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Free-space measurement of dielectric properties of cereal grain and oilseed at microwave frequencies

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Abstract
Principles of dielectric property measurement by microwave free-space transmission measurements are presented, and the important sources of errors in such measurements are discussed. A system, including a vector network analyser, horn/lens antennas, holder for grain and oilseed samples and a radiation absorbing enclosure that was used for such measurements is described, and the techniques and procedures followed to obtain reliable permittivity data for wheat, shelled corn (maize) and soybeans are outlined. Data illustrating linear relationships between microwave attenuation and phase shift per unit sample thickness, each divided by the bulk density of the granular materials, and frequency and moisture content are presented graphically. The linear dependence of calculated permittivity components, dielectric constant and loss factor, on bulk density is also shown, and permittivity components for wheat, corn and soybeans are listed for reference at frequencies from 5 to 17 GHz at different densities and moisture levels at about 23 °C. Permittivity values are also listed for the same three commodities, adjusted to a medium density value through use of the Landau and Lifshitz, Looyenga dielectric mixture equation, for the total range of moisture contents at 10 GHz and at the same temperature.

Keywords: dielectric properties, permittivity, cereal grain, oilseed, free-space measurement, microwave, attenuation, phase shift, bulk density, moisture content, temperature

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Measurement of the dielectric properties of moist granular materials such as cereal grain and oilseed is essential for understanding their electrical behaviour [1] and the development of indirect nondestructive methods for determining their physical characteristics including moisture content and bulk density [2–6]. For better modelling of these materials and effective use of the indirect methods, the dielectric properties have to be measured accurately. The dielectric properties are, by definition, a measure of the polarizability of a material when subjected to an electric field. For lossy materials, the dielectric properties are represented by the relative complex permittivity, $\varepsilon = \varepsilon' - j\varepsilon''$, where ε', the dielectric constant, describes the ability of the material to store energy, and ε'', the dielectric loss factor, reflects the ability of a material to dissipate the electric-field energy.

At radio frequencies and microwave frequencies, dielectric properties of moist granular materials depend on frequency, moisture content, bulk density and temperature [7, 8]. In fact, at these frequencies, water is the most influential factor because of its polar nature. Effects of bulk density and temperature are both water-related effects [4]. A change in bulk density translates into a change in the amount of water interacting with the electric field, and a change in temperature affects the energetic status of the water molecules and hence influences their aptitude to follow the alternating electric field. Because water inside the grain is bound to the inner structure, the frequency dependence of the dielectric properties of moist granular materials is not as spectacular as that of liquid water [9–11]. Dielectric properties of liquid water are well described by the Debye model [10] and show dipolar relaxation at about 17.9 GHz at 22 °C [11]. However, those of bound water lie somewhere between those of ice and those of liquid water depending on how tightly the water is bound. Therefore, dipolar relaxations of bound water are expected to cover a broad frequency range [8].

Dielectric data for moist granular materials are limited in the literature [1, 12, 13], particularly those measured above 2.45 GHz. Very often the data available are given at a single frequency for a limited range of bulk densities and moisture contents. Data that cover a broad frequency range were often taken with different measurement techniques with different degrees of accuracy, given the nature of granular materials. In this study, dielectric properties of three major commodities presenting significant structural and compositional differences, wheat, corn and soybeans, were measured with the same measurement technique over a wide microwave frequency range and at room temperature. The moisture levels are those of interest to the grain industry.

2. Free-space measurements

At microwave frequencies, different measurement techniques can be used. These include transmission line techniques (waveguide, coaxial and free-space), impedance and cavity methods [14]. Amongst these techniques, free-space measurements [15] have the advantages of allowing reflection and transmission measurements without contact with the sample and little, if any, sample preparation is required. For nonmagnetic materials such as cereal grain and oilseed, measurement of either the reflection coefficient or the transmission coefficient is sufficient to determine the relative complex permittivity, ε. Reflection measurements require definition of a reference plane and are subject to surface characteristics. In contrast, transmission measurements do not require the sample to be at a particular position and the information collected is relative to the whole sample volume, thus providing dielectric properties more representative of the sample material. For these reasons, a free-space transmission technique was selected.

For each material, a layer of given thickness was placed between two antennas facing each other. In such a configuration, the material represents, to the incident electromagnetic wave, a random dense medium. Assuming a plane wave is propagating through such material, it is rather difficult to express the electric field inside the material and thus to extract the complex permittivity from such an electric field. Therefore, the complex permittivity is determined from measurement of the scattering transmission coefficient S_{21}, which can be measured with a vector network analyser (VNA). Because of the material nature, errors in permittivity determination are often underestimated if only instrument-related errors are taken into account. Other sources of errors have much greater effect on the permittivity accuracy but are more difficult to calculate rigorously. These sources of error include violation of the far-field condition, multiple reflections within the sample and between the sample and the antennas, surface and volume scattering, interference with surroundings, post-calibration mismatches and multiple-path transmission. Rather than attempting to quantify the contribution of each of these errors in the overall permittivity error, our approach is to minimize their respective effects by taking appropriate precautions, and the use of some of the VNA features.

For this purpose, a pair of horn/lens antennas providing a plane wave at a short distance from the transmitting antenna was used, the sample thickness was selected to ensure at least 10 dB one-way attenuation, the sample was placed in a tunnel-shaped enclosure made of radiation-absorbing material covering the entire space between the antennas and the time-domain gating feature of the VNA was used. Also, to cover as much as possible of the frequency range between 2 and 18 GHz and to optimize the use of the VNA dynamic range for the different moisture and bulk density ranges, measurements were performed with samples of different thickness for each material. Variations of the measured parameters, attenuation and phase shift, as a function of varying physical properties, are presented. Similarly, variations of the dielectric constant, ε', and dielectric loss factor, ε'', with bulk density and moisture content are shown. Bulk density and moisture calibration equations, useful in developing indirect methods, are given first in terms of attenuation and phase shift and then in terms of the dielectric properties. Finally, data normalized to a medium density for each sample and moisture content, with the Landau and Lifshitz, Looyenga mixture equation, are tabulated.

3. Materials and methods

3.1. Sample preparation and physical characteristics

Samples of wheat, *Triticum aestivum* L., yellow-dent hybrid field corn, *Zea mays* L., and soybeans, *Glycine max* (L.) Merrill, of different moisture contents were prepared by spraying distilled water on the grain and seed samples to bring them to the desired moisture level. Each sample consisted of about 7 kg of material. Starting from the lowest moisture level, the moisture content was increased gradually in increments of about 1% until the higher end of the desired moisture range was reached. After adding the proper amount of water, the sample was mixed to distribute the water more evenly throughout the sample. Then, the samples were placed in sealed bags and stored for at least 72 h at 4 °C to equilibrate. Samples were occasionally mixed within the sealed bags to aid uniform moisture distribution. Before the microwave measurements, the samples were removed from cold storage and allowed to equilibrate to room temperature for 24 h.

3.2. Measurement set-up

The measurement set-up shown in figure 1 consists of a Hewlett–Packard[1] 8510C VNA, a computer, two high quality

[1] Mention of company or trade names is for purpose of description only and does not imply endorsement by the US Department of Agriculture.

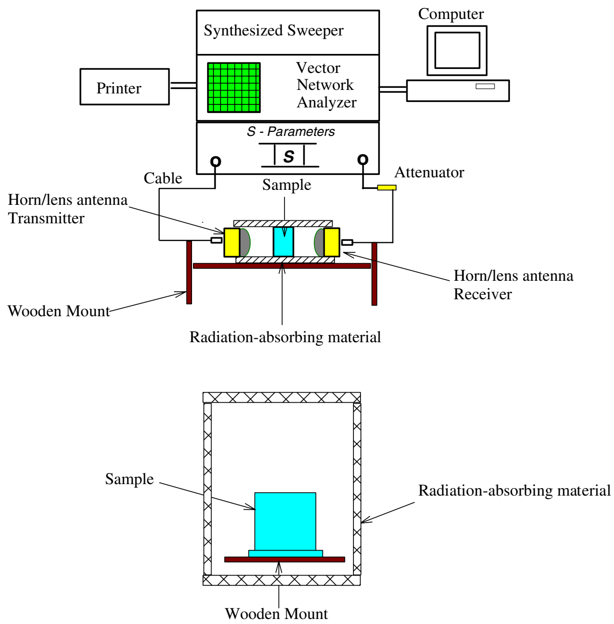

Figure 1. Diagram of measurement arrangement.

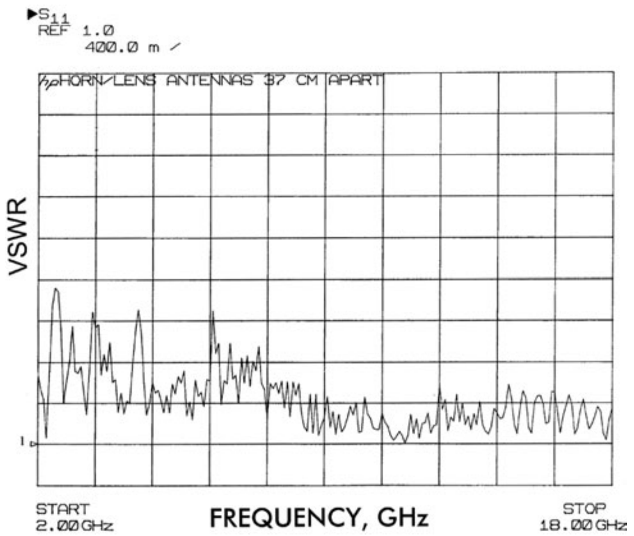

Figure 2. Voltage standing wave ratio for two horn/lens antennas facing each other and 37 cm apart.

coaxial cables with APC-7 connectors at their terminations, two linearly polarized, ultrabroadband (2–26 GHz) horn/lens antennas (BAE Systems model AHO-2077-N), a Styrofoam sample holder and four sheets of Eccosorb AN-79 radiation-absorbing material.

3.2.1. Vector network analyser (VNA). The VNA was used for measurement of the modulus, $|S_{21}|$, and the argument, φ, of S_{21}. It was calibrated between 2 and 18 GHz with a response-type calibration, where the reference values for $|S_{21}|$ and φ were set at zero with an empty sample holder between the two antennas. The VNA was connected to the antennas by two coaxial cables equipped with APC-7 connectors. For each material and each sample, measurement of $|S_{21}|$ and φ were performed between 2 and 18 GHz with an increment of 1 GHz. The measured values were stored on a floppy disk. The whole measurement procedure was automated and controlled by a computer connected to the VNA.

3.2.2. Horn/lens antennas. The two horn/lens antennas were placed facing each other 37 cm apart on a stable wooden fixture that kept them well aligned. Figure 2 shows the VSWR for the two antennas with air space between them as a function of frequency. The measured cross-polarization level was, on average, -25 dB over the 2–18 GHz frequency range, and the E-plane 3 and 10 dB beamwidths at 10 GHz were 10.3° and 13.0°, respectively, based on the radiation pattern provided by the manufacturer. The horn/lens antennas collimate the electromagnetic energy in a relatively narrow beam and provide a plane wave at a short distance from the transmitting antenna. These features allow the measuring system to be compact, reduce the size of the sample required and minimize both the diffraction effects at the edges of the sample and any interference from the surroundings.

3.2.3. Sample holder. The sample holder is a box of rectangular cross section made of 2.5 cm thick Styrofoam sheet. Styrofoam has a dielectric constant of 1.03 and negligible loss and thus does not disturb the measurements. The sample holder was filled with cereal grain or oilseed kernels and placed midway between the two antennas. The layer of material was placed perpendicular to the incident beam. The internal dimensions of the sample holder, which are the layer dimensions, were 25 cm transverse, 25 cm in height and 15.38 cm in thickness. The transverse and height dimensions were selected to minimize effects of diffraction at the edges. They are three times the E-plane 3 dB beamwidth over the considered frequency range. For each material and each moisture content, the sample thickness, d, was selected according to two criteria. First, the material thickness should ensure at least 10 dB one-way attenuation to minimize effects of multiple reflections within the sample. Second, it should optimize the use of the available dynamic range of the VNA and cover as much as possible of the frequency range for each moisture level. Different thicknesses were obtained by placing Styrofoam spacers inside the box. Table 1 shows the different thicknesses used for measurements on wheat, corn and soybeans.

3.2.4. Radiation-absorbing enclosure. The enclosure is made of four 11 cm thick flat square sheets (61 cm × 61 cm) of Eccosorb AN-79 radiation-absorbing material which has a reflectivity of -20 to -25 dB between 2 and 18 GHz. Two sheets were used for the sides and two more for the base and top of the rectangular shaped tunnel. The enclosure entirely covered the space between the two antennas (figure 1). In this way, the sample was completely isolated from the surroundings.

3.3. Measurement procedure

For each material and each sample, preliminary measurements were performed to determine the thickness that allowed optimum use of the VNA over the selected frequency range. Once the thickness was chosen, time-domain gating was

Table 1. Characteristics of grain and seed samples.

Material	Sample thickness (cm)	Temperature (°C)	Density range (g cm^{-3})	Moisture content range (% wb)	Kernel length (mm)
Wheat	6.33; 10.07; 12.75	21–24	0.74–0.89	10.0–18.0	5–7
Corn	4.07; 6.33; 10.07	23–24	0.69–0.88	10.8–25	8–12
Soybeans	4.07; 6.33; 10.07; 12.75	22–24	0.71–0.82	7.1–20.3	5–7

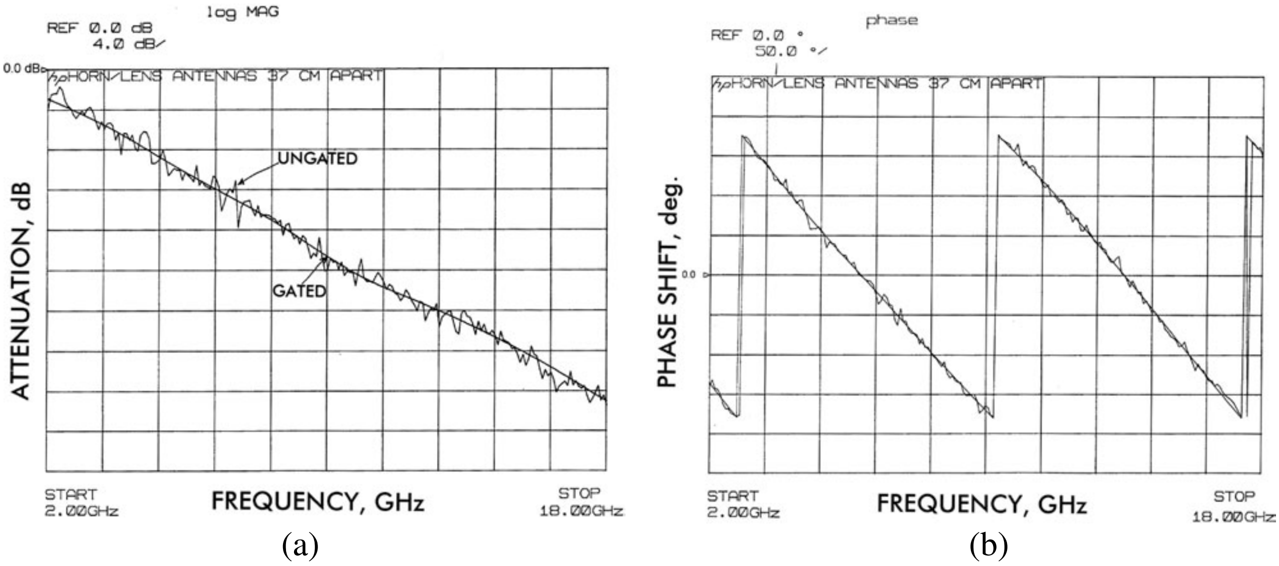

Figure 3. Attenuation and phase shift traces of a 6.33 cm layer of wheat before and after time-domain gating. $M = 17.8\%$, $\rho = 0.785$ g cm^{-3} and $T = 23\,°$C.

applied to filter out effects of post-calibration mismatches and possible multiple-path transmission. Figure 3 shows the traces of $|S_{21}|$ and φ before and after applying time-domain gating for a sample of wheat. Before the gating was applied both traces exhibited ripples caused by post-calibration mismatches and possible multiple-path transmission. After gating, the traces are ripple free, indicating that the effects of responses outside the gate were removed. The gate parameters were selected after converting the frequency-domain trace to the time domain where a gate was applied to the main response. Then, the gated response was converted back to the frequency domain. Performance of selected gate parameters was evaluated by comparing the ungated response to the gated response for both $|S_{21}|$ and φ. An effective time-domain gating was achieved when the gated response was a good average of the ungated response. Once the material thickness and gate parameters for a particular sample were selected, they were introduced into the computer program and the computer-controlled measurement series was launched. For each sample of given moisture content, measurements were carried out at three different densities ranging from loosely packed to compacted by settling the sample on a wooden bench. The sample bulk density was calculated by dividing the sample weight by the inside volume of the Styrofoam container, v:

$$\rho = \frac{m_w + m_d}{v} \tag{1}$$

where m_w is the mass of water and m_d is the mass of dry matter.

After the microwave measurements were completed, the sample temperature, T, was determined with a digital thermocouple thermometer. Moisture content was determined according to standard procedures [16]. The moisture content of the wheat was determined by drying triplicate 10 g samples in a forced-air oven at 130 °C for 19 h. For corn and soybeans, triplicate 15 g samples were dried at 103 °C for 72 h. The moisture content, M, wet basis, is determined as

$$M = \frac{m_w}{m_w + m_d} \times 100. \tag{2}$$

All of the physical characteristics (ρ, M and T) of each sample are assumed to be the same throughout the entire volume of the sample. Physical characteristics of each material as well as the different thicknesses used in this study are summarized in table 1.

3.4. Computation of dielectric properties

The dielectric properties were computed from measurement of the attenuation and phase shift under the following assumptions.

(1) The wave retains its planar nature and the original polarization after propagating through the layer of material.
(2) The material is a low-loss material, $\varepsilon'' \ll \varepsilon'$.
(3) There are no multiple reflections within the sample.

To assess the nature of the wave and presence of multiple reflections, a sample of given moisture content and given bulk density was moved from its initial midway position toward the transmitting antenna and then toward the receiving antenna and the attenuation and phase were measured for each position. Results showed that values of the attenuation and phase shift remained constant within the instrument measurement accuracy (±0.25 dB for the attenuation and ±3.0° for the phase shift). To check the polarization, the receiving antenna was slowly rotated about its axis. A significant drop in the signal level was observed for the smallest angle between the initial position and the adjusted one showing that the wave kept its original polarization after propagating through the layer of material.

The dielectric constant and loss factor were computed as follows [17]:

$$\varepsilon' = \left[1 + \frac{\phi\lambda_0}{360d}\right]^2 \tag{3}$$

$$\varepsilon'' = \frac{A\lambda_0}{8.686\pi d}\sqrt{\varepsilon'} \tag{4}$$

where λ_0 is the wavelength in free space, A is attenuation in decibels and ϕ is phase shift in degrees. The attenuation and phase shift are determined from the measurement of the modulus $|S_{21}|$ and phase φ as follows:

$$A = 20\log|S_{21}| \tag{5}$$

$$\phi = \varphi - 2\pi n \tag{6}$$

where n is an integer. With a VNA, φ can only be measured between −180° and 180°. Hence, when the thickness d of the layer is greater than the wavelength in the material, an ambiguity in the phase occurs. The integer n can be obtained by selecting a thickness for an expected permittivity range or by performing measurements at two frequencies [18]. Also, it can be obtained by repeating the measurements with samples of different thickness [15]. Once the phase shift ambiguity is resolved, the relative complex permittivity can be determined by substituting the values for A and ϕ in (3) and (4). Both A and ϕ are taken as positive numbers. The two components of the relative complex permittivity calculated with equations (3) and (4) are the average values for the entire sample, assuming the physical properties are the same throughout the sample.

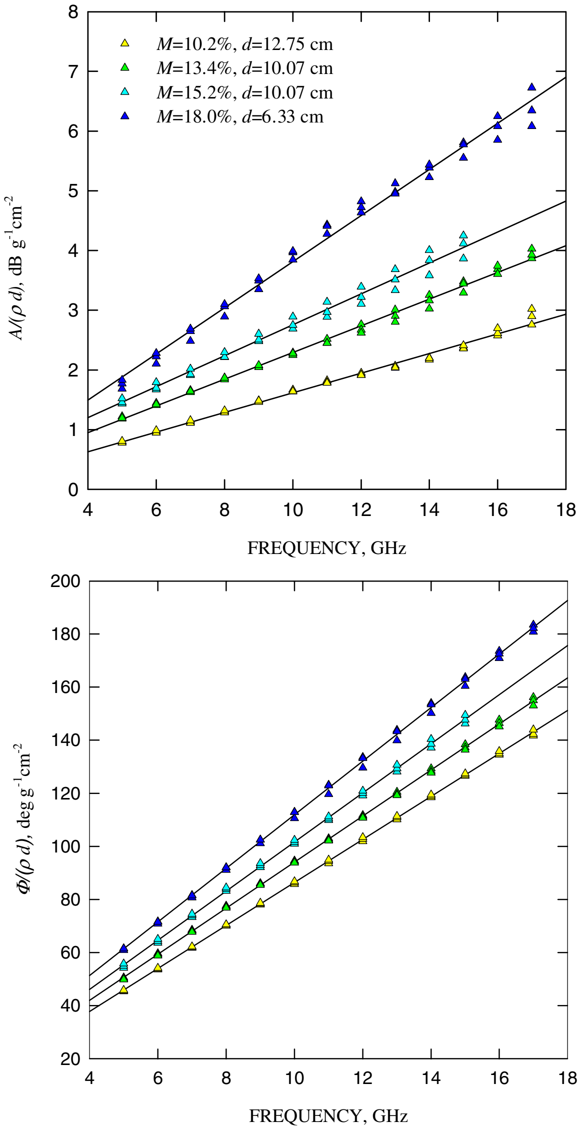

Figure 4. Variations of attenuation and phase shift for wheat, each divided by bulk density and sample thickness, with frequency for indicated moisture contents.

4. Results

All the results reported in this section correspond to attenuation between 10 dB and the upper limit of the instrument dynamic range.

4.1. Dependence of attenuation and phase shift on physical properties of grain and seed

Since attenuation and phase shift are the measured parameters from which the dielectric properties are determined, it is of interest to examine their dependence on the different variables involved. Figures 4–6 show variations of the attenuation and phase shift, divided by bulk density and the sample thickness, with frequency. For each material, they both increase linearly with frequency with higher slopes for higher moisture levels. Therefore, at each moisture level, there exists a linear relationship between the attenuation and phase shift, each divided by bulk density and sample thickness, and the frequency, which can be written as follows:

$$\frac{A}{\rho d} = a_m F + b_m \tag{7}$$

$$\frac{\phi}{\rho d} = c_m F + d_m. \tag{8}$$

Tables 2–4 provide the regression coefficients along with the coefficients of determination for wheat, corn and soybeans. The linear dependence of $A/\rho d$ and $\phi/\rho d$ on frequency is to be expected and can be demonstrated by substituting $\lambda_0 = c/F$, where c is the speed of light and F is the frequency, into equations (3) and (4) assuming that both ε' and ε'' show little variation with frequency over the frequency range [8, 19, 20]. To further investigate the dependence of $A/\rho d$ and $\phi/\rho d$ on moisture content, their variations with moisture are shown in figure 7 for a midband frequency of 10 GHz and temperature of about 23 °C. For each material, they both increase linearly with

Table 2. Regression coefficients and coefficients of determination for the frequency dependence of attenuation and phase shift, each divided by bulk density and sample thickness, for wheat (equations (7) and (8)).

Wheat	$M = 10.2\%$, $T = 23.0\,^\circ$C, $d = 12.75$ cm	$M = 13.45\%$, $T = 23.0\,^\circ$C, $d = 10.07$ cm	$M = 15.24\%$, $T = 23.0\,^\circ$C, $d = 10.07$ cm	$M = 17.96\%$, $T = 23.0\,^\circ$C, $d = 6.33$ cm
a_m	0.165	0.224	0.259	0.386
b_m	−0.028	0.052	0.016	−0.052
r^2	0.990	0.994	0.983	0.990
c_m	8.107	8.677	9.257	10.1
d_m	5.264	7.267	9.077	10.872
r^2	0.999	0.999	0.999	0.999

Table 3. Regression coefficients and coefficients of determination for the frequency dependence of attenuation and phase shift, each divided by bulk density and sample thickness, for corn (equations (7) and (8)).

Corn	$M = 10.79\%$, $T = 23.0\,^\circ$C, $d = 10.07$ cm	$M = 13.68\%$, $T = 24.0\,^\circ$C, $d = 6.33$ cm	$M = 17.79\%$, $T = 24.0\,^\circ$C, $d = 4.07$ cm	$M = 20.4\%$, $T = 23.0\,^\circ$C, $d = 4.07$ cm
a_m	0.280	0.417	0.616	0.788
b_m	−0.474	−0.732	−1.037	−1.371
r^2	0.984	0.998	0.986	0.992
c_m	8.744	9.463	10.684	10.91
d_m	4.38	6.964	14.627	21.769
r^2	0.999	0.998	0.999	0.998

Table 4. Regression coefficients and coefficients of determination for the frequency dependence of attenuation and phase shift, each divided by bulk density and sample thickness, for soybeans (equations (7) and (8)).

Soybeans	$M = 9.8\%$, $T = 24\,^\circ$C, $d = 12.75$ cm	$M = 13.3\%$, $T = 23.0\,^\circ$C, $d = 10.07$ cm	$M = 16.1\%$, $T = 23.0\,^\circ$C, $d = 6.33$ cm	$M = 20.3\%$, $T = 23.0\,^\circ$C, $d = 4.07$ cm
a_m	0.167	0.311	0.487	0.764
b_m	−0.114	−0.336	−0.703	−1.405
r^2	0.995	0.986	0.991	0.994
c_m	9.064	10.059	11.396	11.684
d_m	1.798	4.731	5.543	21.021
r^2	0.999	0.998	0.998	0.999

moisture content. Therefore, there exist linear relationships between the attenuation and phase shift, each divided by bulk density and sample thickness, and moisture content, which can be written as follows:

$$\frac{A}{\rho d} = eM + f \tag{9}$$

$$\frac{\phi}{\rho d} = gM + h. \tag{10}$$

The regression coefficients and coefficients of determination corresponding to equations (9) and (10) are given in table 5. The high correlation between $A/\rho d$, $\phi/\rho d$ and M indicates that equations (9) and (10) can be used to determine simultaneously two important physical properties, bulk density and moisture content, provided that the material thickness is known. Solving (9) and (10) for ρ and M,

$$\rho = \frac{1}{d}\frac{e\phi - gA}{eh - fg} \tag{11}$$

$$M = \frac{hA - f\phi}{e\phi - gA}. \tag{12}$$

At a given frequency, equations (11) and (12) are attenuation- and phase-shift-based calibration equations for bulk density and moisture content determination.

Table 5. Regression coefficients and coefficients of determination for moisture dependence of attenuation and phase shift, each divided by bulk density and sample thickness, for wheat, corn and soybeans at 10.0 GHz and temperature 23 °C (equations (9) and (10)).

Material	Wheat	Corn	Soybeans
e	0.283	0.474	0.419
f	−1.388	−3.063	−2.605
r^2	0.965	0.984	0.988
g	3.254	4.231	4.464
h	52.204	45.67	48.140
r^2	0.979	0.996	0.989

Table 6. Regression coefficients and coefficients of determination for moisture dependence of dielectric constant and loss factor divided by bulk density for wheat, corn and soybeans at 10.0 GHz and temperature 23 °C (equations (13) and (14)).

Material	Wheat	Corn	Soybeans
k	0.093	0.119	0.120
l	2.077	1.899	2.104
r^2	0.981	0.993	0.986
m	0.057	0.105	0.090
n	−0.322	−0.783	−0.631
r^2	0.947	0.972	0.976

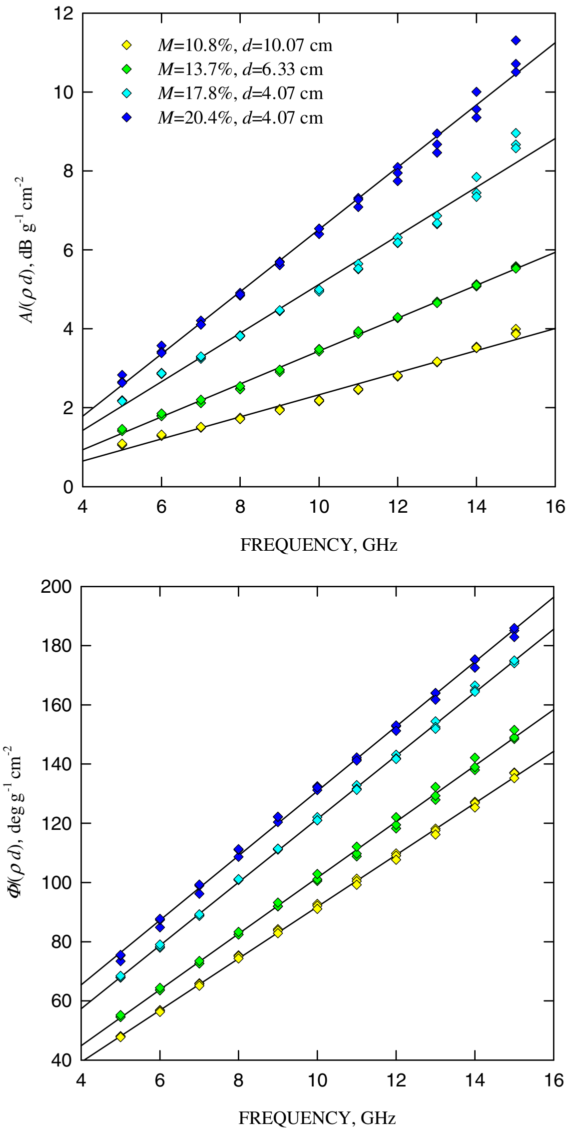

Figure 5. Variations of attenuation and phase shift for corn, each divided by bulk density and sample thickness, with frequency for indicated moisture contents.

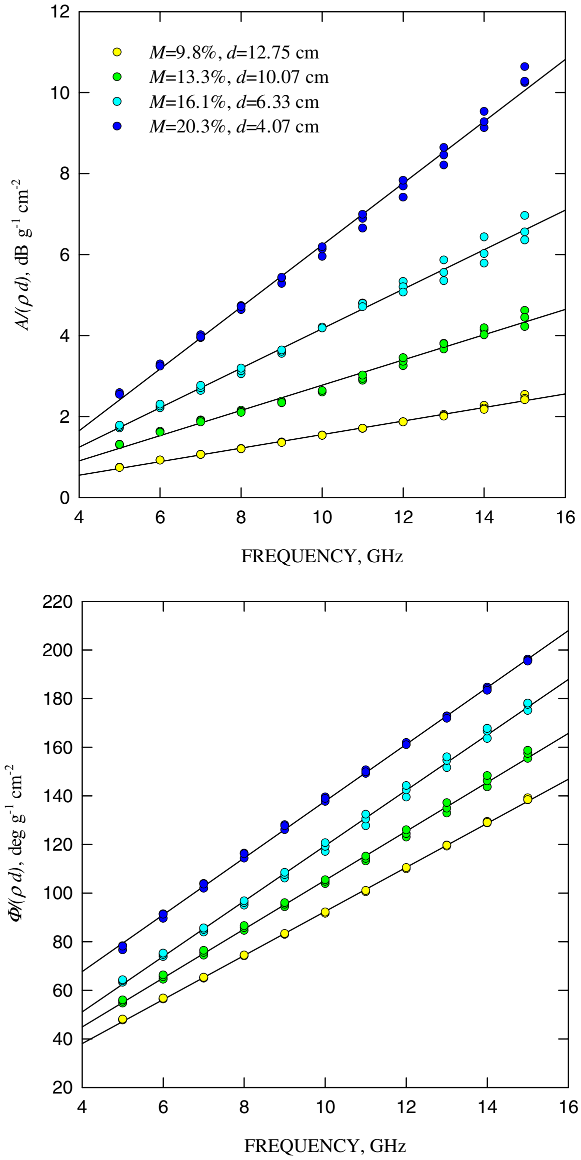

Figure 6. Variations of attenuation and phase shift for soybeans, each divided by bulk density and sample thickness, with frequency for indicated moisture contents.

4.2. Dependence of relative complex permittivity on physical properties of grain and seed

Dielectric properties are intrinsic properties that describe the material/electric field interaction. Therefore, they are the ideal means to probe a given material and to determine indirectly the different parameters describing its physical state. Hence, the first step is to identify relationships between the dielectric properties and the different physical properties, including bulk density, moisture content and temperature. Figure 8 shows variations of ε' and ε'' with bulk density at 10 GHz and 23 °C. For similar moisture levels for all three materials, both ε' and ε'' increase linearly with bulk density. This behaviour is to be expected since an increase in bulk density translates into an increase of the amount of water interacting with the electric field. The increase in the dry mass amount has little influence because the dielectric properties of dry matter are small compared to those of water.

For the purpose of comparing moisture dependence and to minimize bulk-density-related changes, ε' and ε'' were divided by bulk density. Figure 9 shows variations of ε'/ρ and ε''/ρ with moisture content for wheat, corn and soybeans at the midband frequency of 10 GHz at 23 °C. They both increase linearly with moisture content. Linear regressions provide the relationships between the dielectric properties divided by bulk density and moisture content:

$$\frac{\varepsilon'}{\rho} = kM + l \tag{13}$$

$$\frac{\varepsilon''}{\rho} = mM + n. \tag{14}$$

The regression coefficients and coefficients of determination corresponding to equations (13) and (14) are given in table 6. As observed earlier, the high correlation between the dielectric

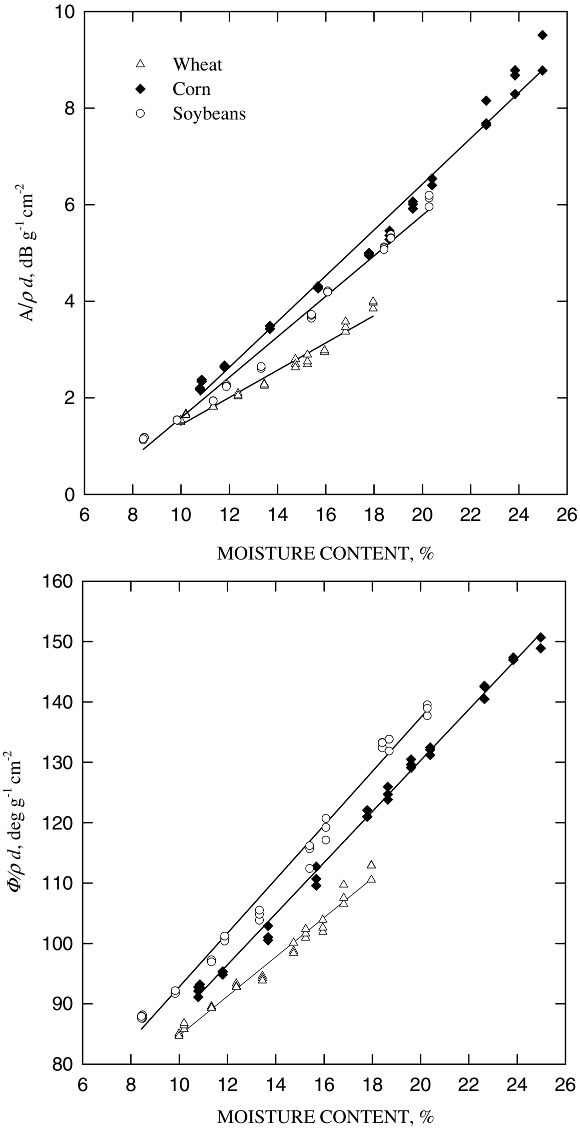

Figure 7. Variations of attenuation and phase shift for wheat, corn and soybeans, each divided by bulk density and sample thickness, with moisture content at 10 GHz and 23 °C.

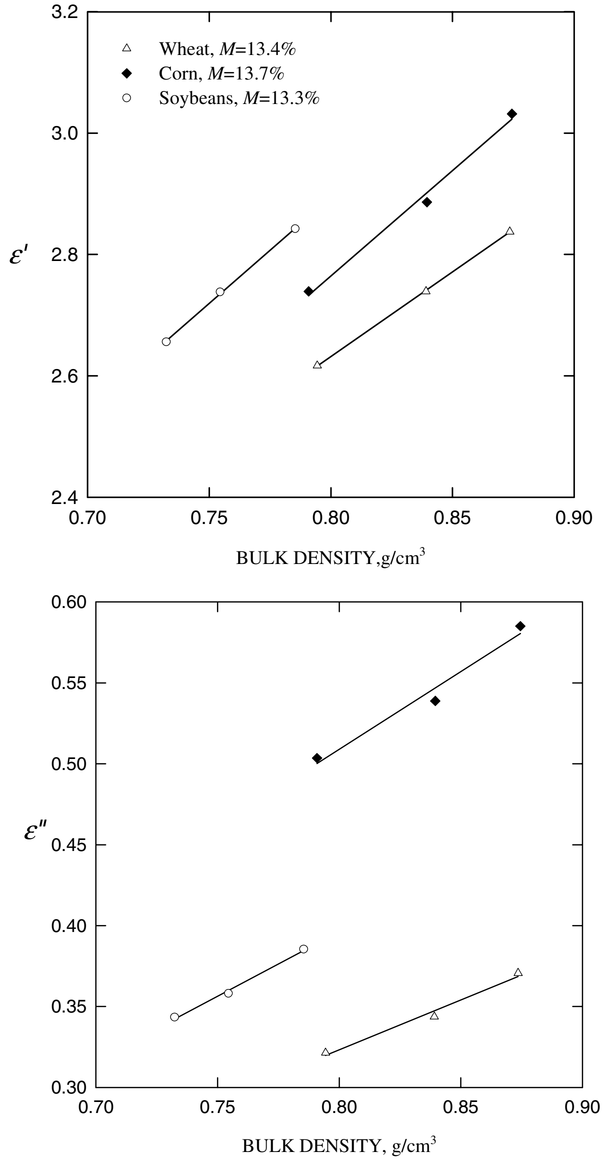

Figure 8. Dielectric constant and loss factor for wheat, corn and soybeans as a function of bulk density at 10 GHz and indicated moisture contents at 23 °C.

properties and physical properties implies the possibility of using these relationships to determine simultaneously bulk density and moisture content of moist granular materials from measurement of ε' and ε''. Solving equations (13) and (14) for ρ and M,

$$\rho = \frac{m\varepsilon' - k\varepsilon''}{lm - kn} \tag{15}$$

$$M = \frac{n\varepsilon' - l\varepsilon''}{k\varepsilon'' - m\varepsilon'}. \tag{16}$$

Bulk density and moisture calibration equations (15) and (16) can be used regardless of the measurement technique used to determine the permittivity, providing more flexibility in the design of a sensing system for a particular application.

5. Reference data

One of the objectives of this study was to provide permittivity data over a wide microwave frequency range. For each moisture level, permittivity values obtained for loosely packed and settled samples were converted to those corresponding to the medium bulk density with the Landau and Lifshitz, Looyenga mixture equation [21]:

$$\varepsilon_2 = \left[(\varepsilon_1^{1/3} - 1)\frac{\rho_2}{\rho_1} + 1\right]^3 \tag{17}$$

where ρ_1 is the original bulk density and ρ_2 is the medium density for a particular moisture content. This mixture equation was selected from several dielectric mixture equations that were tested to find the one with best performance for permittivities similar to those of cereal grains [22]. After the Landau and Lifshitz, Looyenga transform was completed, for a given moisture level, the mean value was calculated. Values obtained for wheat, corn and soybeans are reported for four different moisture levels in tables 7–10 for frequencies between 5 and 17 GHz. In general, the dielectric constant

Table 7. Dielectric properties of wheat, corn and soybeans normalized to a medium density with the Landau and Lifshitz, Looyenga mixture equation.

Frequency (GHz)	Wheat $\rho = 0.862$ g cm^{-3}, $M = 10.2\%$, $T = 23.0\,^\circ$C $d = 12.75$ cm		Corn $\rho = 0.831$ g cm^{-3}, $M = 10.8\%$, $T = 23.0\,^\circ$C $d = 10.075$ cm		Soybeans $\rho = 0.768$ g cm^{-3}, $M = 9.8\%$, $T = 24.0\,^\circ$C $d = 12.75$ cm	
	ε'	ε''	ε'	ε''	ε'	ε''
5	—	—	—	—	—	—
6	2.70	0.25	2.72	0.33	—	—
7	2.67	0.25	2.71	0.32	2.54	0.20
8	2.66	0.25	2.71	0.32	2.54	0.20
9	2.63	0.25	2.69	0.32	2.53	0.20
10	2.62	0.25	2.67	0.33	2.52	0.21
11	2.60	0.25	2.65	0.33	2.51	0.21
12	2.60	0.25	2.64	0.35	2.51	0.21
13	2.59	0.24	2.63	0.36	2.52	0.21
14	2.58	0.24	2.63	0.37	2.52	0.21
15	2.58	0.24	2.64	0.39	2.53	0.22
16	2.57	0.25	—	—	—	—
17	2.56	0.26	—	—	—	—

Table 8. Dielectric properties of wheat, corn and soybeans normalized to a medium density with the Landau and Lifshitz, Looyenga mixture equation.

Frequency (GHz)	Wheat $\rho = 0.839$ g cm^{-3}, $M = 13.4\%$, $T = 23.0\,^\circ$C $d = 10.07$ cm		Corn $\rho = 0.839$ g cm^{-3}, $M = 13.7\%$, $T = 24.0\,^\circ$C $d = 6.33$ cm		Soybeans $\rho = 0.754$ g cm^{-3}, $M = 13.3\%$, $T = 23.0\,^\circ$C $d = 10.07$ cm	
	ε'	ε''	ε'	ε''	ε'	ε''
5	2.88	0.38	—	—	2.86	0.37
6	2.84	0.37	3.02	0.49	2.83	0.38
7	2.81	0.36	2.97	0.49	2.80	0.37
8	2.79	0.36	2.95	0.50	2.78	0.37
9	2.76	0.35	2.93	0.52	2.76	0.36
10	2.74	0.35	2.90	0.55	2.73	0.36
11	2.72	0.34	2.87	0.56	2.72	0.37
12	2.70	0.34	2.86	0.56	2.71	0.38
13	2.69	0.34	2.86	0.56	2.72	0.40
14	2.68	0.34	2.85	0.57	2.72	0.40
15	2.68	0.34	2.85	0.58	2.73	0.41
16	2.68	0.35	—	—	—	—
17	2.66	0.35	—	—	—	—

consistently decreases with frequency, while the dielectric loss factor remains constant or slightly decreases with frequency. For frequencies above about 10.0 GHz the dielectric loss factor of corn and soybeans increases with frequency. This may be related to a scattering effect component that adds to the dielectric losses [23]. However, the changes observed for the dielectric loss factor remain within the margin of the expected measurement error for this kind of material with a free-space measurement technique and thus cannot be conclusive as for the definite trend.

Table 11 shows values of the two components of the relative complex permittivity at 10.0 GHz for several moisture contents and corresponding medium densities. Both ε' and ε'' increase with moisture content, confirming the trends noted in figure 9.

Values obtained for the dielectric constant and loss factor of wheat and corn agree reasonably well with earlier data obtained with the short-circuited waveguide measurement technique, when differences in bulk density are taken into account [8, 24]. The data tabulated here will be useful in studying the electrical behaviour of these granular random dense materials and in developing rapid indirect methods for sensing their physical properties [2, 4, 25].

6. Conclusions

Free-space transmission measurements with a VNA, horn/lens antennas, suitable sample holder and radiation absorbing enclosure around four sides of the sample and the antennas can be used for reliable determination of the dielectric properties of moist granular materials. Reliability of the determinations was improved by providing sufficient sample thickness for 10 dB one-way attenuation, use of the VNA gating function and proper use of the dynamic range of the VNA for the attenuation

Table 9. Dielectric properties of wheat, corn and soybeans normalized to a medium density with the Landau and Lifshitz, Looyenga mixture equation.

Frequency, (GHz)	Wheat $\rho = 0.808$ g cm^{-3}, $M = 15.2\%$ $T = 24\,^{\circ}$C $d = 10.07$ cm		Corn $\rho = 0.839$ g cm^{-3}, $M = 17.8\%$ $T = 24.0\,^{\circ}$C $d = 4.07$ cm		Soybeans $\rho = 0.754$ g cm^{-3}, $M = 16.1\%$ $T = 23.0\,^{\circ}$C $d = 6.33$ cm	
	ε'	ε''	ε'	ε''	ε'	ε''
5	3.01	0.45	—	—	—	—
6	2.95	0.44	3.49	0.80	3.19	0.57
7	2.91	0.42	3.40	0.80	3.12	0.58
8	2.89	0.42	3.40	0.80	3.09	0.58
9	2.86	0.42	3.31	0.81	3.08	0.59
10	2.82	0.42	3.26	0.80	3.07	0.64
11	2.80	0.41	3.22	0.81	3.05	0.64
12	2.78	0.40	3.20	0.83	3.05	0.64
13	2.77	0.40	3.16	0.83	3.05	0.64
14	2.76	0.40	3.17	0.86	3.05	0.64
15	2.75	0.40	3.12	0.92	3.04	0.65
16	2.75	0.40	—	—	—	—
17	—	—	—	—	—	—

Table 10. Dielectric properties of wheat, corn and soybeans normalized to a medium density with the Landau and Lifshitz, Looyenga mixture equation.

Frequency, (GHz)	Wheat $\rho = 0.821$ g cm^{-3}, $M = 17.8\%$ $T = 23.0\,^{\circ}$C $d = 6.33$ cm		Corn $\rho = 0.781$ g cm^{-3}, $M = 20.4\%$ $T = 23.0\,^{\circ}$C $d = 4.07$ cm		Soybeans $\rho = 0.805$ g cm^{-3}, $M = 20.3\%$ $T = 23.0\,^{\circ}$C $d = 4.07$ cm	
	ε'	ε''	ε'	ε''	ε'	ε''
5	—	—	—	—	—	—
6	3.26	0.60	3.70	0.96	4.00	0.97
7	3.19	0.60	3.59	0.97	3.90	1.00
8	3.16	0.61	3.53	0.99	3.81	1.03
9	3.12	0.62	3.46	1.02	3.73	1.03
10	3.09	0.63	3.38	1.04	3.66	1.04
11	3.06	0.63	3.30	1.04	3.59	1.06
12	3.05	0.62	3.26	1.04	3.54	1.07
13	3.03	0.61	3.22	1.05	3.49	1.09
14	3.02	0.60	3.19	1.07	3.46	1.11
15	3.00	0.60	3.15	1.12	3.43	1.19
16	2.99	0.60	—	—	—	—
17	2.98	0.59	—	—	—	—

Table 11. Dielectric properties of wheat, corn and soybeans normalized to a medium density with the Landau and Lifshitz, Looyenga mixture equation at 10 GHz and about 23 °C.

Wheat				Corn				Soybeans			
ρ (g cm^{-3})	M (%)	ε'	ε''	ρ (g cm^{-3})	M (%)	ε'	ε''	ρ (g cm^{-3})	M (%)	ε'	ε''
0.861	10.0	2.58	0.23	0.831	10.8	2.67	0.33	0.768	8.4	2.44	0.15
0.862	10.2	2.62	0.25	0.850	10.9	2.73	0.36	0.762	8.5	2.42	0.15
0.852	11.3	2.66	0.28	0.852	11.8	2.79	0.42	0.768	9.8	2.52	0.21
0.822	12.4	2.67	0.30	0.839	13.7	2.90	0.55	0.786	11.3	2.62	0.26
0.839	13.4	2.73	0.35	0.829	15.7	3.08	0.69	0.761	11.9	2.67	0.30
0.836	14.7	2.84	0.42	0.808	17.8	3.25	0.80	0.754	13.3	2.73	0.36
0.808	15.2	2.82	0.41	0.784	18.6	3.24	0.84	0.775	15.4	3.00	0.55
0.811	15.9	2.86	0.45	0.791	19.6	3.38	0.97	0.767	16.1	3.07	0.62
0.830	16.8	3.02	0.55	0.781	20.4	3.38	1.04	0.766	18.4	3.37	0.79
0.821	18.0	3.09	0.63	0.769	22.6	3.54	1.27	0.785	18.7	3.44	0.86
				0.767	23.8	3.63	1.41	0.805	20.3	3.66	1.04
				0.760	25.0	3.61	1.55				

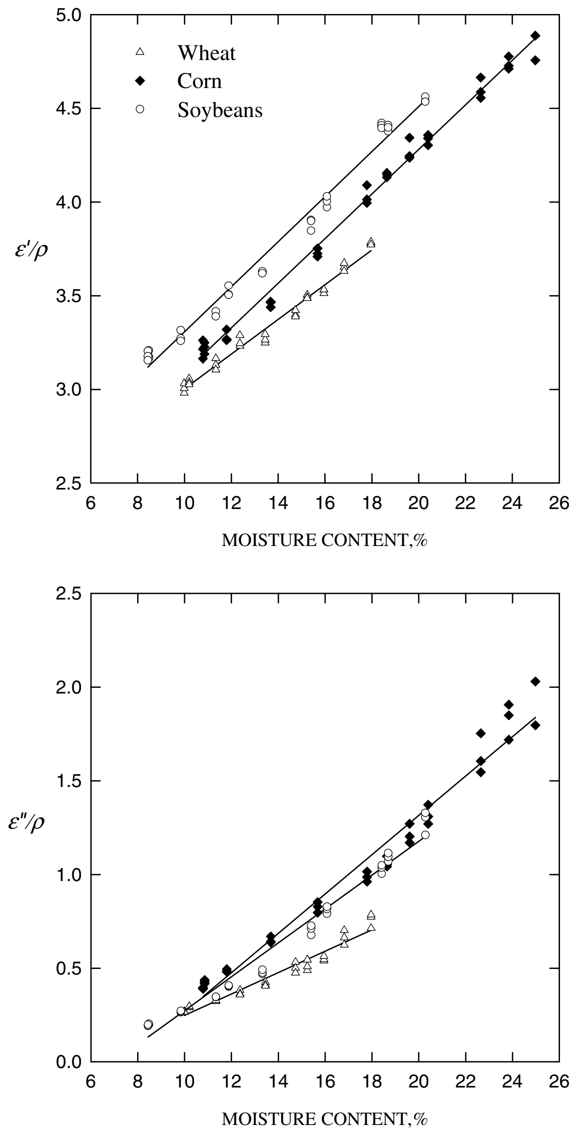

Figure 9. Dielectric constant and loss factor of wheat, corn and soybeans, each divided by bulk density, as a function of moisture content at 10 GHz and 23 °C.

and phase measurements from which the dielectric properties are calculated.

Attenuation and phase shift, due to the sample presence between the transmitting and receiving antenna, each divided by sample thickness and bulk density, are linear functions of frequency and moisture content. Resulting values of dielectric constant and loss factor are linearly dependent on the bulk density of the granular material.

Regression equations were developed from which calibration equations for moisture content and bulk density of wheat, shelled corn and soybeans can be determined for rapid, nondestructive measurement of moisture content and bulk density of these commodities from either attenuation and phase shift or from their dielectric properties. For use of attenuation and phase shift, transmission measurements are required, but for use of the permittivity components, transmission, reflection or any other measurement technique can be used that provides accurate values for the permittivity.

Permittivity components, dielectric constant and loss factor, were determined and tabulated for wheat, shelled corn (maize) and soybeans at specified moisture contents and bulk densities for the frequency range from 5 to 17 GHz at 23 °C. Permittivity values are also tabulated for the same three commodities, adjusted to a medium density value through use of the Landau and Lifshitz, Looyenga dielectric mixture equation, for the range of moisture contents of practical interest at 10 GHz and at the same temperature.

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