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## Microwave Dielectric Relaxation Time Behaviour of Soil Samples under Varying Moisture Content at 9.65 GHz

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**ABSTRACT**: This study investigates the variation in dielectric relaxation time of ten distinct soil samples as a function of moisture content at a microwave frequency of 9.65 GHz. Relaxation time values were measured over a moisture range of 0% to 30%, revealing a non-linear response. Statistical analysis highlighted a peak in relaxation time around 5 to 10% moisture content, followed by a consistent decline with increasing water content. The initial increase is attributed to the dominance of bound water, while the subsequent decrease results from enhanced dipolar mobility due to free water. Variations among soil samples emphasize the influence of intrinsic properties such as texture and mineralogy on dielectric behaviour. These findings are crucial for refining dielectric models and improving microwave remote sensing techniques for soil moisture estimation.

KEYWORDS: Soil Samples, Microwave Frequency, Moisture Content, Relaxation Time.

#### I. INTRODUCTION

The dielectric properties of soils, particularly their relaxation time, play a crucial role in high-frequency remote sensing, soil characterization, and environmental monitoring [1][2]. Relaxation time is influenced significantly by soil composition and moisture content. At microwave frequencies such as 9.65 GHz, these effects are particularly prominent and are relevant for radar remote sensing systems like those onboard Lookout or RADARSAT satellites. This study investigates the variation in relaxation time of ten different soil samples across a range of moisture contents (0% to 30%) at a frequency of 9.65 GHz [2][3]. The purpose is to understand the influence of increasing moisture on the dielectric relaxation behaviour of soils, which aids in the calibration of remote sensing instruments and improves soil moisture retrieval algorithms.

#### **II. RELATED WORK**

#### Materials and Methods:

#### **Sample Collection and Preparation:**

Ten distinct soil samples were collected from different locations, ensuring variability in texture and composition. These soil samples were first sieved by gyrator sieve shaker of size 425  $\mu$ m to remove the coarser particles in the soil. Each sample was dried in an oven at 105°C for 24 hours to eliminate any existing moisture content. Such dry samples are then called as oven-dry or dry base samples as compared with wet samples. Soil samples of various volumetric moisture contents (up to 30%) are prepared by adding an exact amount of distilled water to the known mass of the oven dry soil.

#### **Moisture Content Adjustment:**

After drying, distilled water was added incrementally to each soil sample to reach target moisture contents of 5%, 10%, 15%, 20%, 25%, and 30%, calculated by weight. Samples were thoroughly mixed and sealed in airtight containers for 24 hours to ensure uniform moisture distribution.



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#### **III. METHODOLOGY**

#### **Dielectric Measurement at 9.65 GHz:**

The wave-guide cell method is used to determine the dielectric properties of contaminated and reclaimed soil samples. An automated microwave set-up in the TE10 mode with Gunn source operating at desired X-band frequencies, PC-Based slotted line control and data acquisition system are used for this purpose. The dielectric properties of the moist soils were measured at a fixed frequency of 9.65 GHz. The dielectric parameters will be calculated by using the formulae given below. The relaxation time for each sample at each moisture level was computed from the dielectric data using the Debye relaxation model [5].

#### i) Dielectric constant (ɛ')

$$\varepsilon' = \frac{g_{\varepsilon} + (\lambda_{gs}/2a)^2}{1 + (\lambda_{gs}/2a)^2}$$

ii) Loss factor (ɛ'')

$$\varepsilon'' = -\frac{\beta_{\varepsilon}}{1 + (\lambda_{gs} / 2a)^2}$$

From the measurement of dielectric constant and dielectric loss, other dielectric parameters can be obtained by using following equations: **iii) Relaxation time** 

 $\tau = \varepsilon'' \omega \varepsilon'$ 

Where

a - Inner width of rectangular waveguide  $\lambda_{gs}$  - wavelength in the air-filled guide.

 $\mathbf{g}_{\varepsilon}$  - real part of the admittance

 $\beta_{\varepsilon}$  - imaginary part of the admittance

 $\omega = 2\pi f$  - angular frequency

#### **IV. EXPERIMENTAL RESULTS**

MC	0%	5%	10%	15%	20%	25%	30%
S.N.1	1.86996E-13	5.25499E-13	3.47318E-13	3.58666E-13	2.73004E-13	2.89646E-13	2.88848E-13
S.N.2	2.5838E-13	4.24324E-13	4.39171E-13	3.56338E-13	2.29442E-13	2.34094E-13	2.33039E-13
S.N.3	6.88367E-13	4.14013E-13	2.72224E-13	2.66223E-13	2.50119E-13	2.57225E-13	2.564E-13
S.N.4	1.23673E-13	4.2194E-13	4.45099E-13	2.66664E-13	2.94108E-13	2.30837E-13	1.90614E-13
S.N.5	3.7467E-13	3.7206E-13	3.6835E-13	2.8229E-13	2.22973E-13	1.60956E-13	1.33651E-13
S.N.6	2.66914E-13	2.93082E-13	3.43378E-13	2.73887E-13	2.6285E-13	2.77033E-13	2.85166E-13
S.N.7	3.65725E-13	3.48535E-13	4.1033E-13	2.50374E-13	2.5398E-13	2.05284E-13	2.14232E-13
S.N.8	2.96004E-13	3.30089E-13	3.68515E-13	2.3358E-13	1.55861E-13	1.22521E-13	1.22159E-13
S.N.9	1.59569E-13	1.86968E-13	2.47992E-13	2.24669E-13	1.6201E-13	1.46715E-13	1.14204E-13
S.N.10	1.51536E-13	2.01841E-13	2.00202E-13	2.10657E-13	1.56671E-13	1.20932E-13	1.23396E-13

Table 1. Variation in relaxation time with increasing moisture content for ten different soil samples.



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This graph shows the variation of relaxation time with moisture content for each of the 10 soil samples. Initial Increase Followed by Decrease or Stabilization: Many samples (e.g., S.N.1, S.N.2, S.N.4) exhibit an increase in relaxation time with initial moisture content (0–5%), followed by a gradual decline or stabilization as moisture content increases further. This behaviour suggests that bound water initially contributes to increased polarization delay, but as more free water dominates, the overall relaxation time decreases due to higher molecular mobility.

Moisture Content (%)

Sample-Specific Behaviour: Some samples, such as S.N.3 and S.N.6, exhibit less variation with moisture content, indicating a more stable dielectric response. In contrast, samples like S.N.8 and S.N.9 show a steady decline, likely due to differences in soil texture, organic matter, or mineral composition.

Effect of High Moisture Content: At higher moisture levels (20–30%), most samples demonstrate a downward trend in relaxation time. This is consistent with the known behaviour of water at microwave frequencies [4], where free water's relaxation dominates and reduces the overall dielectric relaxation time.

Logarithmic Distribution of Values: The relaxation time values span approximately one order of magnitude (from ~1.1E-13 to ~6.8E-13 s), justifying the use of a logarithmic scale in the figure for clearer differentiation. Anomalous Trends: Certain deviations from expected trends (e.g., peak shifts in S.N.3 and S.N.4) could be attributed to inhomogeneous moisture distribution, measurement artifacts, or unique mineralogical compositions that affect the dielectric behaviour. These findings emphasize that while general moisture-dielectric trends hold, the specific relaxation behaviour at 9.65 GHz is highly dependent on individual soil characteristics. These differences must be accounted for

in dielectric models and satellite-based soil moisture retrieval algorithms [2][4][5].

Moisture Content (%)	Mean (s)	Std Dev (s)	Min (s)	Max (s)
0	2.87×10 <sup>-13</sup>	1.66×10 <sup>-13</sup>	1.24×10 <sup>-13</sup>	6.88×10 <sup>-13</sup>
5	3.52×10 <sup>-13</sup>	1.04×10 <sup>-13</sup>	1.87×10 <sup>-13</sup>	5.25×10 <sup>-13</sup>
10	3.44×10 <sup>-13</sup>	8.16×10 <sup>-14</sup>	2.00×10 <sup>-13</sup>	4.45×10 <sup>-13</sup>
15	2.72×10 <sup>-13</sup>	5.03×10 <sup>-14</sup>	2.11×10 <sup>-13</sup>	3.59×10 <sup>-13</sup>
20	2.26×10 <sup>-13</sup>	5.10×10 <sup>-14</sup>	1.56×10 <sup>-13</sup>	2.94×10 <sup>-13</sup>
25	2.05×10 <sup>-13</sup>	6.31×10 <sup>-14</sup>	1.21×10 <sup>-13</sup>	2.90×10 <sup>-13</sup>
30	1.96×10 <sup>-13</sup>	6.93×10 <sup>-14</sup>	1.14×10 <sup>-13</sup>	2.89×10 <sup>-13</sup>

Table 2. Statistical Summary of Relaxation Time vs. Moisture Content at 9.65 GHz

Mean Relaxation Time: The average relaxation time increases from 0% to 5% MC, peaking at 5%, and then shows a consistent decline with increasing moisture. This confirms the non-linear dielectric response of soil with added water.



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Standard Deviation Trends: The highest variability among samples occurs at 0% MC ( $1.66 \times 10^{-13}$  s), indicating greater heterogeneity in dry conditions. Variability decreases at mid-range moisture (10-20%) and then increases slightly at 30%, possibly due to differences in free vs. bound water contributions.

Minimum and Maximum Ranges: The maximum relaxation time  $(6.88 \times 10^{-13} \text{ s})$  is observed in S.N.3 at 0% MC, while the minimum  $(1.14 \times 10^{-13} \text{ s})$  appears in S.N.9 at 30% MC. This wide range (~6×) reflects strong dependency on both soil type and water content.

Trend Implications: These statistics support the conclusion that small increases in moisture initially increase polarization delays (through bound water effects), but with more water, faster reorientation of dipoles (due to free water) reduces the relaxation time.

#### V. CONCLUSION

The experimental results demonstrate that soil dielectric relaxation time at 9.65 GHz is strongly dependent on moisture content and soil-specific characteristics. A peak in relaxation time at low moisture levels (5-10%) indicates the influence of bound water, which delays polarization processes. As moisture content increases beyond this point, the relaxation time decreases due to the greater mobility of free water molecules, leading to faster dielectric response.

Statistical analysis across all samples confirms this trend, with the highest variability observed under dry conditions. The relaxation time spans approximately one order of magnitude, from  $\sim 1.1 \times 10^{-13}$  s to  $\sim 6.9 \times 10^{-13}$  s, reflecting substantial diversity among the soil types studied. These insights underscore the importance of accounting for soil heterogeneity in electromagnetic models and highlight the potential of high-frequency dielectric measurements in soil moisture sensing applications.

Future work may involve correlating these results with soil physical properties such as texture, bulk density, and organic matter, and extending the study across broader frequency ranges for improved dielectric modelling..

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