Sensitivity Analysis of Microwave Sensors to Various Soil Types and Their Soil Moisture Content

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Abstract: ***Understanding soil moisture content is extremely important to model areas for suitability analysis of different plantations and to predict natural disasters like landslides, floods, etc. It also influences hydrological and ecological processes. In the present work, a microwave sensing system with transmitter and receiver antennas in the C band is experimented with. The sensitivity of the sensor system is compared with the changes in soil moisture levels for different soil types available in the North Eastern Region of India using the laboratory-based setup. Suitable frequency determination for such a microwave-range soil moisture sensor is directly related to remote sensing satellite applications. The sensor system is found to be highly sensitive to soil moisture changes in various soil types. However, the determination of the exact frequency range that is suitable to detect soil moisture changes in different soil types is required for satellite remote sensing applications in the microwave range. Especially for the typical alluvial soil types of the Brahmaputra valley, a detailed sensitivity study using the microwave sensor is done in the current study. Thus, this paper presents the study results for determining the most suitable C-band frequency for soil moisture monitoring using active microwave sensors.***

Keywords: Active Microwave Sensor; backscattering Power, C-band; Soil Moisture.

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1. Introduction

Rich in agricultural fields, India is among the top producers of corps worldwide. Despite the advantage, there are only a few attempts to monitor agriculture through its primary object, soil from both space and ground level. The soil moisture study can be used to improve crop yield prediction and irrigation scheduling. Natural disasters like landslides, flood prediction, etc. also require soil moisture monitoring using satellite data. Optical sensors have previously been established for the use of soil moisture monitoring [1]. But its limitations in cloudy and rainy weather necessitate the use of microwave radar. Microwave radar can penetrate through clouds and has a good scattering property through clouds and haze, which makes it more efficient and helpful for remote sensing of different tropical areas. Microwave radiometry is also a well-established technique for surface remote sensing. Microwave sensors are useful for sensing soil-related parameters because of their low frequency and high spatial resolution. Time-domain reflectometry (TDR) was the first method applied for measuring moisture. TDR sends a pulse down into the soil, and the system determines the water content by measuring how long it takes to come back. Next, for FDR sensors, it uses an oscillator to propagate an EM signal through a metal line or waveguide; with this method, the difference between the output wave and the return wave frequency is measured to determine soil moisture [2].

A swept-frequency domain instrument was examined for low-cost, high-accuracy measurements of water content in various materials, which was an alternative to the traditional and more expensive time-domain reflectometry. The technique obtains permittivity measurements of soil in the frequency domain by utilizing a thorough transmission configuration, transmissometer, which provides a frequency domain transmissometer measurement [3]. A multi-frequency algorithm capable of retrieving soil moisture content from C-band data was tested with the data sets collected in agricultural regions in southern France and Italy with IROE airborne or ground-based radiometers.

The instrument for radio observation of the earth (IROE) sensor consists of five microwave channels: the L-band (1.4 GHz) can operate at Vertical (V) or Horizontal (H) polarization, the C (6.8 GHz) and X (10 GHz) bands measure H and V polarizations simultaneously [4]. The 1.41 GHz horizontal polarization channel showed the greatest sensitivity to soil moisture over the range of vegetation observed, and the radar measurements show a response to soil moisture change and can provide useful information on the spatial and temporal variability of soil moisture [5].

A calibrated passive/active L/S-band (PALS) microwave aircraft radiometer and dual-frequency radar system with a 2.86 kHz pulse repetition frequency (PRF) was developed to study and make measurements of soil moisture and ocean salinity [6]. Various integral equation methods (IEMs) have been developed and applied to retrieve soil moisture from the backscattering coefficient [7]. The recorded value of received power (in dBm) and the coefficient of backscattering can be computed using the following radar range equation [8].

$$\boldsymbol{\sigma} = \frac{(4\pi)^3 (R_t)^2 (R_r)^2 P_r}{G_t G_r A \lambda^2} \quad (1)$$

where R is the target distance, R_t is the distance of the point of reflection from the transmitter, R_r is the distance of the point of reflection from the receiver, P_r is the received power, P_t is the transmitted power, $_{It}$ is the gain of transmitting antennae, G_r is the gain of receiving antennae, A is the common illuminated area, and λ is the wavelength of the signal.

The experimental setup is based on frequency domain reflectometry and is utilized to measure moisture content in various soil types from 0% to 20% at an interval of 5% using C-band. C-bands are used for a wide range of applications, including radar, microwave sensor systems, and satellite communication. The ground-level study is based on the experiments conducted at the Assam Don Boaco University, Assam, India, during the months of September and October 2022. From the analysis of the experiments carried out, the data appears to be promising, as it can very well distinguish the sensor's response to variations in soil moisture in the C-band. It provides a reliable method for soil moisture monitoring. The advantages of the proposed experimental setup are its high frequency, quickness of measurement, and ease of implementation.

2. Methodology

Various soil samples, like red soil, black soil, sandy soil, river soil, etc., are collected from different places of Assam and kept in an oven at a temperature of 105^0-110^0 for 24 hours to make the moisture content zero, before experimenting with. After that, 155 grams of each soil sample is taken into the measuring cylinder and put under the antennae for the purpose of measurement. The measurement of backscattering power is carried out by varying the frequency from 4.08 to 5.72 GHz for the soil sample with 0% moisture content. Then, water equal to 5% of the weight of the soil taken is added to the sample with 0% moisture content. In the same way, water equal to 10%, 15%, and 20% of the soil weight are added to the soil sample, respectively. To make sure the distribution of moisture content throughout the soil is uniform prior to the experiment, a stirrer is used. For different soil moisture contents, the power measurement is carried out, by varying the frequency.

As shown in Fig. 1, a C-band microwave source is used to transmit the signal onto the target material using the transmitter antenna. The scattered microwave power from the target is then received by the power meter that is connected to the receiver antenna, which is also pointed toward the target. Received power values are recorded and compared to determine the most sensitive frequency level in the C-band for different soil types, using the Regression technique.

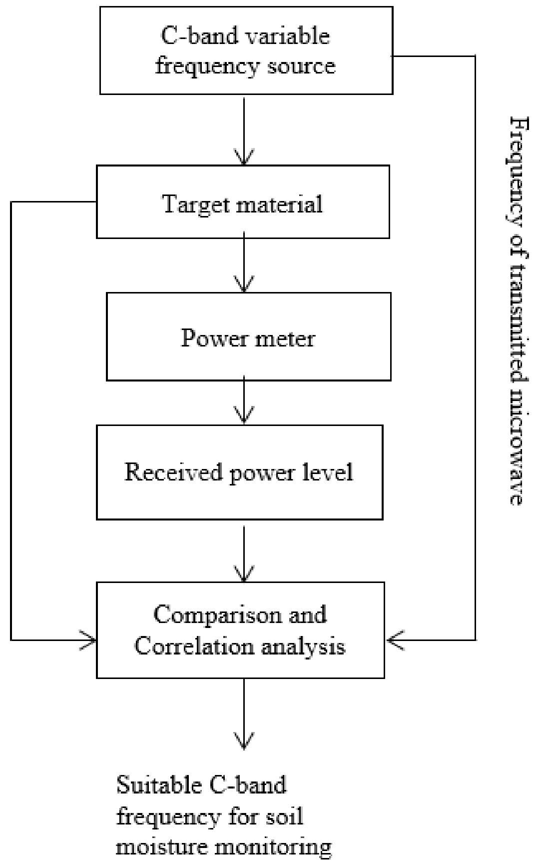

Fig. 1: Methodology for experimental work

Table 1 represents the specifications of the C-band scatterometer system used for the study. Fig. 2 shows the system, which is mainly composed of dual-polarimetric horn antennas, a microwave frequency source, coaxial cables, and a power meter. The picture of the actual experimental set-up is shown in Fig. 3. Numerous experiments were carried out and a good number of repeatability tests were conducted to detect soil moisture-related variations for the targeted soil types. Five different soil samples were used for the experiment, and Fig. 4 shows four of them.

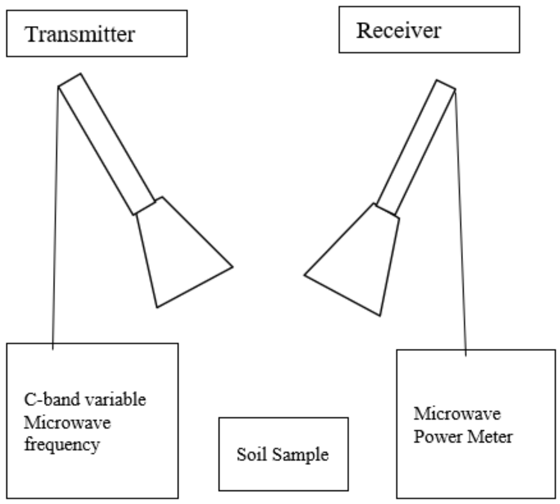

Fig. 2: Schematic Representation of the Experimental Set-up

Table1: Specifications of the scatterometer system

Specifications	C-band scatterometer value
Centre Frequency	4.83 GHz
Bandwidth	4.08-5.72 GHz
Antenna Type	Parabolic Horn
Polarization	HH

In Fig. 3, two horn antennae (the transmitter and receiver) are pointed at the same target sample of soil to overlap the footprint of the two antennae. Both antennas are used in horizontal-horizontal (HH) polarization. The scattered power measurement of the soil samples is carried out with an incident angle of 45⁰ to maintain the antenna geometry. Then, the received power values are recorded, and comparison, as well as analysis, is done to find the sensitive frequency level for different soil types using Equation 1. The setup used will provide the suitable data required to estimate soil moisture content with better accuracy.

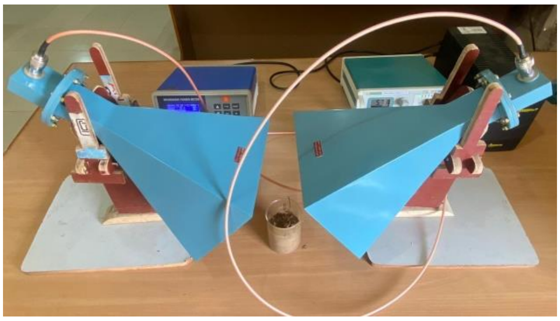

Fig. 2: Actual experimental set-up

In Fig.4, Four different types of soil samples each carrying 155 grams are shown:

Soil No. 1- Soil collected from Paddy fields of Assam
Soil No.2 - Sandy soil
Soil No. 3- Soil collected from Tea Garden
Soil No. 4- Soil collected from the hills of Assam

Fig. 4: Four different soil types

Table 2 represents the experimental value of Specific Gravity of all the soil samples using the formula given below

$$SG = \frac{(W_2 - W_1)}{(W_2 - W_1) - (W_3 - W_4)} \quad (2)$$

Where,
w_1 = Weight of the pycnometer
w_2 = Weight of the pycnometer containing 300 grams of soil
w_3 = Weight of the pycnometer containing 300 grams soil and water
w_4 =Weight of the pycnometer with water

Table 2: Specific Gravity of all soil samples

Specific Gravity Value			
Soil No. 1	Soil No. 2	Soil No.3	Soil No. 4
1.72	2.5	2.2	2.6

Table 3 represents the particle size distribution for all the soil samples performed in laboratory using different sieve keeping the initial value of soil 765 grams.

Table 3: Particle size distribution for all soil samples

IS sieve size (in cm)	Weight of soil Retained (in grams) in different soil types				Percentage weight of soil retained in different soil types (%)			
	1	2	3	4	1	2	3	4
2	80	10	71	22	10.4	1.3	9.2	2.8
21	155	18	160	40	20.2	2.3	20.9	5.2
.600	190	24	175	85	24.93	3.1	22.87	11.11
.425	165	40	155	134	21.5	5.22	20.2	17.51
.212	105	120	95	210	12.7	15.6	12.4	27.4
.150	25	365	60	240	3.26	47.7	7.84	31.3
0.075	50	188	49	33	6.53	24.57	6.40	4.31

3. Results and Discussion

The received power levels at different frequencies for a particular soil type and a definite soil moisture level are recorded. The received power varies with the change in soil moisture level, as observed from the recorded data. This variation is significant at some selected frequencies in the C-band. With repeated test trials, the most sensitive frequencies to soil moisture variations for a particular soil type are determined. It is also observed that for different soil types, different frequencies show sensitivity to soil moisture. Hence, it is necessary to determine the frequency or frequencies that are suitable for a specific soil type. The analysis of the correlation study done between the different frequencies in the C-band and the soil moisture changes in the different types of soils is presented in the following.

After the received power levels are recorded, the correlation coefficient and coefficient of determination (R^2 values) are computed using linear regression techniques. The R^2 values give the idea regarding the best correlation between certain frequencies and the soil moisture change in the specific soil type.

For tea garden soil, the most sensitive frequencies are 4.47–4.48 GHz, 4.63–4.70 GHz, and 4.79 GHz as seen from the computed R^2 values in Fig. 5.

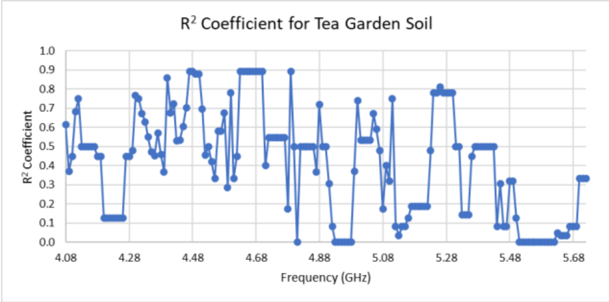

Fig. 5: Relation between frequency and R^2 Coefficient for Tea Garden Soil

Relationship between power received (dBm) in power meter and soil moisture (%) for Tea Garden Soil can be found from the Fig. 6 using the second order polynomial equation given below:

$$y = 1.25x^2 + 8.75x + 7.5 \quad (3)$$

Where, y is the soil moisture content and x represents the power received.

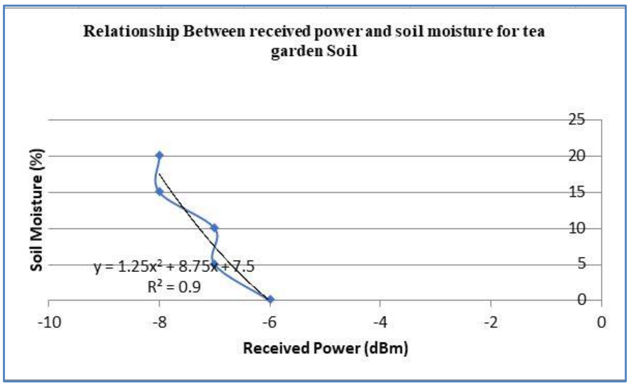

Fig. 6: Relationship Between received power and soil moisture for Red Soil

For Sandy soil collected from the bank of the river Brahmaputra, the most sensitive frequencies are 4.38 GHz, 4.62 GHz, 5.01-5.02 GHz, 5.11 GHz, 5.17 GHz, 5.28-5.29 GHz as seen from the computed R^2 values in Fig. 7.

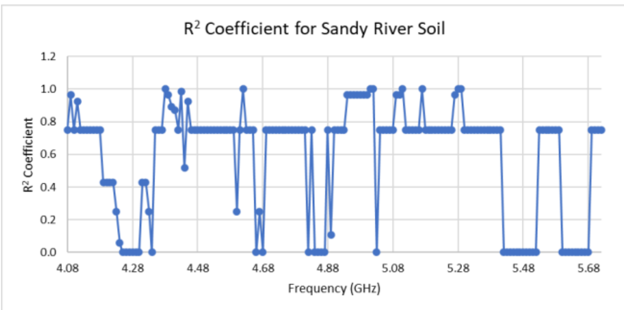

Fig. 7: Relation between frequency and R^2 Coefficient for Sandy River Soil

Relationship between power received (dBm) in power meter and soil moisture (%) for Sandy River

Soil can be found from the Fig. 8 using the second order polynomial equation given below:

$$y = 1.25x^2 + 26.25x + 130 \quad (4)$$

Where, y is the soil moisture content and x represents the power received.

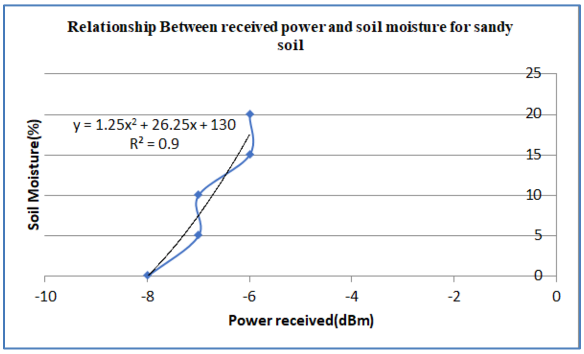

Fig. 8: Relationship Between received power and soil moisture for Sandy Soil

For Red Sandy Soil collected from the hills of the lower Assam area, the most sensitive frequencies are 5.16 GHz, 5.20-5.23 GHz, and 5.54-5.59 GHz as see seen from the computed R^2 values in Fig. 9.

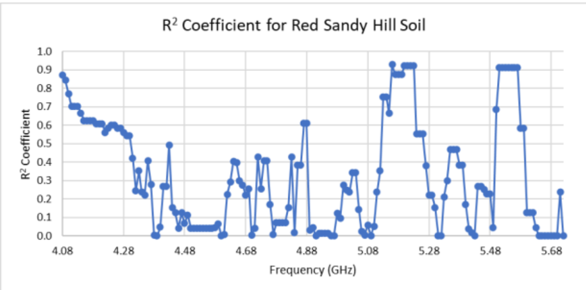

Fig. 9: Relation between frequency and R^2 Coefficient for Red Sandy Hill Soil

Relationship between power received (dBm) in power meter and soil moisture (%) for Red Sandy Hill Soil can be found from the Fig. 10 using the second order polynomial equation given below:

$$y = -2.3333x^2 - 23x - 36.667 \quad (5)$$

Where, y is the soil moisture content and x represents the power received.

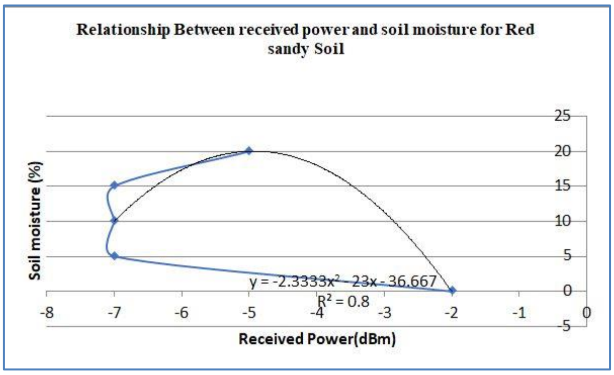

Fig. 10: Relationship Between received power and soil moisture for Red Sandy Hill Soil

For the clayey soil collected from the paddy fields of the lower Assam area, the most sensitive frequencies are 5.28-5.32 GHz as seen from the computed R^2 values in Fig. 11.

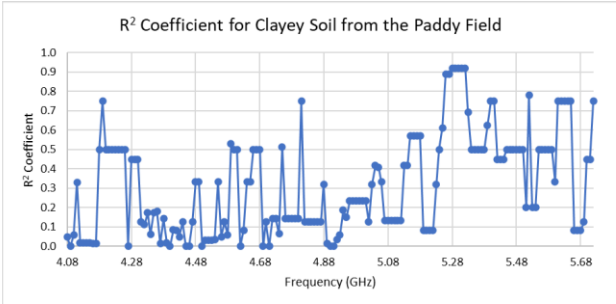

Fig. 11: Relation between frequency and R^2 Coefficient for clayey Soil from the Paddy Field

Relationship between power received (dBm) in power meter and soil moisture (%)for clayey Soil from the Paddy Field can be found from the Fig. 12 using the third order polynomial equation given below::

$$y = -0.625x^3 - 8.125x^2 - 27.5x - 7.5 \quad (6)$$

Where, y is the soil moisture content and x represents the power received.

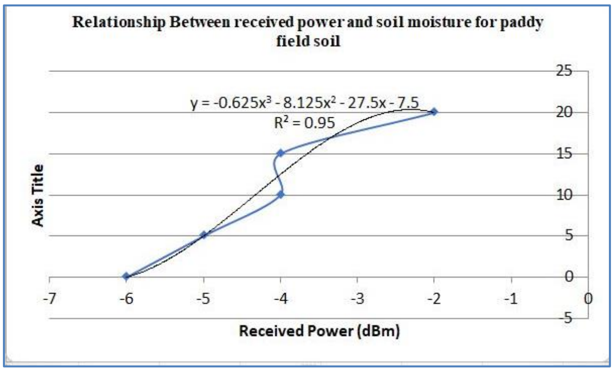

Fig. 12: Relationship Between received power and soil moisture for Paddy field soil

The above discussion shows the sensitivity of different frequencies to soil moisture variations in different soil types. These frequencies are determined with several repeated trials with the same soil types, under various weather and ambient conditions. Hence, these frequencies are considered to be suitable for any sensing application using a C-band microwave set-up. Especially for satellite-based remote sensing applications, for soil moisture monitoring, the frequencies which are found to be the most suitable for different soil types can be used for the purpose.

4. Conclusions

This paper describes the experiments performed and highlights the response and characteristics of the C-band tested for different soil types. This paper introduces the experiment carried out for the analytical study of soil moisture measurement. The methodology of acquiring C-band backscattering power data and corresponding soil moisture information is summarized and discussed. The results of this study will help the scientists working in the field of microwave remote sensing by providing information as measured physically in the field.

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