18]. However, the use of UWB to measure the water content in deeper soil layers has interference problems due to reflections from other objects that are difficult to overcome. So, a reliable method is required to overcome the interference. In addition to using pulse radar, CW radar system has been successfully applied in measuring SWC. In [19], the SFCW radar works by emitting electromagnetic signals in the form of pulses that are emitted continuously with different frequencies. This study compares the performance of using full bandwidth and narrow bandwidth in measuring SWC. The use of full bandwidth has a high resolution in detecting the ground surface. However, to measure up to a certain depth of the ground, full bandwidth will not work optimally because high frequencies will be attenuated below the noise level of the receiver. In addition, the use of full bandwidth will require a longer time in the process of generating frequencies [20, 21]. Apart from SFCW radar, FMCW radar has also been studied for its application to detect groundwater content [22]. FMCW radar transmits electromagnetic waves continuously with a linearly increasing frequency [23]. The difference in the frequency of the reflected signal and transmitted signal contains information about the target [24]. The difference in the dielectric properties of the target is affected by the signal delay of the transmitted signal. FMCW radar can operate at high frequencies even though it uses a lower bandwidth than UWB [25]. However, the resolution of the FMCW radar in distinguishing two or more adjacent targets is highly dependent on the width of the bandwidth it uses.

The problem found when measuring SWC in plantation areas using a radar system is the vegetation that covers the ground surface. In wave propagation, the signal will hit the vegetation before it hits the ground. This phenomenon can cause signal propagation to the ground to weaken due to being blocked by vegetation. This problem has similarities to the Through Wall Radar (TWR). From the results of the analogy with the TWR case in [26, 27], the presence of vegetation as a barrier will affect the amplitude and phase values of the soil reflected signal. These influences will affect the estimation of the ground's dielectric characteristics, so the SWC estimation cannot directly use the reflected signal received by the radar. Vegetation influences the reflected signal, so additional methods are needed to estimate SWC in the plantation area.

This research focuses on the method for estimating the SWC in the plantation area using FMCW radar. The proposed method uses the wave propagation of a layer medium propagation model, so the radar system is sufficient to detect the vegetation surface layer to obtain information about the SWC. Low power consumption in using FMCW radar can be utilized in detecting large areas such as plantation areas [25]. A simulation study using the proposed method was carried out in [28]. Field experiments were carried out in this study to determine the capability of the proposed method in estimating SWC in plantation cases.

This paper is divided into four sections and structured as follows. Section 1 contains the background of the problem raised in this study. Section 2 describes the FMCW radar, the proposed method, and the experimental methodology. The experimental results and analysis are explained in Section 3. Section 4 is the conclusion of this research.

2. PROPOSED RADAR SYSTEM

2.1. FMCW Radar

FMCW radar has been widely applied in several fields because it has various advantages, such as low power consumption, higher operating frequency than other radars, better resolution, and high accuracy. These advantages make the design of the FMCW radar device have lower power and be cheaper. However, these advantages still depend on several aspects, such as the signal bandwidth, working frequency used, target gap from the radar, and linearity of the oscillator, which is controlled

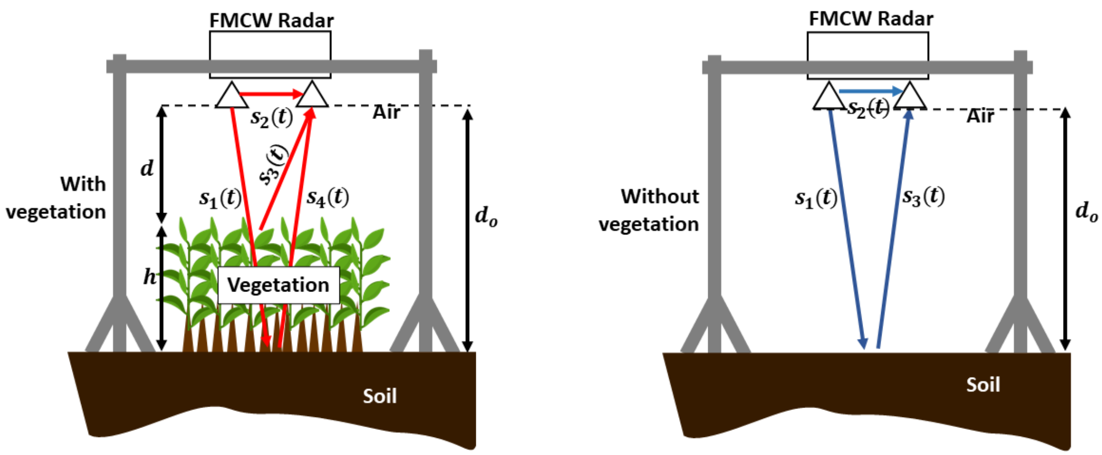


Figure 1. Concept of measuring the SWC using the proposed FMCW radar system.

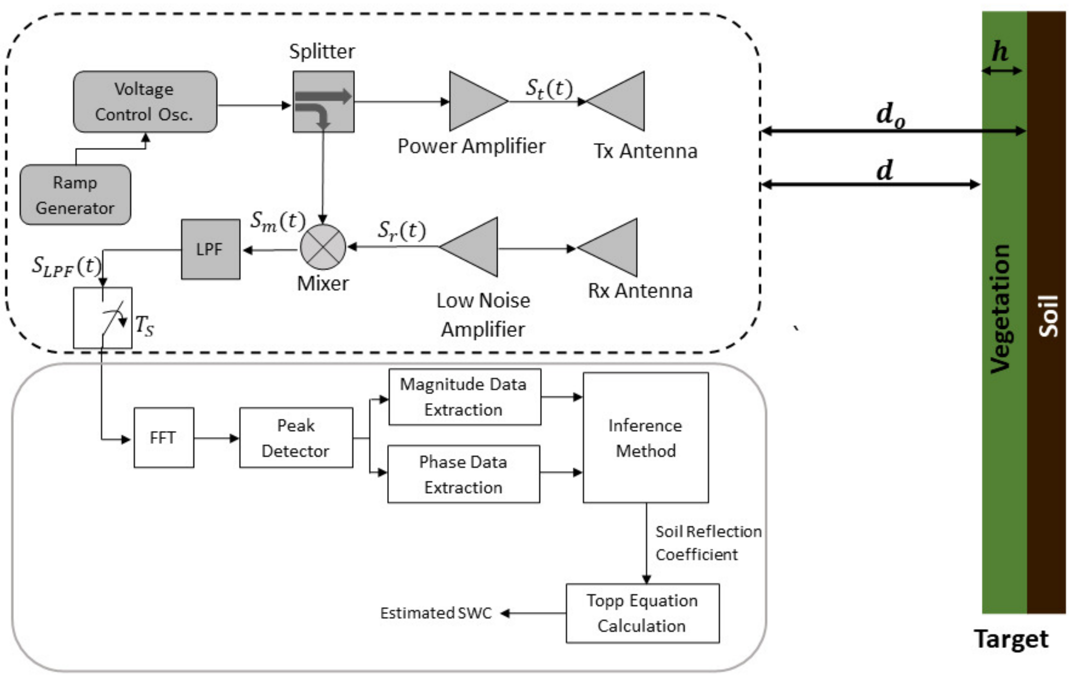


Figure 2. Block diagram of the proposed FMCW radar for SWC estimation.

by voltage controlled oscillator (VCO) voltage and VCO phase noise [25]. FMCW radar transmits electromagnetic waves continuously from low frequency to high frequency, which increases linearly [23]. FMCW radar detects targets by identifying the change in the frequency beat or the change in phase between the transmitted signal and received signal [24, 29]. This research proposes an FMCW radar at 24 GHz frequency to estimate the SWC in tea plantation areas. FMCW radar is focused on detecting the surface layer of vegetation, so it does not need a wide range of bandwidth. The FMCW radar measurement concept used in this study is shown in Figure 1.

In Figure 2, the FMCW radar block diagram is presented. The transmitted section in the FMCW radar includes a ramp generator and VCO as a chirp generator, splitter, power amplifier, and transmitter. The output of the chirp generator is forwarded to the splitter, and next to the power amplifier to be amplified before being sent through the transmitting antenna. The step of the SWC

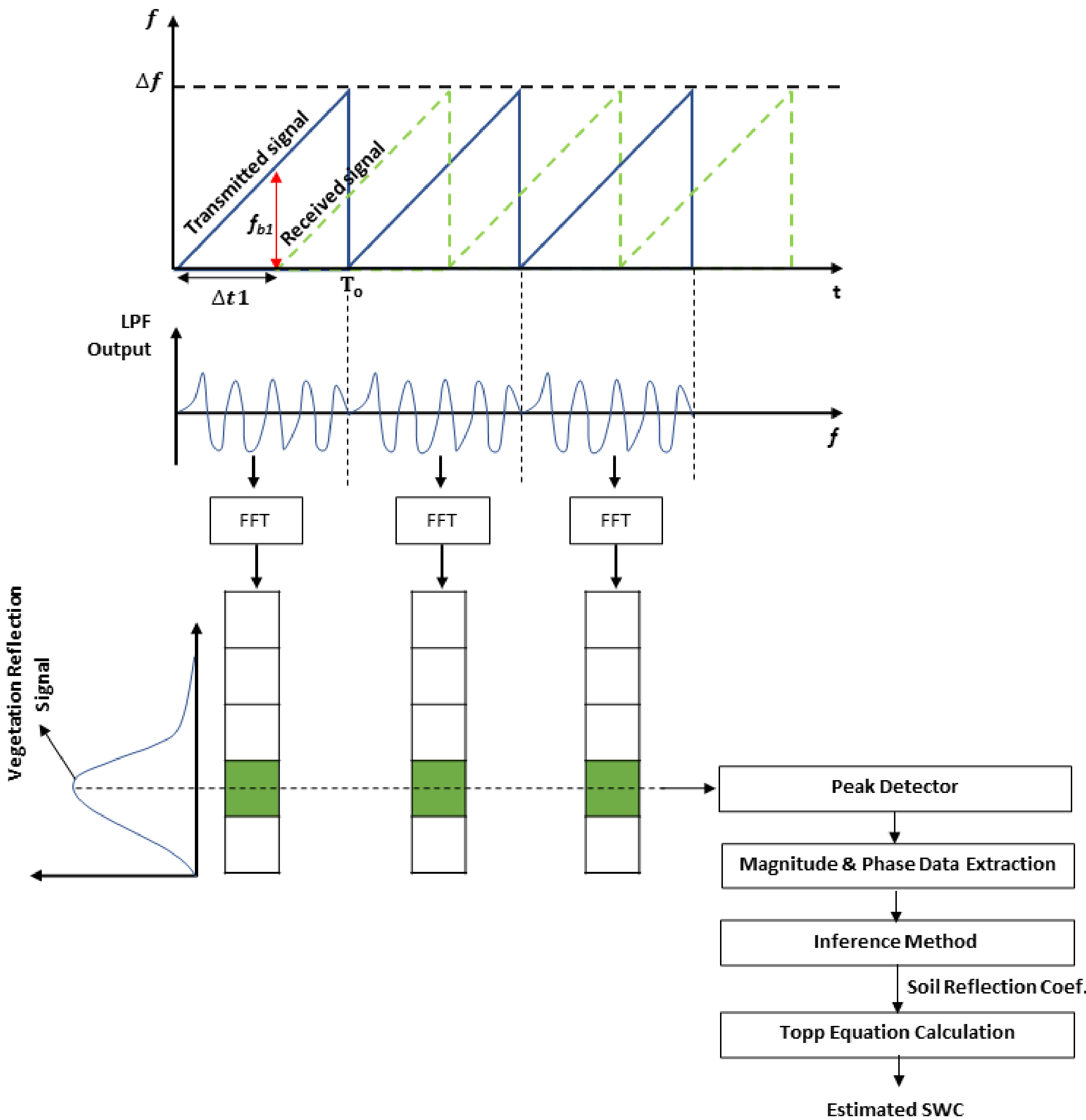


Figure 3. The proposed flow of the SWC estimation using FMCW radar.

estimation which is used to process the Low-Pass Filter (LPF) output of the FMCW radar system is shown in Figure 3. f_b is the beat frequency, namely the difference in frequency between the transmitted signal and the received signal; Δt is the time difference between the sent signal and reflected signal; and Δf is the bandwidth of the radar system.

Equation (1) represents the signal transmitted by the FMCW radar with the amplitude of A_T, operating frequency of f_o, transmitted wave frequency of Δf, chirp period of T_c, and time of t. The bandwidth and chirp period on the FMCW radar can be determined based on the period of the triangular signal.

$$S_{\text{FMCW}}(t) = A_T \cos(2\pi(f_o + \Delta f/T_c t)\, t) \tag{1}$$

The transmitted signal will reach the object and be reflected back to the radar, and the received signal is then written as Equation (2). Δt is the propagation delay that occurs when the radar detects a target at a distance d from the radar. v_p is the phase velocity of the radar wave. A_R is the amplitude of the received signal.

$$S_{\mathrm{FMCW}\Delta t}(t) = A_R \cos\left(2\pi\left(f_o + \frac{\Delta f}{T_c}(t-\Delta t)\right)(t-\Delta t)\right) + n_o \tag{2}$$

$$\Delta t = \frac{2d}{v_p} \tag{3}$$

When detecting a target, the FMCW radar may receive multiple reflected signals that come from every point at the target. So, the received signal is the sum of multiple reflected signals from the object detected by the radar, which are written in Equation (4).

$$S_{\mathrm{FMCW}\Delta t}(t) = \sum_{n=1}^{N} A_N \cos\left(2\pi\left(f_o + \frac{\Delta f}{T_c}(t-\Delta t_N)\right)(t-\Delta t_N)\right) \tag{4}$$

The output signal of the FMCW radar in the form of LPF output then arranged into an Fast Fourier Transform (FFT) sequence to find the highest peak spectrum. The magnitude and phase data are obtained by extracting the highest peak of the magnitude, and it also contains information about the vegetation characteristic. The electric properties of the vegetation is essential information that is used to minimize the effects of vegetation in estimating the SWC in the case of tea plantation.

2.2. Estimation of Vegetation Dielectric Characteristic

In tea plantations, the vegetation's effect needs to be investigated in estimating SWC using a radar system. This incident has similarities to the problem in the Through Wall Radar (TWR) case [26, 27]. In TWR, the detected target is behind the wall. So, the signal from the wall is bigger than the signal from the target. This makes the targets challenging to be detected. The presence of vegetation as a barrier will affect the amplitude and phase values of the soil reflected signal which will determine the estimation of the soil dielectric characteristics. The amount of influence caused by vegetation is determined by its electric properties.

Equations (5) and (6) are used to find α_t and β_t values of vegetation. In this research, the values of α_t and β_t are characterized from the reflected signal data from field experiments. The value of α_t is estimated by calculating the decrease in the amplitude of the reflected signal when vegetation is present. The value of β_t is estimated from the shift of the peak point of the reflected signal when vegetation is present.

$$\alpha_t = \omega\sqrt{\mu\varepsilon}\left(\frac{1}{2}\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right)\right)^{\frac{1}{2}} \tag{5}$$

$$\beta_t = \omega\sqrt{\mu\varepsilon}\left(\frac{1}{2}\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}+1\right)\right)^{\frac{1}{2}} \tag{6}$$

After obtaining the values of α_t and β_t, we can then find out the electric properties of vegetation using Equation (7) by assuming the value of the dielectric characteristics as the variable x as written in Equation (8). Therefore, (7) can be written as (9).

$$\frac{\alpha_t}{\beta_t} = \frac{\left\{\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right]\right\}^{\frac{1}{2}}}{\left\{\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}+1\right]\right\}^{\frac{1}{2}}} \tag{7}$$

$$x = \frac{\sigma}{\omega\varepsilon} \tag{8}$$

$$\frac{\alpha_t}{\beta_t} = \frac{\left\{\left[\sqrt{1+(x)^2}-1\right]\right\}^{\frac{1}{2}}}{\left\{\left[\sqrt{1+(x)^2}+1\right]\right\}^{\frac{1}{2}}} \tag{9}$$

Equation (10) is an equation for finding the value of x.

$$x = \left\{\left[\frac{\left(1-\left(\frac{\alpha_t}{\beta_t}\right)^2\right)}{\left(1+\left(\frac{\alpha_t}{\beta_t}\right)^2\right)}\right]^2 - 1\right\}^{\frac{1}{2}} \tag{10}$$

The x value obtained from (10) is then substituted into (6) for determining the value of ε. After obtaining the value of ε, the relative permittivity value of the vegetation ε_t can be found using Equation (11).

$$\varepsilon_t = \frac{\varepsilon}{\varepsilon_o} \tag{11}$$

Vegetation intrinsic impedance can be determined by using Equation (12). If we assume a small σ value and a large ω value, then Z_t can be found using Equation (13).

$$Z_t = \sqrt{\frac{\mu}{\varepsilon - j\frac{\sigma}{\omega}}} \tag{12}$$

$$Z_t = \sqrt{\frac{\mu}{\varepsilon}} \tag{13}$$

2.3. The Methodology for Estimating Soil Relative Permittivity

The relative permittivity of the soil is affected by the SWC. Figure 4 shows the relationship between the soil relative permittivity ε_s and the SWC m_v based on the Topp Equation. So, the estimation of SWC of m_v can be obtained [30].

$$m_v = -5.3 \times 10^{-2} + 2.92 \times 10^{-2}\varepsilon_s - 5.5 \times 10^{-4}\varepsilon_s^2 + 4.3 \times 10^{-6}\varepsilon_s^3 \tag{14}$$

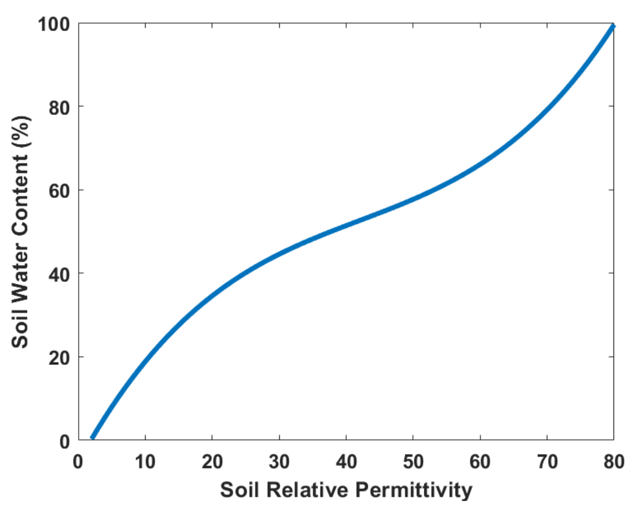


Figure 4. The relationship between soil permittivity and SWC based on the Topp equation [30].

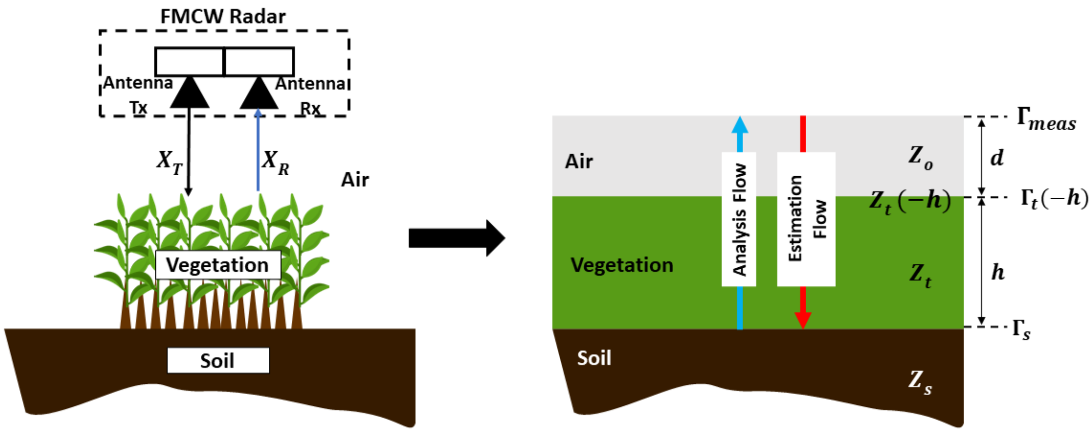


Figure 5. Illustration of flow analysis and estimation of soil relative permittivity using a radar system.

The reflected signal data from field experiments using FMCW radar can be used to estimate the SWC. In the actual case of plantation, the signals will reach the vegetation first before it reaches the soil. Therefore, the SWC estimation needs to consider vegetation's presence. An illustration of analysis flow and estimation flow using a layer medium propagation model is illustrated in Figure 5. A layer medium propagation model for estimating soil relative permittivity has been proposed in [31]. Analysis flow is carried out to determine the effect of the relative permittivity of the soil on the reflected signal received by the radar. The estimation flow is carried out to obtain an estimated value of the soil's relative permittivity, which is then used as an input to estimate the soil water content. In Figure 5, the analysis flow is represented by a blue arrow. It means that the analysis is carried out from the lowest layer. Starting from the soil electrical properties that influence the soil reflection then we can determine the effect on the layers above it. Meanwhile, the flow of the estimated relative permittivity of the soil is represented by a red arrow. This is because the estimated relative permittivity of the soil is obtained using the reflected signal data received by the radar. The flowchart of the estimation of relative soil permittivity is shown in Figure 6.

The flow of analysis that is described in Figure 6 is used to define the relationship between the soil permittivity and the radar signal. The magnitude of the reflection coefficient of the soil can be determined from the intrinsic impedance of the soil (Z_s) and the vegetation (Z_t). By assuming that the mediums are homogeneous-isotropic, the electromagnetic wave propagates in Transversal Electromagnetic mode (TEM), and the wave is normally incident on the plane interface between mediums. The soil reflection coefficient can be determined from Equation (15). Furthermore, the intrinsic impedance of a medium can be calculated by referring to its electric properties as written in Equations (16) and (17). Some simulations studied by employing the Finite Different Time Domain (FDTD) method were also conducted to validate the TEM approach taken. The electric properties variation over the layered medium is taken in the FDTD computation. The result shows the reflection coefficient difference of 0.055. This result is then used as consideration in selecting the TEM approach for analysis flow derivation.

$$\Gamma_s = \frac{Z_s - Z_t}{Z_s + Z_t} \tag{15}$$

$$Z_s = \sqrt{\frac{\mu_o \mu_s}{\varepsilon_o \varepsilon_s - j\dfrac{\sigma_s}{\omega}}} \tag{16}$$

$$Z_t = \sqrt{\frac{\mu_o \mu_t}{\varepsilon_o \varepsilon_t - j\dfrac{\sigma_t}{\omega}}} \tag{17}$$

Considering the range of soil conductivity of 25 to 65 mS/m [32] and low conductivity of vegetation layer [33–36], the layered mediums are approximated as dielectric layers. By assuming that σ_s and σ_t

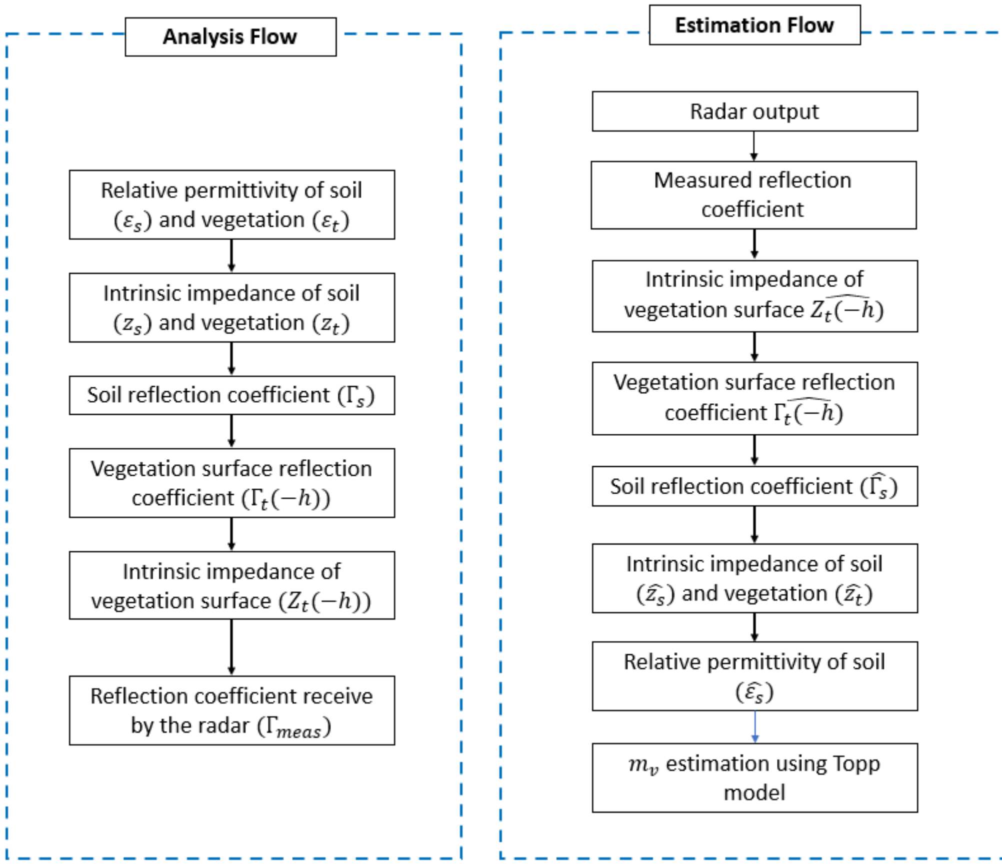


Figure 6. Flowchart of estimation of soil relative permittivity.

are small, and ω is large, then Z_s and Z_t can be simplified as Equations (18) and (19).

$$Z_s = \sqrt{\frac{\mu_o \mu_s}{\varepsilon_o \varepsilon_s}} \tag{18}$$

$$Z_t = \sqrt{\frac{\mu_o \mu_t}{\varepsilon_o \varepsilon_t}} \tag{19}$$

The reflection coefficient of vegetation is obtained using Equation (20). α and β values are propagation constants of the waves when they propagate through vegetation layers. α and β are estimated by conducting field measurements in tea plantations. The measurement mechanism of vegetation layer propagation constant is explained in Section 2.2.

$$\Gamma_t(-h) = \Gamma_s e^{-2(\alpha + j\beta)h} \tag{20}$$

In Equation (21), $Z_t(-h)$ is the intrinsic impedance of the vegetation at the boundary between the vegetation layer and the air.

$$Z_t(-h) = Z_t \left(\frac{1 + \Gamma_t(-h)}{1 - \Gamma_t(-h)} \right) \tag{21}$$

The value of $Z_t(-h)$ depends on the characteristics and height of the vegetation. The reflection coefficient (Γ_{meas}) measured by radar is influenced by a mismatch between the intrinsic impedance of the air (Z_o) and the impedance of the vegetation layer at the boundary between vegetation and air ($Z_t(-h)$). Furthermore, measured reflection coefficient is written in Equation (22).

$$\Gamma_{meas} = \frac{Z_t(-h) + Z_o}{Z_t(-h) - Z_o} \tag{22}$$

The analysis flow in this study is conducted referring to Equations (15)–(22). Furthermore, the soil reflection coefficient is obtained by employing the estimation flow in Figure 6 that follows the computation step from Equations (24)–(30). Based on the concept of electromagnetic waves, Γ_{meas} is the ratio between the reflected wave (X_R) wave and the transmitted wave (X_T).

$$\Gamma_{meas} = \frac{X_R}{X_T} \tag{23}$$

The relation between Z_s and X_R can be determined from Equations (15)–(22). The SWC will influence ε_s, and finally this relation will affect Z_s. Referring to the concept of layered medium propagation, X_R is also affected by layers below it. Based on X_R radar data, the $\widehat{\Gamma_{meas}}$ value can be estimated.

$$\widehat{\Gamma_{meas}} = \frac{X_R}{X_T} \tag{24}$$

After estimating $\widehat{\Gamma_{meas}}$ from signal obtained by radar and taking the free space intrinsic impedance to approximate the air intrinsic impedance, the impedance at the surface of the vegetation ($\widehat{Z_t(-h)}$) can be found using Equation (25).

$$\left(\widehat{Z_t(-h)}\right) = Z_o \frac{\left(1+\widehat{\Gamma_{meas}}\right)}{\left(1-\widehat{\Gamma_{meas}}\right)} \tag{25}$$

After obtaining $\widehat{Z_t(-h)}$ from Equation (25), the reflection coefficient at the vegetation surface can be determined using Equation (26) with Z_t being the intrinsic impedance of vegetation layer obtained from measurement explained in Section 2.2.

$$\widehat{\Gamma_t(-h)} = \frac{\left(\widehat{Z_t(-h)}\right) - Z_t}{\left(\widehat{Z_t(-h)}\right) + Z_t} \tag{26}$$

Furthermore, the estimated reflection coefficient of the soil ($\widehat{\Gamma_s}$) can be calculated using Equation (27).

$$\widehat{\Gamma_s} = \widehat{\Gamma}_t\, e^{2(\alpha + j\beta)h} \tag{27}$$

The reflection coefficient of the soil ($\widehat{\Gamma_s}$) is affected by the vegetation above it and the soil below. Considering that these layers are approximated as a dielectric medium, $\widehat{\Gamma_s}$ in Equation (28) can then be written as Equation (29).

$$\widehat{\Gamma_s} = \frac{Z_s - Z_t}{Z_s + Z_t} \tag{28}$$

$$\widehat{\Gamma_s} = \frac{\sqrt{\varepsilon_t} - \sqrt{\varepsilon_s}}{\sqrt{\varepsilon_t} + \sqrt{\varepsilon_s}} \tag{29}$$

Thus, estimating the soil relative permittivity (ε_s) by considering the vegetation layer can use Equation (30).

$$\widehat{\varepsilon_s} = \varepsilon_t \left(\frac{1+\widehat{\Gamma_s}}{1-\widehat{\Gamma_s}}\right)^2 \tag{30}$$

2.4. Experiment Methodology

In this research, field experiments are conducted for further study of the proposed method. The radar system module used in this study is from OmniPresence which operates at a frequency of 24 GHz and a bandwidth of 200 MHz. A 4×4 rectangular patch array antenna is used in this radar as a transmitter and receiver antenna. This antenna has a 20° of beamwidth and about 18 dB of gain. In the radar system, the FMCW system is connected to a Mini PC, which can be controlled remotely using a laptop that is connected to the Mini PC through a Wi-Fi connection. In addition, the power supply of this

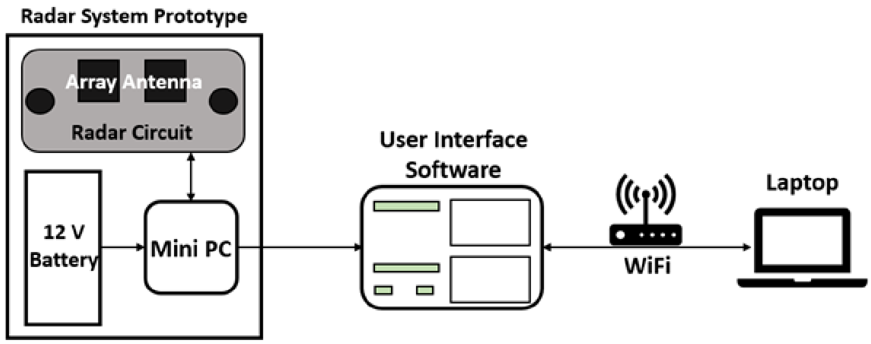


Figure 7. Realization of the FMCW radar system for estimating SWC.

system is a rechargeable battery with an output voltage of 12 V and a capacity of 2000 mAh. The realization of the radar system is shown in Figure 7. The software interface design for data collection and remote monitoring is included in the realization of the proposed radar system.

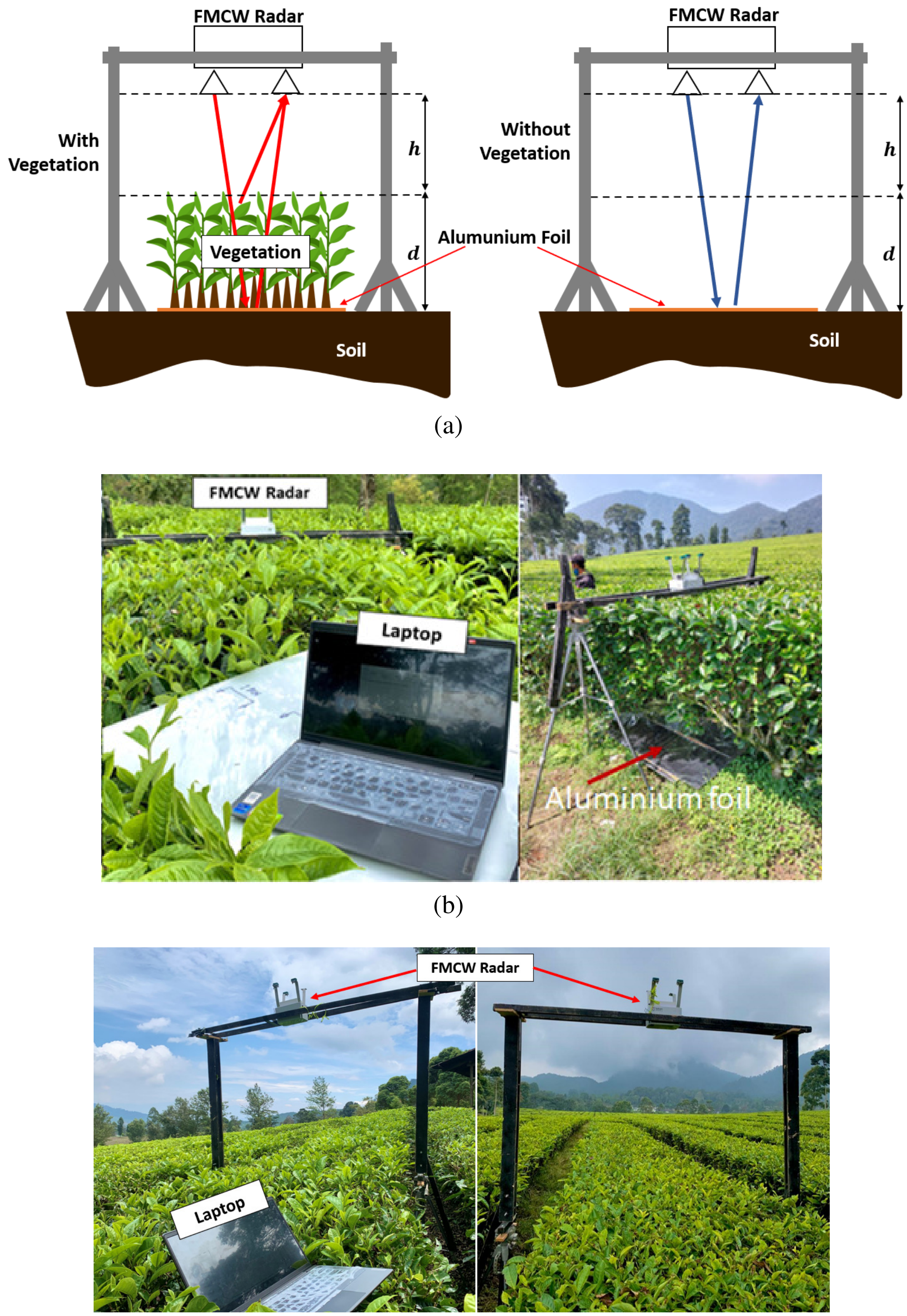
This study conducts experiments to determine the vegetation layer's characteristic to deal with the problem of vegetation layer effect on the radar's reflected signal. The measurements are taken on several samples of tea vegetation with different heights to obtain α_t and β_t of vegetation. Furthermore, the result is used to estimate SWC in the presence of a vegetation layer using the proposed method. The measurement setup is illustrated in Figure 8. Experiments to determine the effect of the vegetation layer on the signal received by the radar and to obtain α_t and β_t were carried out in 2 different conditions, namely with and without the vegetation layer. In this measurement, the soil surface is covered with aluminum foil as a conductor layer to eliminate the effect of the soil on the measurement results. The radar is placed at a height of d from the soil surface, which is the height of the vegetation, using wooden support, both during the experiment with and without the vegetation layer. The documentation of data collection α_t and β_t of vegetation is shown in Figure 8(b). The difference between the reflected signals with and without vegetation indicates the influence of the presence of vegetation. α_t and β_t values obtained from the measurement results are used to calculate vegetation electric properties.

Experiments to estimate SWC were carried out in several blocks of tea plantations with different heights of tea plants to determine the performance of the proposed method. Blocks on tea plantations are related to year pruning, in which the tea plants will be pruned periodically at a specific time so that the height of the tea plants will be relatively the same in 1 block. SWC in 1 area block may be various, so data collection is conducted at several points. Data collection at one point is carried out several times to ensure that the reflected signal data is relatively constant. In this experiment, aluminum foil was not used so that the soil conditions affect the reflected signal received by the radar. The radar is placed at a constant height of $h + d$, 2 meters above the ground. The documentation of SWC estimation data collection is shown in Figure 8(c). For each measurement, soil samples in the measurement area are taken and brought to the laboratory to calculate the SWC using the gravimetric method. The gravimetric method is used to validate the proposed method's performance in estimating SWC in plantation areas.

3. RESULT AND ANALYSIS

3.1. The Effect of Vegetation on Reflected Signals Received by Radar

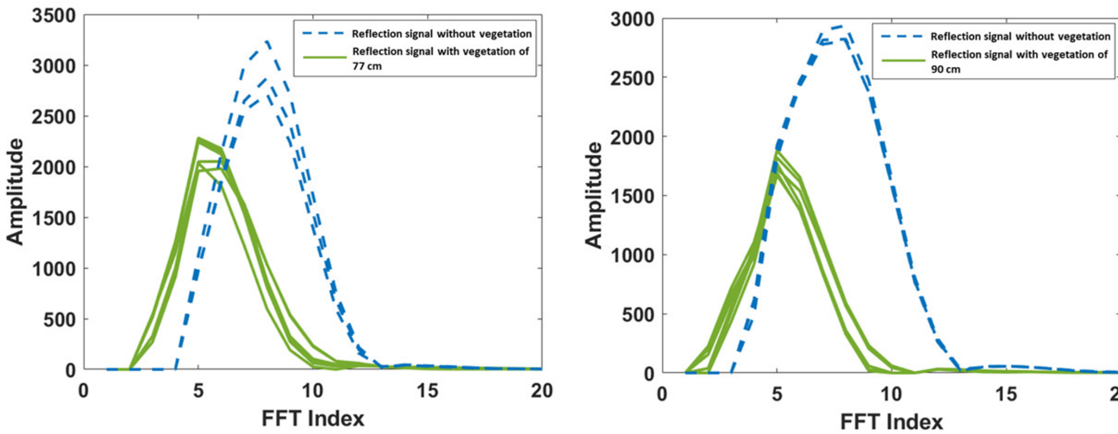
This research is a further study of the simulation results in [28]. In this study, vegetation in the form of tea plants acts as a barrier when SWC is estimated using an FMCW radar system. The FMCW radar system has an operating frequency of 24 GHz and a bandwidth of 200 MHz. With these specifications, the resolution of the used FMCW radar is about 75 cm, so it is difficult to distinguish the beat frequency from soil in the presence of dominant beat frequency from vegetation surface. The proposed method concept is extracting the soil reflection coefficient from vegetation reflection that is directly obtained



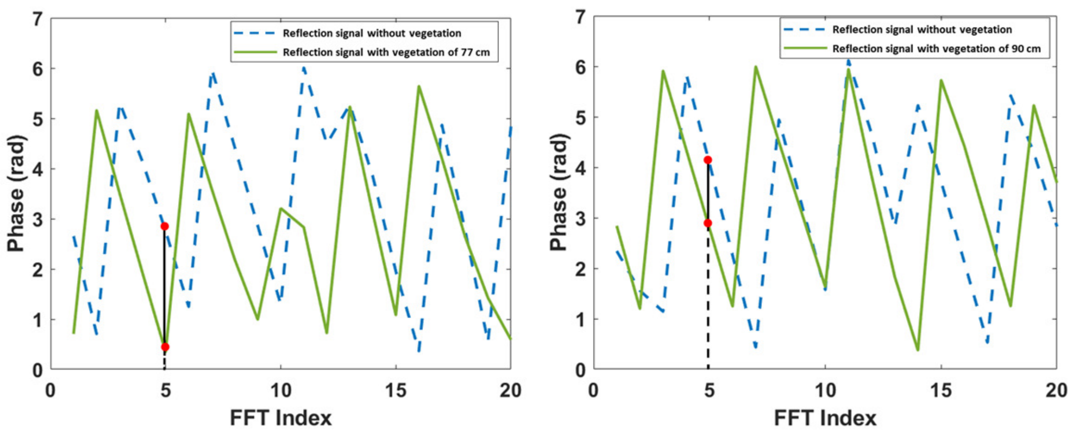
(a) (b) (c)

Figure 8. Field experiment setup. (a) Illustration of experimental setup. (b) Data collection documentation of α_t and β_t of vegetation. (c) Data collection documentation of SWC estimation.

from radar. In this study, a comparison of the radar detection results from two different conditions, i.e., with and without vegetation is shown in Figure 9. The results represent the radar output for two different vegetation heights. The vegetation surface contributes the most dominant reflected signal



(a)



(b)

Figure 9. Reflected signal received by the radar system with and without vegetation. (a) Magnitude of reflected signal. (b) Phase of reflected signal.

received by the radar. Without the presence of vegetation, the radar system can directly detect the soil surface, and the range detection result is the same with the radar height. Left and right result of Figure 9(a) shows that the peak magnitude of the reflected signal from the soil is found at FFT index of 8. When the measurements are performed in the presence of vegetation, the peak spectrums are found at FFT index of 5 and 6 for plantation height of 77 cm and 90 cm, respectively. These results have lower FFT index than that without vegetation. This is because the radar detects the soil farther than the vegetation surface. From the results in Figure 9(a), it appears that the vegetation surface is dominantly detected by the radar.

Likewise, in Figure 9(b), the presence of tea plants causes a phase shift. The phase difference in the results is caused by the additional time delay when the radar signal crosses the vegetation layer. If the reflected signal is directly converted to calculate the SWC, then the results will be inaccurate. Therefore, the SWC estimation needs to consider the vegetation's effect.

This study also analyses the effect of vegetation on the reflected signal received by the radar. The radar signal will propagate crossing the vegetation layer, as illustrated in Figure 5. The vegetation propagation constant is important information for extracting the soil reflection coefficient from the measured reflection coefficient. The measurement setup in Figure 8 is used to obtain the vegetation reflection coefficient. In this measurement the soil surface is covered with aluminum foil as conductor layer to eliminate the effect of the soil on the measurement result.

To analyze the vegetation effect, the radar is located above the vegetation with the height from the soil the same as the vegetation height. The measurement results are shown in Figure 10. The results show a significant decrease in the peak magnitude caused by the presence of vegetation. The estimation of SWC in this study is highly dependent on the reflected signal received by the radar. Therefore, to obtain an accurate estimate of the SWC, the vegetation effect needs to be considered in estimating the soil reflection from radar's reflected signal.

The layered medium propagation model discussed in Section 2 is elaborated to determine the relationship between the reflected signal and SWC in the presence of vegetation. The propagation constant characteristics of the tea plant are required if we need to minimize the vegetation effect. α_t and β_t values of tea plants were obtained by a series of measurements as illustrated in Figure 8. Furthermore, α_t and β_t values are used to calculate the relative permittivity of tea plants.

We carried out measurements to analyze the effect of vegetation on the reflection coefficient received by the radar. This measurement is carried out by comparing the results of radar detection with and without vegetation. An aluminium foil as a metal conductor is placed on the top of the soil surface to eliminate the soil effect on the reflected signal. The radar is set at the same height as the vegetation height. The measurement results are shown in Figure 10. Based on the figure, there is a significant decrease in the peak magnitude when there is vegetation. This decrease in the peak magnitude makes the estimation of SWC inaccurate. The estimation of SWC in this study is highly dependent on the reflected signal received by the radar. Therefore, to obtain an accurate estimate of the SWC, the radar's reflected signal must be obtained accurately.

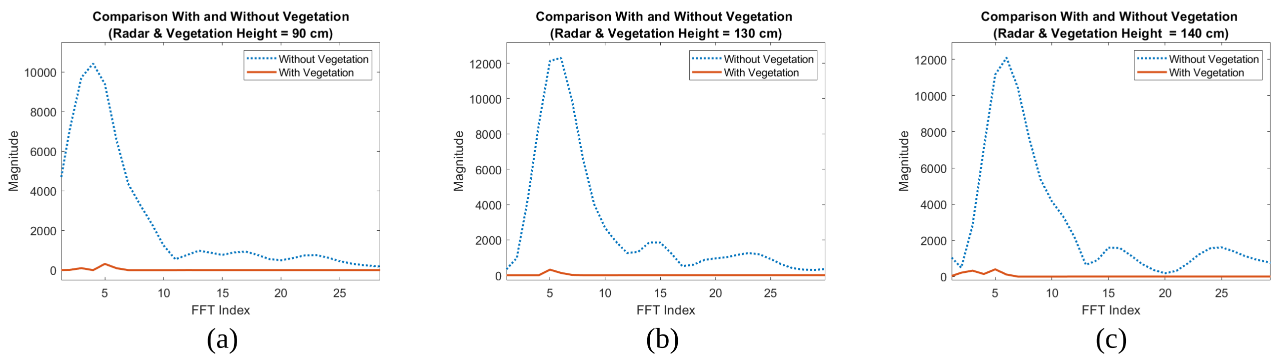


Figure 10. Comparison of measurement results with and without vegetation with the same height of radar and vegetation. (a) 90 cm. (b) 130 cm. (c) 140 cm.

The presence of vegetation layer needs to be considered to minimize the vegetation effect in estimating the SWC. This paper uses a layer medium propagation model to determine the relationship between the reflected signal and SWC in the presence of vegetation. The distribution of leaves and stems, or vegetation structure, varies over the plantation area, even at the same vegetation height. The variation is also found in the SWC over a particular area. Therefore, it is necessary to evaluate the effect of the variation on the estimation result taken at a certain point. In developing the proposed method, the vegetation propagation constant was characterized first in determining the proposed method. The vegetation propagation constant is characterized by taking the radar's received signal when the soil surface is covered by aluminium foil. The measurement was then taken under two different conditions, i.e., with and without vegetation. The vegetation constant (α_t and β_t) can be obtained from the measurement data by comparing the data obtained with and without vegetation. The illustration and photographs of this activity are depicted in Figure 8. The variation of α_t and β_t is found on the collected result obtained from different sampling points over a certain area.

Further analysis is conducted by simulating the effect of α_t and β_t variations on the SWC estimation result. Figure 11 shows the variations of α_t and β_t values obtained from vegetation with a height of 77 cm and a radar height of 200 cm above the soil at different sample points. The same measurement is also performed for several different vegetation heights. From the collected data, the result shows that the average value of α_t is 0.3 Np/m with a deviation 0.1 Np/m. The average value of β_t is 161.6 rad/m with a deviation of 0.75 rad/m. The leaves, stems distribution, or vegetation structure is varied over

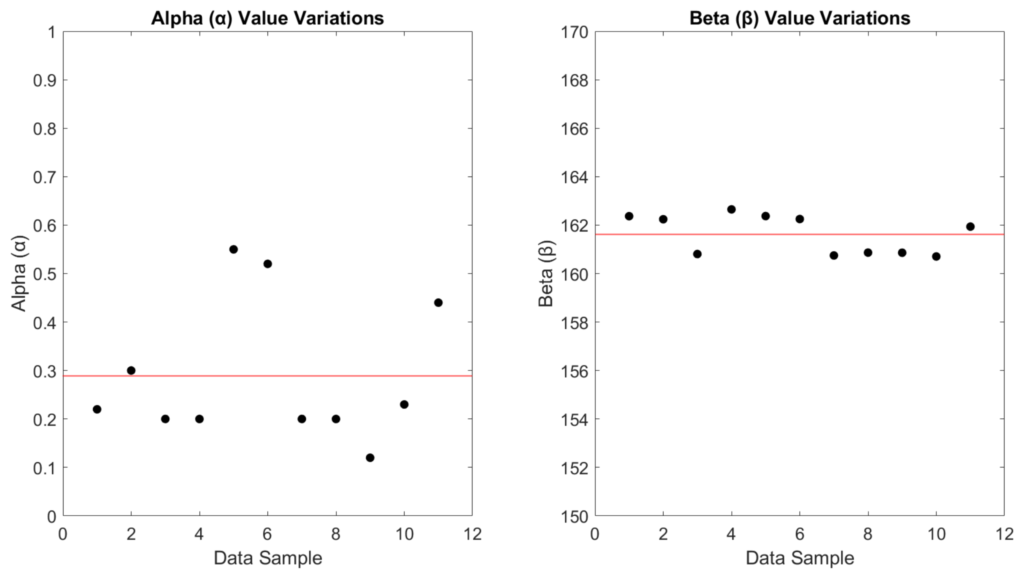


Figure 11. α_t and β_t variation values.

the plantation area, even at the same vegetation height. The variation is also found in the SWC over a certain area. Therefore, it is necessary to evaluate the effect of the variation on the estimation result taken at a certain point. In developing the proposed method, characterization of the vegetation propagation constant was performed first in determining the proposed method.

To observe the SWC variation. The gravimetry is performed for some samples that are taken around the observation point. 10 soil samples are collected from 1 observation point for gravimetry measurement. Figure 12 shows the result from 10 samples collected from a certain location in the tea plantation over 1×1. The obtained result shows that the average SWC (m_v) is 47 with the deviation of 0.3, and the average soil relative permittivity (ε_s) is 33.43 with the deviation of 3.36. The result indicates that the variation of soil relative permittivity and SWC on the 1×1 area is small and can be ignored in the proposed method. It is relevant with the tea plantation area condition that most of the

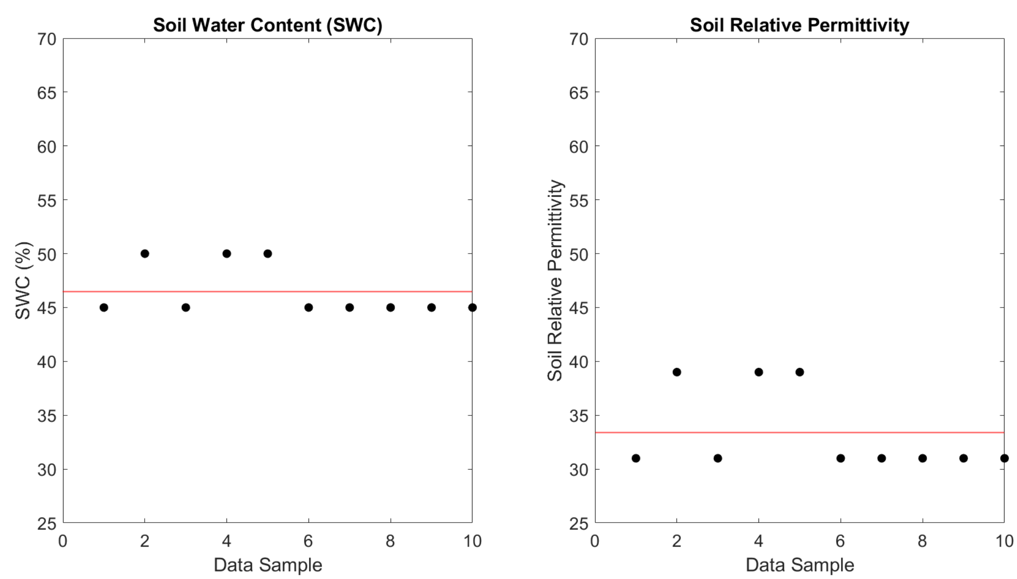


Figure 12. m_v and ε_s variation values.

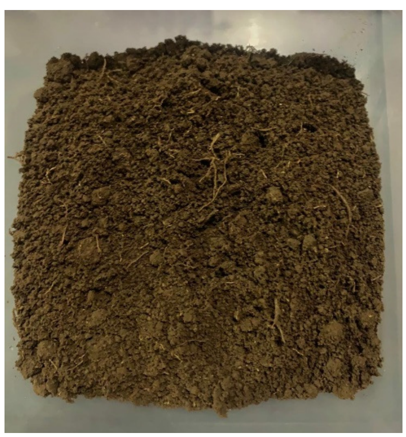
soil surface is covered by the tea vegetation.

The simulation for estimating SWC considering the variation of the α_t and β_t results in a tolerable error on SWC estimation. The simulation result shows that SWC estimation error is 5.78%. Although the variation of vegetation propagation constant affects the reflected signal, its variation is still tolerable when the average value is used to represent the propagation constant of the vegetation layer. Therefore, the average value is then selected in this study.

3.2. Estimation of SWC by Considering the Presence of Vegetation

Estimating the SWC, considering the presence of vegetation, has been carried out. Estimation is carried out using reflected signal data received by the radar system. As explained in Equations (25)–(31) concerning the medium wave propagation model, the reflected signal received by the radar is affected by the SWC. After getting the reflected signal data received by the radar, we can estimate the SWC. The peak magnitude of the reflected signal contains information about the tea plant. The inference method is used to obtain the soil reflection coefficient. The steps of the inference method were already explained in Section 2. The soil reflection coefficient is used to estimate the soil relative permittivity. After obtaining the soil's relative permittivity, the SWC estimation by considering the presence of tea plants is carried out using the Topp Model formula in Equation (14).

Usually, when the measurement is taken after rain that occurred on the previous days, the SWC is higher than 40%. The SWC used in this study was calculated using the gravimetric method, which is used to validate the SWC estimation results using the proposed method. Figure 13 shows the differences in soil texture with different SWC values. Soil with a higher water content has a lumpier texture than soil with a lower water content. The soil samples in this study have 47% and 40% SWC. This shows that soil conditions with an SWC of $> 40\%$ are not inundated by water and can still be calculated using the gravimetric method.



(a)

(b)

Figure 13. Differences in soil texture with different values of soil water content. (a) SWC = 40%. (b) SWC = 47%.

SWC measurements were carried out on five blocks with different heights, namely 75 cm, 77 cm, 80 cm, 90 cm, and 110 cm. Table 1 shows the SWC measurement results obtained from the procedure described in Section 2.4. Measurements on each block were carried out at several different time periods. For example, in block 1, measurements were conducted at two different times, and in block 3, measurements were conducted at 6 different times.

At each measurement, soil samples from the measurement area were taken to calculate SWC using gravimetry method to validate the accuracy of the SWC estimation using the proposed method. A comparison of SWC estimation using the gravimetric method and the proposed method is also shown in Table 1. The results show differences in the value of SWC between the estimation using the gravimetric

Table 1. The comparison of SWC values using gravimetric method and the proposed method.

Block	Vegetation Height	Experiment Periode	Gravimetric	Proposed Method
1	77 cm	1	40%	40.04%
		2	40%	55.38%
2	75 cm	1	33%	33.27%
		2	27%	27.08%
3	80 cm	1	40%	40.05%
		2	40%	30%
		3	47%	53.75%
		4	47%	55%
		5	47%	47.29%
		6	47%	57%
4	90 cm	1	47%	47.14%
		2	53%	53.38%
		3	60%	60.89%
		4	60%	62.05%
5	110 cm	1	47%	53.34%
		2	53%	49.51%

method and the proposed method. This difference indicates an error when estimating SWC using the proposed method, with an average error of 3.57%. The value of this error is obtained from the average deviation between the estimation using gravimetric method and the proposed method in Table 1. The error measurement can be caused by the homogeneous medium approximation for vegetation and soil layer that is taken in determining the proposed method. However, the error is still tolerable in the SWC estimation case in the plantation field. SWC estimation using the proposed method depends on the radar's reflected signal. The variations in the magnitude and phase of the reflected signal received by the radar will also significantly affect the results of estimating SWC. The variation of reflected signal can be caused by the movement of vegetation leafs due to the wind. It can contribute additional errors when estimating SWC. For anticipating additional error, the measurements are performed when the wind is not significant. This fact also needs to consider when the measurement will be implemented by elaborating a drone as a platform used to convey the radar during measurement. A method for mitigating the problem of radar movement variation, which impacts reflected signal variation, needs to be studied.

In collecting SWC data using a radar system, several factors can cause errors. Table 2 shows the measurement results to show the false sample that may occur during measurement. These data are then included as outlier data because the estimation results do not make sense. This outlier data can be caused by wind in the area that makes the tea plants swing and affects the radar's reflected signal. We cannot control this factor, so the outlier data could come from vegetation swaying due to the wind. In addition, the presence of people close to the data collection area can affect the reflected signal. However, this factor is already known, so when collecting data, the condition is already anticipated to avoid any outlier data.

Table 2. Outlier data of estimation results using the proposed method.

Block	Vegetation Height	Gravimetric	Proposed Method
2	75 cm	47%	15524000%
3	80 cm	47%	2977600%

In future development, the proposed method can be applied using a drone for data collection in large plantation areas. In [31], with a different radar system, SWC estimation was carried out using the same method as this study. The research used a drone to collect data on the SWC in plantation areas with an accuracy of 96%. However, drones that fly at elevations that are not constant need to be considered, and the effects should be minimized.

4. CONCLUSION

The method for estimating SWC in the tea plantation area using an FMCW radar with the operating frequency of 24 GHz has been proposed in this study. Simulation studies using computers and field experiments in tea plantation areas have been carried out. Field experiments were carried out in 5 blocks of plantation areas with different heights of tea plant. The results of field experiments show vegetation's influence on the reflected signal. The presence of vegetation causes a decrease in the peak magnitude and a phase shift of the reflected signal received by the radar, so the accuracy of the detection results decreases. This study elaborates a layered medium propagation model to determine the relationship between the reflected signal received by the radar and the SWC. The characteristics of tea plants were obtained from field measurements. This proposed method successfully reduces vegetation's effect in estimating SWC using a radar system. The gravimetric method is used in this study to validate the estimation of SWC. The method proposed has an average error of 3.57% in estimating the SWC. The proposed method can be used on plantations with various vegetations by first measuring the vegetation characteristics. For further research, the radar system and the proposed method in this paper can be applied to drone systems for data collection.

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