Chapter

Microwave Sensors for Soil Moisture Detection: An Application toward Healthy Date Palm

Mohammed M. Bait-Suwailam, Rand Mousa Tbaileh, Hassan Al-Lawati and Yaseen Al-Mulla

Abstract

Soil moisture is an important key parameter in the earth ecosystem that has an impact on both landscape and atmospheric conditions. Moreover, sudden changes to soil moisture due to environmental conditions result in degradation to food plants and, thus, may consequently affect food yields. This chapter aims to investigate numerically an application for crops health through soil moisture detection using microwave-based sensors. The numerical studies are carried out using full-wave electromagnetic simulations. More emphasis on the numerical setup of microwave antennas with customized modeled soil layer is presented.

Keywords: agriculture, date palm, microstrip patch antenna, microwave sensor, remote sensing, soil moisture

1. Introduction

Soil and water resources are considered the backbone support of our life ecosystem and civilization. While soil and water are precious substances, they are inseparable and collectively termed as *soil moisture* when it comes to maintaining a reliable health status for the soil [1]. Soil is also very essential to the growth and yield of crops that are part of our daily food and nutrition. In fact, healthy soil is directly proportional to human being health. One of the main global challenges that worldwide may suffer from in the coming years is the lack of water resources. Water is a natural ingredient that is of paramount importance for life and survival of plants. As the world's population is expected to grow drastically, such natural resources produce dynamic challenges in terms of feeding mankind, especially in the developing countries [2, 3]. It is expected that when the human population increases, food production is expected to rise and be made available globally. In addition, a drastic growth is expected to land-cover infrastructure and civilization, which will result in exponential rise in water consumption [3]. As such, this has a direct impact on crops' health and food production [4].

Agriculture depends heavily on water, with approximately 70% of the depletion of water around the world being consumed by many agricultural crops [5], among which is date palm, which is considered an important food product that aids in the economic growth of many countries in the arid region. In fact, the amount of daily water consumption by date palm trees varies from one place to another, depending on many factors, including environmental and atmospheric conditions. In order to alleviate any water shortage, modern irrigation management systems are needed. It is the act of regulating water at the appropriate time according to the crops' need in amount that can be held in the soil. This produces the proper growth of plants and healthy soil [6]. The amount of soil water is important to know or estimate because soil moisture is a fundamental carrier of food nutrients for plant growth, regulates soil temperature, forest fire prediction, drought, and flood forecasting [7, 8]. The amount of water content in soil could be estimated either quantitatively or qualitatively by using digital technologies in order to have a better decision and, thus, improve productivity [9–12].

Soil presents the earth's top level, which is a mixture of minerals, water, and air including organic matter [13]. Such combination determines soil properties, for instance, soil color and texture, although the combination is complex and soil is dynamic in nature. **Figure 1** depicts a soil texture triangle. This soil triangle is a visualization figure of soil texture that is composed of three main percentages, namely sand, clay, and silt. The intersection point from three lines extending from each side of the triangle (percentage of each substance) determines soil's texture class.

The two basic and commonly used methods to estimate water content in soil are either by considering the mass of a soil sample and comparing it to its dry weight (also known as the gravimetric method) or by taking the ratio of water to soil volumes (volumetric method) [15]. However, it may not be a practical and convenient way to consider drying the soil samples over a long period in oven. Moreover, it is also possible to quantify the water contents by measuring the soil capacitance or conductance. In many capacitance-based sensor configurations, probes are used and integrated with the sensors' electronics. The probes come with two parallel electrodes, and through the two electrodes, one can measure the capacitance and hence, estimate the water

Figure 1.
Soil's texture triangle classification diagram [14].

content in soil. There are many traditional volumetric-based water-content-sensing modalities that have been introduced in the literature, including, but not limited to, the use of frequency/time-domain reflectometry [16–18], resistivity methods [19–21], and radiation-based techniques [22–25]. Over the past decade, earth observation imagery data have been also utilized widely and deeply to retrieve and monitor soil moisture using a variety of low-earth orbital space-borne sensors [26–28].

In this section, an overview of soil degradation due to climate change, land-cover changes, and water shortage is presented. A brief summary of earlier studies in soil moisture characterization and detection was provided. In the next sections, an application for soil moisture detection using microwave antennas is presented. A microstrip inset-fed patch antenna is designed and numerically modeled at L-band, which makes it suitable for remotely sensing soil moisture. One soil type is considered in this study, and results are analyzed and discussed.

2. Microwave properties of soil

No doubt that agriculture depends heavily on the management of soil and water. Both soil and water are considered as main natural resources, since soil is the host medium for crops to grow and is known for supporting the structure of plant life as water sustains the plant life. It is vital to understand the nature and status of soil, since the soil supplies water, oxygen, and nutrients to the plants to grow and flourish by the root support. Hence, healthy soils produce healthy plants. In this section, we provide a brief background on the microwave properties of soil, where the complex electric permittivity of soil is discussed, and its dependence on the volumetric moisture level is also presented graphically for both dry and wet soil.

Soil can be considered as a mixture of minerals and organic matter that contains microorganisms, water, and air. Furthermore, soil has several layers known as horizons, which are distinguished from one another in texture and color [29]. The combination of organic matter, mineral matter, water, and air that forms soil determines the soil's properties such as its texture, structure, porosity, and color [30].

In principle, the generic form of electric permittivity is complex, carrying a real part that corresponds to the material's relative permittivity, that is, dielectric constant, and an imaginary part that relates to the associated losses in the material. It is given in the form:

$$\varepsilon^*(\omega) = \varepsilon_r - j\varepsilon_i, \tag{1}$$

where ε_r is the dielectric constant of the material, and ε_i is the imaginary component. The electric permittivity of a material is usually frequency and temperature-dependent, and its imaginary part will determine the amount of losses encountered. The variation of the loss term will play a role in the microwave sensing of soil, since it is variant depending on the level of water moisture contents.

Based on experimental studies of several soil types [31–33], the dielectric constant of dry soil is independent of frequency and temperature, but it is dependent on the soil bulk density. Bulk density can be defined as the dry weight of soil per unit volume of soil. It can be numerically modeled by relating it to electric permittivity of dry soil as

$$\varepsilon' = (1 + 0.44\,\rho_{sb})^2, \tag{2}$$

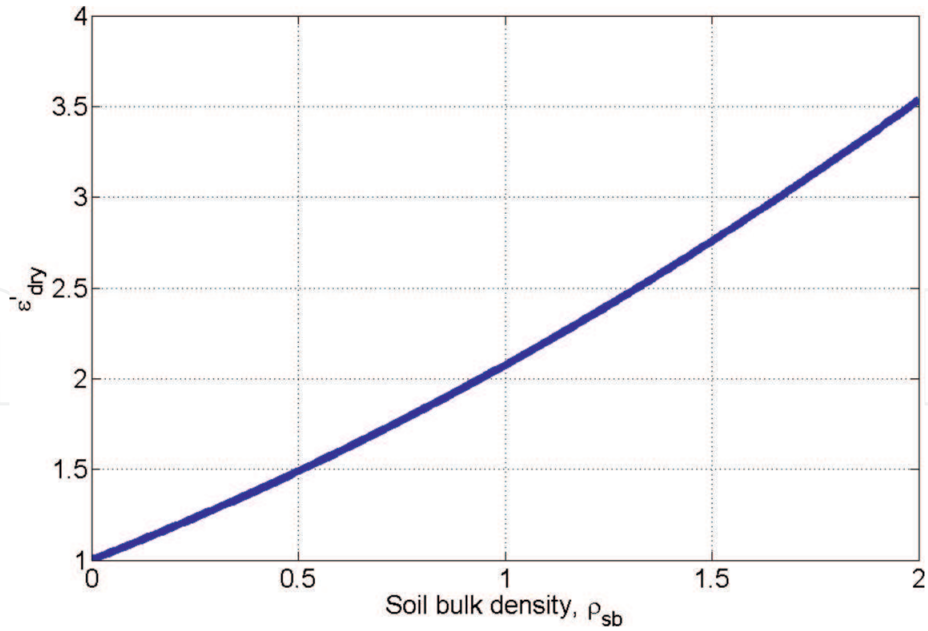

Figure 2.
Relationship between electric permittivity of dry soil and its bulk density.

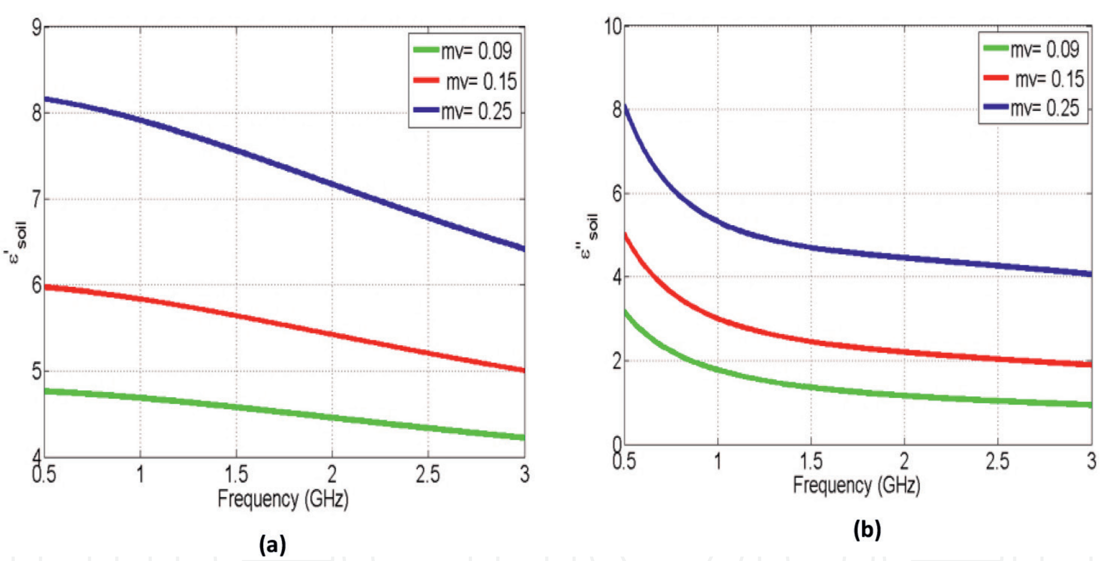

Figure 3.
The electric permittivity of wet soil with moisture volume: (a) its real part and (b) imaginary part (loss term).

where ρ_{sb} is the soil bulk density. **Figure 2** shows the relationship between dry soil's permittivity and its bulk density. As can be seen, the relationship shows independency of the dry soil from temperature.

Figure 3 depicts the complex electric permittivity profile of wet soil as a function of frequency for various moisture levels. As moisture volume is increased, the dielectric constant of wet soil increases substantially, as shown in **Figure 3a**. Moreover, a decaying profile of permittivity's loss factor is observed as frequency is increased for each volumetric moisture level, as shown in **Figure 3b**.

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3. Microwave sensors for soil moisture detection

Over the past decade, plenty of soil moisture sensors and meters had been developed and commercialized for personal and industry use [34]. Such sensors could help low-income farmers to enhance their food products by saving water. Many soil moisture sensors have sustainability issues, in which their structure is quite weak and fragile that could easily be damaged after being used for few times. Moreover, various products are not well calibrated and do not offer very high accuracy.

The deployment of microwave antennas for remote sensing of soil moisture is still an active research area, especially with the drastic technology development of unmanned aerial vehicles (UAVs) that have made significant revolution to many engineering and science applications. The benefits of these microwave sensors include their ability to measure large acre areas and are insensitive to the error associated with airgaps between the soil and the sensor.

Among many configurations of microwave antennas, microstrip antennas are widely deployed and preferred, due to their low profile, easy to integrate with other radio frequency/microwave circuits and subsystems, conformability to both planar and flexible surfaces, and versatility in terms of performance and polarization.

A microstrip patch antenna is composed of a thin metallic strip placed above the ground plane and suspended by a thin host substrate (dielectric material), as shown in **Figure 4**, where the commonly adopted host substrate is used as FR-4 laminate with its dielectric constant of 4.4 and loss factor of 0.02. The optimized dimensions of the studied microstrip patch antenna can be found in **Table 1**, where the antenna has been designed to operate within the L-band. An interesting application for remotely sensing soil moisture is to integrate a thin microstrip patch antenna, either a single unit or an array (depending on the mission) with a UAV platform for ease of scanning and mobility.

In order to show the capability of the microwave patch antenna for sensing and detecting soil with various properties and thicknesses, a three-dimensional numerical model is constructed, using Ansys HFSS [35]. Ansys HFSS simulation package is a finite-element-based numerical full-wave simulator that solves Maxwell's equations based on a tetrahedral mesh scheme.

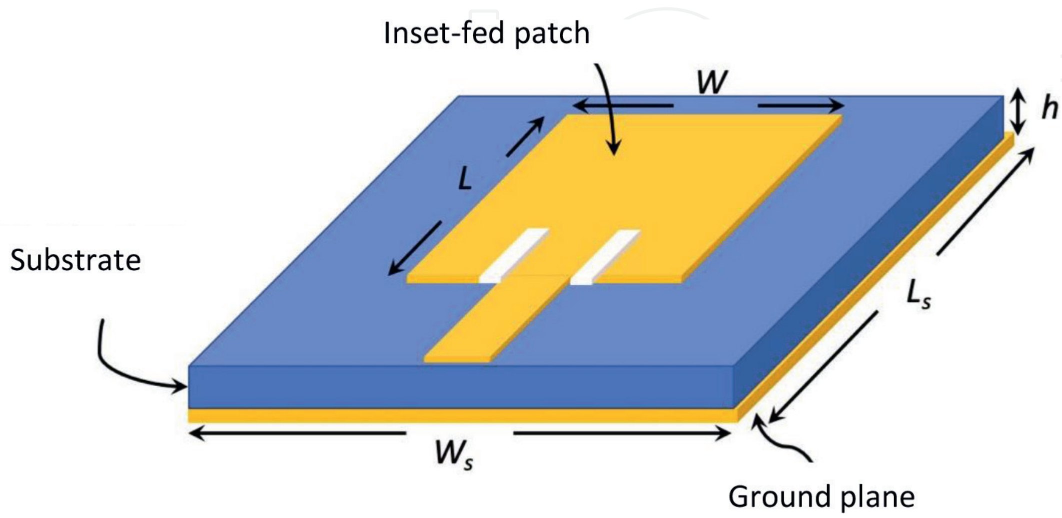

Figure 4.
Generic schematic of a microstrip inset-fed patch antenna.

Parameter	Dimension (mm)
Patch length, *L*	50.8
Patch width, W	65.2
Substrate length	100
Substrate width	100
Substrate height	1.6
Feedline length	24.6
Feedline width	3.01
Inset-fed point	13

Table 1.
Structural dimensions of the microstrip inset-fed patch antenna.

Loamy soil	Electric properties	
Moisture level (ML) percentage	**Dielectric constant**	**Loss tangent**
0%	3.0	0.003
5%	3.9	0.053
10%	5.3	0.27
15%	7.5	0.107
20%	10.8	0.111
25%	14.5	0.138
30%	17.5	0.143

Table 2.
The microwave electric properties of Loamy soil.

In this numerical study, it was assumed that soil properties are known a priori, where the antenna is used to judge the soil properties based on the reflected electromagnetic energy from the soil surface back to the antenna, that is, from the reflection coefficient profile. Without loss of generality, Loam soil has been considered in this study. **Table 2** presents the estimated microwave properties of Loamy soil at L-band (1.4 GHz) from earlier measured data from [31]. Depending on the percentage level of Loam's moisture as illustrated in **Table 2**, the microwave electric properties are injected into the modeled Loam soil. This has been done within the 3D numerical model in order to mimic a realistic scenario of Loam with its moist level. For example, in the case of dry Loam soil (moisture level of 0%), the dielectric constant is 3.0, while its loss factor is estimated as 0.003.

Figure 5 depicts the 3D numerical model illustrating the microwave sensor placed underneath a cubical box mimicking Loamy soil. All electric properties of the soil and its associated moisture level are considered. Numerical studies are also carried out to investigate the effect of the detection strength as the Loamy soil layer is varied (varying its thickness, H in **Figure 5**).

The ability of the microwave sensor to detect abnormalities in the moisture level of Loam soil is assessed by recording the reflection coefficient, that is, the scattering coefficient of the 1-port structure. For instance, at a thickness of 10 mm, **Figure 6** depicts the reflection coefficient profile for the Loam substrate as a function of varying the moist level. As can be seen, due to the excessive moisture level, higher reflection from the microwave sensor is expected, due to the high loss profile of the moist-Loamy substrate.

Figure 7 shows the amount of frequency shift for 10% moist-Loamy soil as a function of the soil's thickness, H. One can observe an increased shift in the sensor's resonance as soil's thickness is increased, due to the excessive loading of the lossy

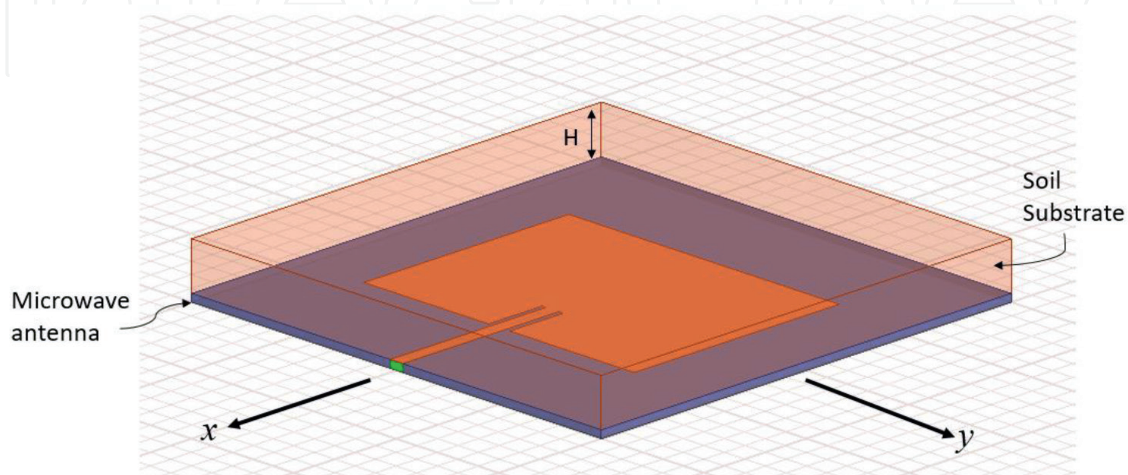

Figure 5.
3D numerical model showing the microwave antenna beneath modeled Loam soil.

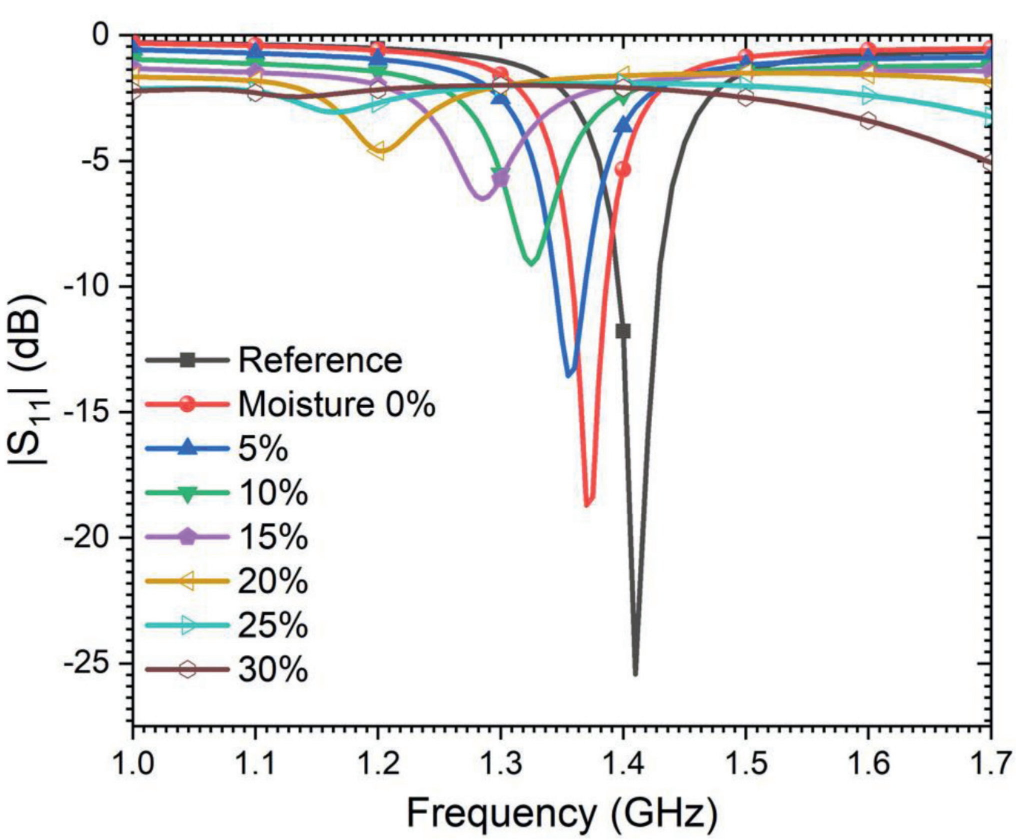

Figure 6.
The reflection coefficient of the microwave sensor for various moist levels of Loamy soil substrate with thickness, H = 10 mm.

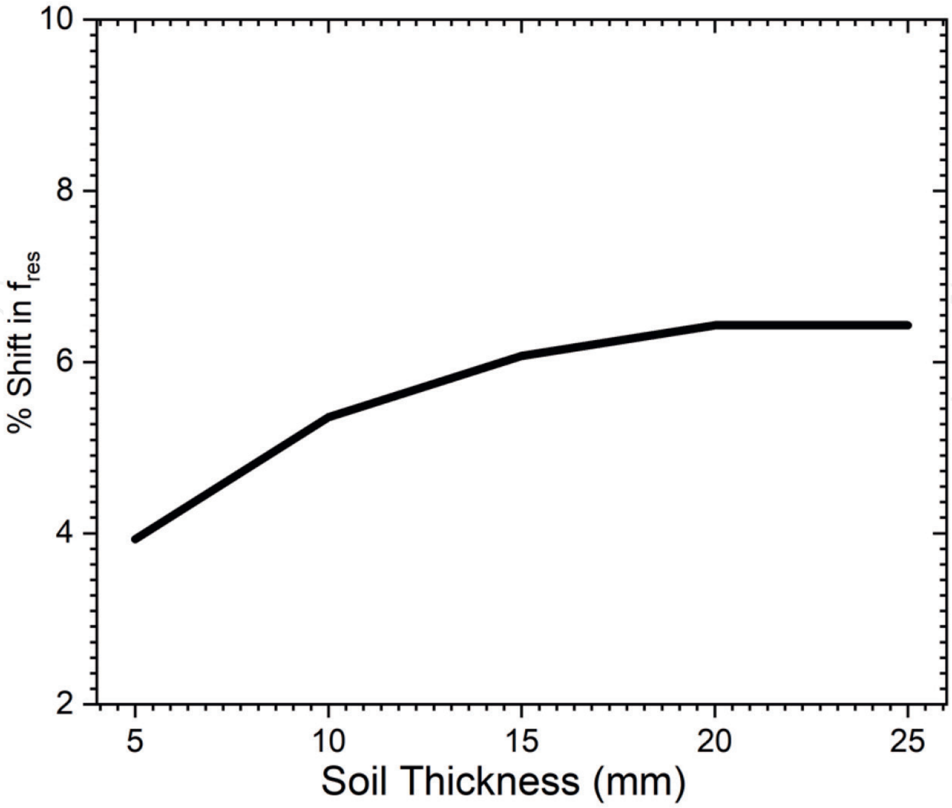

Figure 7.
Parametric study showing the behavior of the microwave antenna as a function of soil thickness for the case of Loamy soil with 10% moisture level.

soil layer. Furthermore, the increased shift in resonance frequency of the sensor is minimal after a thickness of 20 mm.

4. Conclusion

In this chapter, we presented an overview of the potential advantages of microwave sensors for soil moisture detection. First of all, the basic background covering microwave electric properties of soil is presented and discussed. Furthermore, we presented one 3D numerical case study comprising the deployment of a microstrip patch antenna for remotely sensing soil moisture quantitatively by measuring the percentage shift in the sensor's resonant frequency. Moreover, we presented a detailed study on the percentage detection for various soil moisture levels. Based on the numerical results, microwave antennas are very attractive and provide easy means for soil moisture detection, which can be integrated with aerial platforms for ease of remote sensing.

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