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Measurement and modelling of soil dielectric properties as a function of soil class and moisture content

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Abstract
In this study, four textural classes soil (Clay, Clay Loam, Loam, and Loamy Sand) were used to investigate the dielectric properties of soils, using a vector network analyser with an open-ended coaxial probe kit at room temperature (25±2°C) in the 700 to 7000 MHz microwave frequency range. Four levels of soil moisture content (oven dry, 33% field capacity, 66% field capacity and 100% field capacity) were maintained to perform the experiment with three replication and three observation each. The result showed that, with increasing soil moisture, from oven dry conditions to 100 % field capacity, both the real (Dielectric Constant) and imaginary (Loss Factor) components of the dielectric properties increased; however, the responses were not linear. The dielectric properties of oven dry soils were very low compared with the soils with higher moisture content. Therefore, soil moisture was the major contributor to the dielectric behaviour of soil. The dielectric properties of sandy soil were much lower than the other soils; however, the dielectric loss factor of the Dookie clay soil was higher compare with the other soils. Models were developed to explain the dielectric properties of soils as a function of frequency and moisture content. The goodness of fit (r^2) for these models varies between 0.952 for the Dookie Sandy Soil to 0.997 for the Dookie Loam Soil, suggesting that these models were adequate to describe the dielectric properties of these soils over the range of frequencies and moisture contents assessed in this study. Another model was developed to estimate the expected penetration depth of electromagnetic waves in these soils, based on the model of dielectric properties. It was clear that penetration decreases with both frequency and moisture content. Low frequencies penetrate further into the soils than higher frequencies. Similarly, dry soils allow further penetration than moist soils.

1. Introduction
Microwave energy has been applied to: food processing [1-5]; textiles and leather processing [6]; medical application [7]; plasma [8] and solvent-free chemistry [9]; drying of wood [10, 11], paper and cardboard [12]; pest control [13]; enhancing seed germination [14, 15]; and removal of hazardous waste from contaminated soil [16-22]. Furthermore, current studies also reveal that, microwave soil treatment can kill the soil weed seed bank, which results in: the reduction of weed emergence [23-27]; increased carbon and nitrogen mineralization [28]; and increased plant growth [29]. Thus, microwave heating has extended acceptance and is gaining popularity due to its major advantages of: short start up time; precise control; and volumetric heating [6].
The application of microwave radiation into the soil induces rotation of the dipoles of polar or semi-polar molecules, like water and hydrocarbon-contaminants, due to the oscillating electromagnetic field. This results in the generation of heat by intermolecular friction [8]. However, to develop a proper understanding of microwave soil treatment and to explain soil heating, the dielectric properties of soil are required.

Microwave heating depends on the ability of a material to convert the adsorbed microwave energy into heat. This is associated with the dielectric properties of the material. The dielectric properties of materials are generally illustrated by relative complex permittivity, $\varepsilon = \varepsilon' - j\varepsilon''$, where the real part ($\varepsilon'$) of the dielectric property, known as the dielectric constant, implies the material's ability to store energy and the imaginary part (ε'') of the dielectric property, known as the dielectric loss, indicates the ability to convert the energy to heat, and j is $\sqrt{-1}$ [30-32]. The dielectric loss factor is linked to the absorbance of microwave energy by the material. Generally, the dielectric properties of a material, like soil, are controlled by the operating frequency, temperature, moisture content, density and composition of the material [33].

Soil is a complex solution of mineral particles, water, ions, gasses (mostly air), and micro and macro organisms. The size of the mineral particles provides one tool for soil classification, with soils being classified according to the percentage of sand, silt and clay present in the mineral portion of the solution.

There have been several studies of the dielectric properties of soil. Some of these are particularly focused on interpreting remotely sensed data [34, 35], especially passive microwave emission and radar response, while others have soil heating as their focus [36]; however, the industrial, scientific and medical (ISM) microwave frequencies (896/915/922 MHz, 2450 MHz and 5800 MHz) seem to have been neglected in most of these studies. Thus, the dielectric behaviour of soil, at these ISM frequencies, is becoming important.

Based on other studies [37], moisture content will probably have the greatest effect on dielectric properties. For developing fast moisture measurement with microwave sensors, the dielectric properties have great importance due to their direct relationship with moisture content [38-40]. Other factors that will affect the dielectric properties include: soil class (i.e. the proportions of sand, silt and clay); the organic matter content; the level of soil compaction (i.e. bulk density of the soil solution); and finally, the temperature of the soil. Because the dielectric behaviour of most materials varies profoundly with frequency, there is an imperative to study the dielectric properties of soils across the main ISM microwave frequencies.

Soil temperatures, for disinfection and seed deactivation applications, are normally in the range from 60 °C to 120 °C; however, Falciglia and Vagliasindi [41] demonstrated that microwave soil heating can achieve temperatures well in in excess of 200°C during their study of microwave treatment of hydrocarbon-polluted soil.

Organic matter will affect the water holding capacity of the soil and these organic materials have a different dielectric behaviour to soil minerals; therefore, some understanding of the effect of soil organic matter should be included in a comprehensive study of the dielectric properties of soil. According to Certini [42], the consumption of soil organic matter during forest fires begins at about 200 °C; therefore, the effect of organic matter concentration on soil heating during microwave treatment is important. Salinity will also affect the dielectric behaviour of soil, because it affects the absorption of electromagnetic energy due to ion conduction and therefore affects the loss factor of moist soil [43], especially at lower frequencies.

Hence, the key parameters of interest in the study of the dielectric properties of soil, in order of their importance, are: frequency (700 MHz to 7000 MHz); soil type (texture); soil moisture content; soil temperature; soil organic matter content; and soil salinity. It is difficult to set up a single experiment to cover all these factors; however, it is suggested that a multi-factor analysis of a subset of these soil properties be initiated, to examine the impact of some of these parameters on the complex dielectric properties of soils.

The common methods for dielectric property measurements include: cavity resonator perturbation; free space analyses; lumped circuit; transmission line; and coaxial probe techniques. The cavity resonator approach is suitable for frequencies between 50-100 MHz and applicable for material with low loss. The free space method is applicable for large, flat, thin and parallel faced samples and is suitable for high frequencies (3 GHz to 100 GHz) as well as being used for measuring materials at high temperature, since this method is non-destructive and noncontact. The lumped circuit method is suitable for low frequencies (below 100 MHz) and not applicable for low loss materials. The transmission line method is mostly applicable for liquid and solid materials in the frequency range of 30 MHz to 100 GHz, but it is not suitable for gases due to their low permittivity [44-46]. The open ended coaxial probe, with a vector network analyser, has been used commonly for dielectric property measurements of food grains, such as chickpea, green pea, lentil, soybean, mung bean, black eye pea and Macadamia nut Kernel with a frequency range of 10-1800 MHz [47-50]. This method is also suitable for measurement of soil dielectric properties [51-53].

On the basis of the soil properties, the most commonly used dielectric mixing model is proposed by Peplinski et al. [54]. This semi-empirical model was proposed by considering soil texture, moisture content, bulk density and temperature in a wide range of frequencies (0.3-1.3 GHz). Peplinski et al. [54] modified another dielectric mixing model developed by Dobson et al. [55].

To determine the dielectric properties of soil and its heating pattern, a wide range of soil types, moisture contents and frequencies need to be addressed. Therefore, this study was conducted to: (i) determine the dielectric properties of soil over a wide range of frequency (700-7000 MHz); and (ii) to develop a multi-factor mixing model for predicting the dielectric properties of soil using various mathematical models, based on the dipole studies of Debye and various mixing models.

2. Materials and methods

2.1 Soil sample collection

To investigate the dielectric properties of different soil, four types of soil were used in this study (Table 1). Clay loam soil was collected from South Australia (34° 42’ S, 138° 35’ E) and the other three soil types were collected from Dookie College. These were: Loam soil from the Macpoyels wheat paddock (36°23′S, 145°42′ E), Clay soil from the H12 paddock (36°24′ S, 145°43′ E) and sandy soil from a pasture paddock (36°25′ S, 145°43′ E). After collection, the soil samples were air-dried for 7 days. The aggregates were broken down prior to being sieved through a 2 mm soil sieve to remove unwanted materials (viz. dry roots, grasses, stones and gravel) and to ensure uniform soil aggregates for better evaluation of the dielectric properties. Then the separate soils was thoroughly mixed by following the quartering method to ensure homogenous condition.

2.2 Analysis of soil properties

Different physicochemical properties of experimental soils were determined by drying at 40°C for 24 hr prior to sending them to the Nutrient Advantage laboratory (NATA Accredited Laboratory # 11958, Australia) for complete analyses. The results of these analyses are highlighted in Table 1.

Table 1. Physicochemical properties of experimental soils

Soil properties	Analytical method	Units	Soil types			
			Dookie Clay	South Australian	Dookie Loam	Dookie Sand
Texture			Clay	Clay loam	Loam	Loamy Sand
Sand	Hydrometer and sieve analysis	%	47.0	48.7	56.2	83.8
Silt			8.6	17.1	23.8	8.7
Clay			44.4	34.2	20.0	7.5
Field capacity	Gravimetric	%	72	64	66	16.8
Organic carbon	Walkley & Black	%	0.47	0.86	1.40	0.70
Organic matter	Walkley & Black	%	0.81	1.48	2.41	1.2

Electrical conductivity	Saturated extract	dS/m	2.1	1.6	0.6	0.6
pH	1:5 $CaCl_2$	N/A	7.2	7.8	5.0	5.1
Cation exchange capacity (CEC)	$BaCl_2$ exchange	cmol(+)/kg	32.9	28.1	7.9	2.95
Nitrate nitrogen	Kjeldahl	mg/kg	37.0	38.0	37.0	7.4
Ammonium nitrogen	Kjeldahl	mg/kg	3.6	1.3	2.0	3.6
Available Potassium	Atomic emission	mg/kg	310	440	340	130
Sulphur	0.25M KCl at 40^0C	mg/kg	9.9	9.5	7.1	3.9
Phosphorus	Colwell	mg/kg	< 5.0	17	180	23
Calcium	Ammonium acetate	cmol(+)/kg	16	22	5.7	2.0
Magnesium	Ammonium acetate	cmol(+)/kg	14	4.2	1.3	0.57
Sodium	Ammonium acetate	cmol(+)/kg	1.9	0.69	0.03	0.08
Aluminium	Ammonium acetate	cmol(+)/kg	< 0.10	< 0.10	< 0.10	< 0.10
Sodium % of cations (ESP)	N/A	%	5.9	2.4	0.41	2.6
Calcium/magnesium ratio	N/A	N/A	1.1	5.2	4.4	3.5
Chloride	Soluble chloride	mg/kg	110	12	14	< 10
Copper	DTPA	mg/kg	1.4	1.6	4.3	0.72
Zinc	DTPA	mg/kg	9.2	45	2.7	3.8
Manganese	DTPA	mg/kg	18	11	49	24
Iron	DTPA	mg/kg	17	13	120	67
Boron	DTPA	mg/kg	2.5	2.8	0.64	0.20

2.3 Maintaining of soil moisture

Four levels of soil moisture (oven dry, 33% field capacity, 66% field capacity, and 100% field capacity) were maintained. To determine the soil field capacity, 25 g of oven dry soil was placed in a funnel with filter paper (Whatman No 1). Then, 25 ml of distilled water was added to the soil. The funnel was placed in a measuring cylinder and kept for 24 hours to allow the gravitational water to drained out. Then the field capacity of that soil, on volume basis, was calculated using the following equation

$$FC = \frac{(V_i - V_f)}{V_i} \times 100 \qquad (1)$$

where, V_i is the initial water added to the soil and V_f is the water collected in the measuring cylinder, after 24 hours.

For oven dry soil, the soil samples were dried at 105°C for 24 hours. To achieve the other moisture contents, the required amount of deionised water was added into the soil and thoroughly mixed. After getting the desired moisture for further dielectric measurement, all the soil samples were stored at 4°C in plastic zip lock bags to prevent soil moisture loss.

2.4 Experimental design

Table 2 illustrates the experimental design for the simultaneous study of all the factors, to determine the dielectric properties of soils.

Table 2. Experimental design

Soil Type	Moisture content	Density	Temperature	No. of observation
Clay	Oven dry	Compact	Room temperature (25±2°C)	9
	33% Field capacity			9
	66% Field capacity			9
	100% Field			9
Clay Loam	Oven dry			9
	33% Field capacity			9
	66% Field capacity			9
	100% Field			9
Loam	Oven dry			9
	33% Field capacity			9
	66% Field capacity			9
	100% Field			9
Loamy Sand	Oven dry			9
	33% Field capacity			9
	66% Field capacity			9
	100% Field			9

2.5 Dielectric properties measurement

To measure the complex permittivity (real part, ε', and imaginary part, ε'') a vector network analyser (E8364B PNA network analyser) with an open-ended coaxial probe kit (Agilent 85070E Dielectric Probe kit 200 MHz to 50 GHz, Performance Probe 85070-60010) was used (Figure 1). The network analyser had the potential frequency range of 10 MHz to 50 GHz to measure the dielectric properties of materials. The main part of the analyser was connected to an external computer with corresponding Agilent analysis software with an embedded algorithm to calculate ε' and ε''.

Before starting the measurement, the network analyser was calibrated using three standards (i.e. on open air, with a short block and in water). To get the electrical short, a metal sheet (e.g. Al or Cu) was placed under the probe. After calibration, the dielectric properties of a reference sample, for example water at room temperature or Teflon or ceramic were measured to confirm the calibration. After getting good values for the reference samples, the dielectric properties of the experimental samples were measured.

The dielectric properties of different soil samples were measured over the frequencies range of 700 MHz to 7000 MHz. This frequency range covers the most useable microwave frequencies for industries, scientific and medical applications. The samples were measured with three replications, with three observation each for each replication and the mean values were considered for further statistical analysis. The measurements were carried out in a 4.5 cm long Teflon container with a diameter of 1 cm. To ensure that the probe could enter the vial and the soil surface was wide enough to assume no influence of the container on the measurements. The whole experiment was carried out at room temperature (25±2°C).

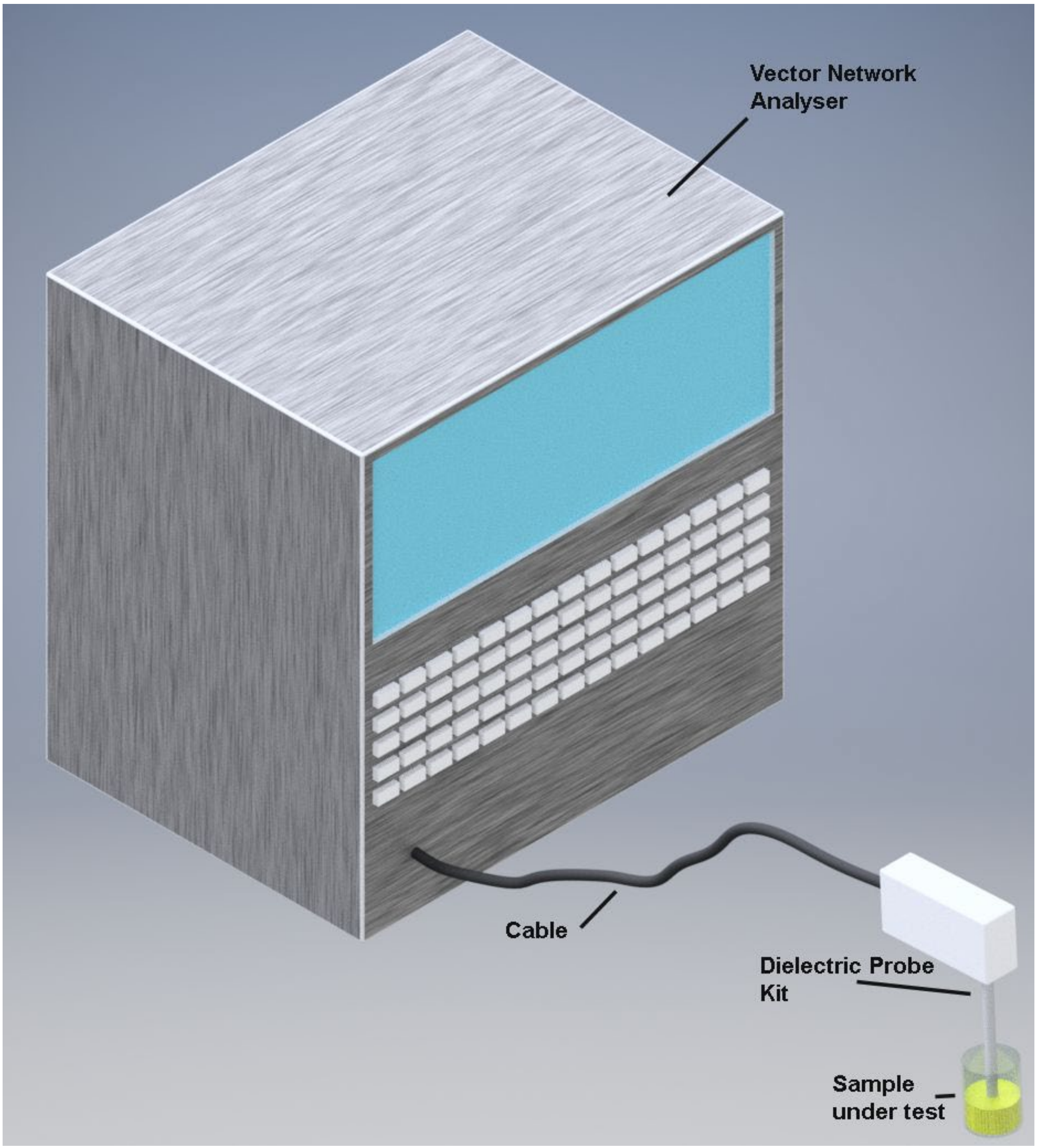

Figure 1. Schematic of vector network analyser (E8364B PNA) with open ended coaxial probe kit and sample under test

2.6 Penetration depth and wavelength

Dielectric constant and dielectric loss are two key factors of dielectric properties of a material, which can determine the heating pattern of a particular geometry during microwave treatment. Other important parameters, which can be derived from the dielectric measurements, are the penetration depth and wavelength of the electromagnetic waves in the soil.

The penetration depth (d_p) is the distance at which the electromagnetic power density decline to a value of $1/e$ (e = 2.718) or 36.8% from its initial value at the surface and is stated as [30, 56]

$$dp = \frac{c}{\sqrt{2}\pi f\left[\sqrt{(\kappa\prime)^2+(\kappa'')^2} - \kappa'\right]^{1/2}} \quad (2)$$

where the dielectric properties are described by: $\kappa = \kappa' + j\,\kappa''$
and the wavelength (λ_m) can be calculated as [56]

$$\lambda_m = \frac{c\sqrt{2}}{f\left[\sqrt{(\kappa\prime)^2+(\kappa'')^2} + \kappa'\right]^{1/2}} \quad (3)$$

where c is the velocity of light in space (3×10^8 ms^{-1}) and f is the frequency (Hz).

2.7 Cole-Cole Analysis

For further analysis of the measured complex permittivity, a curve-fitting technique is usually used based one of the following models: Debye model; Cole–Cole model; Davidson–Cole model; Havriliak–Negami model; and KWW model. Typically, the curve-fitting study is used to inspect the dielectric relaxation time and the Debye relaxation model has been used widely for these studies. The simplest form of the Debye equation [57] to describe the complex dielectric permittivity of a pure polar material is:

$$\varepsilon = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1+j\omega\tau} - j\frac{\sigma}{\omega\varepsilon_o} \quad (4)$$

where, ε_o is the permittivity of free space, ε_s is the static permittivity; ε_∞ is the permittivity at high frequency; ω is the applied angular frequency ($2\pi f$), σ is a conductivity term to account for free ion movement, and τ is the relaxation time.
Since all the materials are not purely polar, there are several relaxation times, which result in a modification to the Debye equation [58].

$$\varepsilon = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{(1+j\omega\tau)^{1-\alpha}} - j\frac{\sigma}{\omega\varepsilon_o} \quad (5)$$

where a is a power factor that accounts for a distribution of relaxation times associated with many real materials. Cole and Cole [58] showed that this can be resolved into the real and imaginary parts of the dielectric properties:

$$\varepsilon' = \varepsilon_\infty + \frac{(\varepsilon_s - \varepsilon_\infty)\left[1+(\omega\tau)^{1-\alpha} sin\left(\frac{\alpha\pi}{2}\right)\right]}{\left[1+2(\omega\tau)^{1-\alpha} sin\left(\frac{\alpha\pi}{2}\right)+(\omega\tau)^{2(1-\alpha)}\right]} \quad (6)$$

and

$$\varepsilon'' = \frac{(\varepsilon_s - \varepsilon_\infty)(\omega\tau)^{1-\alpha} cos\left(\frac{\alpha\pi}{2}\right)}{\left[1+2(\omega\tau)^{1-\alpha} sin\left(\frac{\alpha\pi}{2}\right)+(\omega\tau)^{2(1-\alpha)}\right]} + \frac{\sigma}{\omega\varepsilon_o} \quad (7)$$

It is also evident that the dielectric properties of most natural materials, in the microwave frequency range, are linked to the moisture content of the material. Therefore:

$$\varepsilon(m) = \left[\varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{(1+j\omega\tau)^{1-\alpha}} - j\frac{\sigma}{\omega\varepsilon_o}\right] \cdot F(m) \quad (8)$$

where *F(m)* is some function of moisture content, which is to be determined from the data.

2.8 Statistical and other software analysis

MatLab software (MathWorks, Inc., USA) was used to analyse and display the dielectric data. Equations (6), (7) and (8) were used in MatLab's Curve Fitting Tool as the basis for developing a semi-empirical model for the dielectric properties of the four soils.

3. Results and discussion

Figure 2 shows the dielectric properties of the four soils under study as a function of frequency and moisture content. Table 3 also shows a subset of the dielectric data as a function of soil type, frequency and soil moisture status, obtained during this study. Both the real (Dielectric Constant) and imaginary (Loss Factor) components of the dielectric properties increase as moisture increases from oven dry conditions to 100 % Field Capacity, through the intermediary moisture levels (i.e. Oven dry, 33 % Field Capacity, 66 % Field Capacity and Field Capacity).

The dielectric properties of dry soil are very low; therefore, soil moisture is the major contributor to the dielectric behaviour of soil. This increase in dielectric value with moisture was also observed by Wang [59] and Dobson, Ulaby [60].

Because sand has a much lower surface area per unit volume than the other mineral components of soil, the moisture holding capacity, and therefore the field capacity of soils is inversely related to their sand content. Therefore, the field capacity of the Dookie Sand Soil is much lower than that of the other three soils, because of its high sand content (83.8 % - Table 1), compared with the other soils (47.0 % to 56.2 % - Table 1). This is evident in the dielectric properties of this soil, which are much lower than those of the other soils (Figure 2).

The dielectric loss factor of the Dookie Clay soil rises considerably as frequency drops. This is probably due to the ionic conductivity of this soil, associated with its higher electrical conductivity of 2.1 dS m^{-1} (Table 1), compared with the other soils. Ionic conductivity, according to equation (7), is inversely proportional to angular frequency (ω), which implies that it is higher at low frequencies and lower at higher frequencies and is consistent with these data. The soil from South Australia, has the next highest soil conductivity (1.6 dS m^{-1}) and exhibit a moderate rise in the dielectric loss factor at lower frequencies, especially at higher moisture content.

The moisture in soil, which is at field capacity or below, is predominantly bound water because the free water component will have mostly drained away under the influence of gravity. Boyarskii et. al. [35] studied the dielectric behaviour of bound water in soil and derived an empirical expression to approximate the Debye relaxation time (τ) for bound water. Their equation for the relaxation time of bound water at 27 °C is:

$$\tau_{bw} = \frac{1}{-4.9648\times10^{24}\cdot h^2 - 3.0867\times10^{11}\cdot ln(h) - \frac{7.5092\times10^3}{h} + 3.9121\times10^{19}\cdot h - 5.2036\times10^{12}} \quad (9)$$

where h is the thickness of the bound water film (cm). They observe that as the thickness of the water film approaches the thickness of 10 water molecules (Note: a water molecule has a diameter of approximately 2.8 x 10^{-8} cm), τ_{bw} approaches the relaxation period of free water. Based on equation (9), and assuming a water film thickness of approximately 10 water molecules at field capacity, it was assumed that τ_{bw} is 7.5 picoseconds. This value of τ_{bw} was used, in conjunction with equations (6), (7), and (8), to develop a model for the dielectric properties of these soils, between 700 MHz and 7,000 MHz.

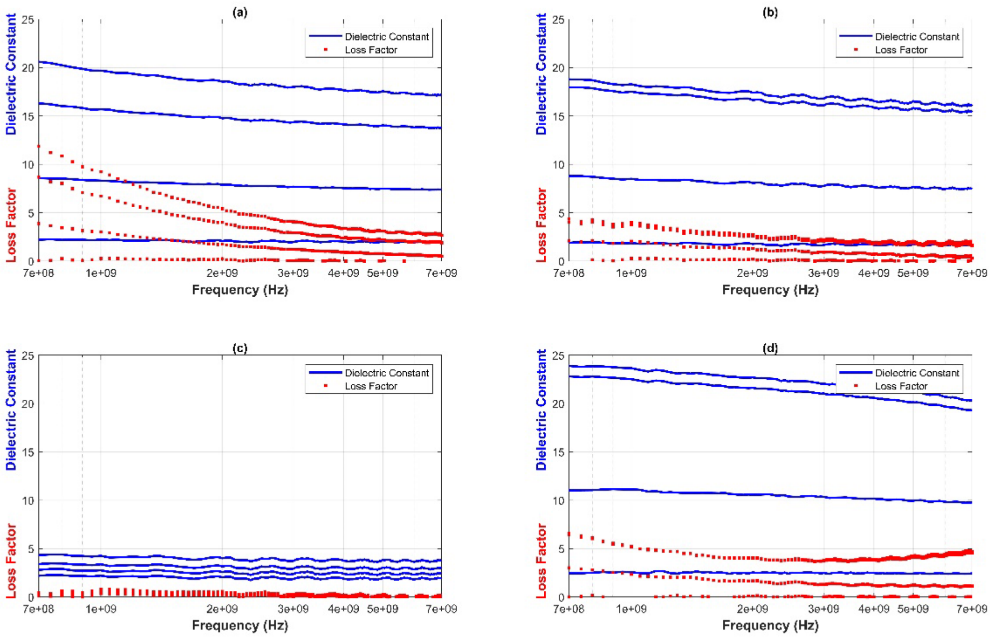

Figure 2. Measured Dielectric properties of the four soils: (a) Dookie Clay Soil, (b) Dookie Clay Loam Soil, (c) Dookie Sand Soil, and (d) South Australian Soil, as a function of frequency and moisture content (Note: both the dielectric constant and the loss increase with increasing moisture content)

Table 3. Subset of dielectric data as a function of soil type, frequency and soil moisture status

Soil Type	Frequency (GHz)	Moisture Status							
		Oven Dry Soil		33 % Field Capacity		66 % Field Capacity		100 % Field Capacity	
		ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''
Dookie Clay	0.7	2.205	0.060	8.578	3.872	16.309	8.678	20.603	11.860
	0.9	2.154	0.141	8.344	3.067	15.641	6.880	19.689	9.435
	1	2.218	0.261	8.314	3.006	15.692	6.717	19.687	9.230
	2	2.070	0.247	7.873	1.744	14.762	4.005	18.548	5.411
	2.45	1.992	0.145	7.772	1.438	14.523	3.408	18.205	4.672
	3	1.971	0.039	7.685	1.205	14.359	2.926	17.990	4.059
	4	1.996	0.007	7.546	0.918	14.119	2.403	17.643	3.366
	5	2.042	0.021	7.489	0.779	14.048	2.209	17.575	3.109
	5.8	2.018	0.117	7.432	0.629	13.890	1.987	17.324	2.827
	6	1.947	0.131	7.396	0.613	13.813	2.012	17.222	2.868
	7	2.005	0.196	7.384	0.507	13.723	1.882	17.076	2.652
Dookie Clay Loam	0.7	1.900	0.028	8.781	2.091	17.959	4.036	18.787	4.350
	0.9	1.845	0.150	8.435	1.878	17.411	3.556	18.194	3.869
	1	1.869	0.279	8.504	2.052	17.517	3.740	18.270	3.997
	2	1.772	0.200	8.071	1.300	16.639	2.598	17.404	2.748
	2.45	1.683	0.149	7.899	1.110	16.354	2.316	17.087	2.469

	3	1.668	0.056	7.759	0.919	16.083	2.076	16.801	2.227
	4	1.669	0.022	7.644	0.719	15.853	1.825	16.532	1.948
	5	1.738	0.048	7.675	0.677	15.829	1.905	16.537	2.052
	5.8	1.692	0.085	7.530	0.451	15.591	1.631	16.272	1.748
	6	1.632	0.082	7.447	0.473	15.438	1.713	16.107	1.854
	7	1.686	0.158	7.451	0.297	15.364	1.560	15.999	1.668
Dookie Sandy Soil	0.7	2.199	0.104	2.808	0.104	3.402	0.209	4.319	0.412
	0.9	2.125	0.141	2.728	0.332	3.289	0.416	4.179	0.594
	1	2.209	0.344	2.755	0.508	3.379	0.641	4.251	0.821
	2	2.036	0.259	2.577	0.396	3.162	0.449	4.006	0.576
	2.45	1.891	0.197	2.440	0.297	3.011	0.343	3.838	0.444
	3	1.857	0.067	2.373	0.147	2.925	0.185	3.731	0.275
	4	1.887	0.021	2.393	0.076	2.954	0.097	3.744	0.169
	5	1.979	0.082	2.481	0.156	3.045	0.173	3.845	0.238
	5.8	1.935	0.129	2.433	0.105	2.986	0.100	3.773	0.053
	6	1.829	0.132	2.308	0.109	2.859	0.103	3.638	0.051
	7	1.922	0.235	2.409	0.234	2.960	0.240	3.736	0.207
South Australian Clay Loam	0.7	2.460	0.001	11.029	3.010	22.805	6.601	23.884	6.470
	0.9	2.534	0.012	11.146	2.541	22.669	5.546	23.759	5.473
	1	2.559	0.031	11.114	2.336	22.512	5.219	23.648	5.193
	2	2.539	0.092	10.571	1.664	21.622	3.978	22.700	4.064
	2.45	2.404	0.044	10.388	1.499	21.246	3.807	22.265	3.870
	3	2.493	0.009	10.351	1.301	21.034	3.735	22.047	3.793
	4	2.479	0.001	10.182	1.192	20.573	3.791	21.623	3.880
	5	2.425	0.052	9.945	1.243	20.121	4.092	21.173	4.259
	5.8	2.477	0.018	9.924	1.136	19.842	4.221	20.890	4.356
	6	2.407	0.054	9.845	1.081	19.673	4.260	20.675	4.408
	7	2.434	0.039	9.783	1.129	19.283	4.535	20.292	4.677

The best moisture variation function (F(m)) that would fit the measured data was:

$$F(m) = erf[-c(m - m_o)] \tag{10}$$

where erf(x) is the Gaussian error function of the parameter x, c is a parameter associated with the specific soil, m is the fractional moisture content of the soil, and m_o is a threshold moisture content associated with each specific soil. Therefore, in this study, the dielectric constant and loss factors of these soils are adequately described by:

$$\varepsilon' = \varepsilon_\infty + \frac{(\varepsilon_S - \varepsilon_\infty)\left[1+(\omega\tau)^{1-\alpha} sin\left(\frac{\alpha\pi}{2}\right)\right]}{\left[1+2(\omega\tau)^{1-\alpha} sin\left(\frac{\alpha\pi}{2}\right)+(\omega\tau)^{2(1-\alpha)}\right]} \cdot erf[-c(m - m_o)] \tag{11}$$

and

$$\varepsilon" = \left\{\frac{(\varepsilon_S - \varepsilon_\infty)(\omega\tau)^{1-\alpha} cos\left(\frac{\alpha\pi}{2}\right)}{\left[1+2(\omega\tau)^{1-\alpha} sin\left(\frac{\alpha\pi}{2}\right)+(\omega\tau)^{2(1-\alpha)}\right]} + \frac{\sigma}{\omega\varepsilon_o}\right\} \cdot erf[-c(m - m_o)] \tag{12}$$

For example, Figure 3 shows surface plots for the dielectric constant and loss factors for the Dookie Loam Soil and the South Australian Clay Loam soil, as a function of frequency and moisture content. *Table 3* provides a complete list of parameters for the model equations for all four soils. The goodness of fit (r^2) for these models varies between 0.952 for the Dookie

Sand Soil to 0.997 for the Dookie Loam Soil, suggesting that these models are adequate to describe the dielectric properties of these soils over the range of frequencies and moisture contents assessed during this study.

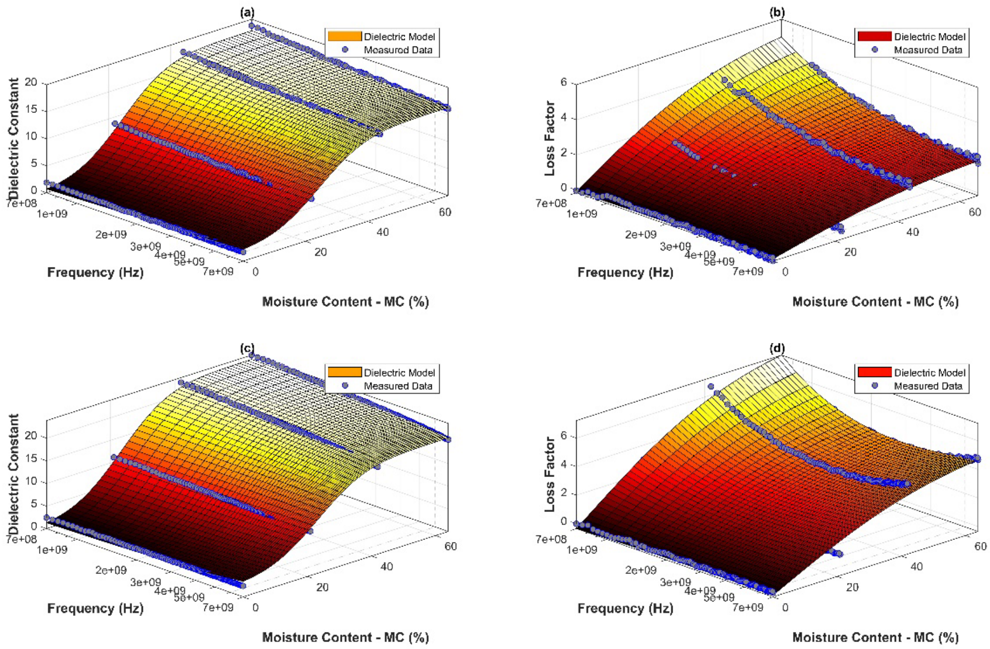

Figure 3. Comparisons between the predicted and measured dielectric properties for (a - b) Dookie Loam Soil and (c - d) South Australian Clay Loam Soil, as a function of frequency and moisture content.

Table 4. List of parameters used to model the dielectric properties of all four soils tested during this study

Parameter	Soil Type			
	Dookie Clay	**Dookie Loam**	**Dookie Sand**	**South Australian Clay Loam**
ε_∞	8.886	9.133	3.181	11.890
ε_S	20.570	21.920	4.775	23.260
α	0.210	0.782	0.000	0.232
σ	0.472	0.154	0.114	0.264
c	2.512	6.110	7.622	6.129
m_o	0.277	0.245	0.117	0.234
r^2	0.996	0.997	0.952	0.996

A more linear response to moisture content may have been expected during this study. During the measurement process, it was essential to apply some pressure onto the dielectric probe to make good contact between the end of the probe and the soil. Moisture acts as a lubricant within soil, sliding the particles together and increasing the bulk density of moist soil [61], which will have an impact on the dielectric properties. Optimal soil compaction occurs below field capacity; therefore, the measurements at 66 % of field capacity may have been higher than they should have been, due to the influence of some soil compaction of the moist soil under test.
Based on the models for dielectric properties of the different soils, as a function of both frequency and moisture content, it is possible to model the expected penetration depth of

electromagnetic waves in these soils (Figure 4). Because penetration depth is a function of frequency and dielectric properties, and the dielectric properties are a function of soil moisture content, it is clear that penetration decreases with both frequency and moisture content. Low frequencies penetrate further into the soils than higher frequencies. Similarly, dry soils allow further penetration than moist soils, because their dielectric properties and therefore the amount of electromagnetic field attenuation are lower.

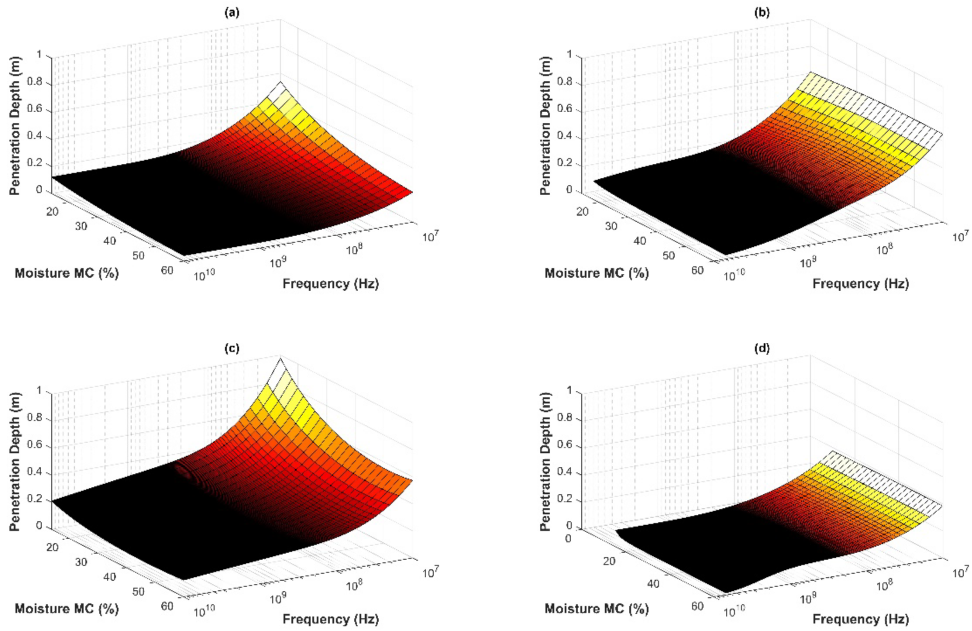

Figure 4. Comparisons between the electromagnetic penetration depths for (a) Dookie Clay Soil, (b) Dookie Loam Soil, (c) Dookie Sandy Soil and (d) South Australian Clay Loam Soil, as a function of frequency and moisture content.

It is also evident from Figure 4 that soil texture has some influence over electromagnetic penetration into these soils, because Dookie Sand Soil (Figure *4* c) has a much greater electromagnetic penetration at 10^7 Hz and 14 % moisture than for example the South Australian Clay/Loam Soil at the same frequency and moisture content.

4. Conclusions

The dielectric properties of four soils have been measured over a decade of frequencies, which cover three important ISM frequencies. The data clearly shows the influence of soil particle distribution (i.e. soil classification), soil electrical conductivity, and soil moisture. An adequate mathematical model has been developed for the measured data. This model can be used in future studies of these soils.

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