Calibration Methods for Nondestructive Microwave Sensing of Moisture Content and Bulk Density of Granular Materials

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Abstract. *The principles of a nondestructive multiparameter microwave sensor operating at a single frequency are presented. Two calibration methods are reviewed and compared for simultaneous, independent determination of bulk density and moisture content in granular materials. The first calibration method is based on measurement of attenuation and phase shift through a layer of material in free space. The attenuation and phase shift were used to determine simultaneously bulk density and moisture content, and the attenuation−to−phase ratio was used to determine moisture content independent of bulk density changes. For the second calibration method, relationships are established between the dielectric properties and bulk density and moisture content. The dielectric properties were used to determine simultaneously bulk density and moisture content, and a calibration function, expressed in terms of these properties, was used to determine moisture content independent of bulk density. In addition, a complex−plane representation of the dielectric properties provided bulk density independent of temperature and moisture content. Performance of these calibration methods in predicting bulk density and moisture content was compared for wheat, corn, and soybeans at 10.0 GHz at room temperature. Bulk density and moisture content calibration equations are given for each material along with corresponding standard errors of calibration.*

Keywords. *Attenuation, Bulk density, Corn, Dielectric properties, Free space, Granular materials, Microwaves, Moisture content, Multiparameter sensor, Phase shift, Soybeans, Wheat.*

Sensors play an important role in modern agriculture. They are used in the field and at different stages during the processing of agricultural products. With highly automated industries, requirements of precision farming, and the need for real−time decision−making, there is a growing need for on−line sensors. Microwave sensors provide a suitable solution to meet some of these challenges. They have the advantages of being nondestructive and instantaneous (Kraszewski, 1996; Nyfors and Vainikainen, 1989). In agriculture, they can be used, for example, for bulk density and moisture content sensing in grain and seed. The purpose of this article is to review and compare performance of microwave sensing methods for determining physical properties of grain and seed of importance to the agricultural community.

The concept of a multiparameter microwave sensor operating at a single frequency is very attractive economically and technically. Economically, a multiparameter sensor replaces multiple sensors based on different technologies and provides the same amount of information, thus allowing considerable cost reduction. Technically, a sensor that is based on the same technology to provide the desired physical properties simplifies considerably the sensor design and calibration algorithms. The availability of low−cost, reduced−size microwave components developed for wireless telecommunications offers additional incentives for the commercialization and widespread use of such a sensor. Here, the concept of a multiparameter microwave sensor (Trabelsi et al., 2000a) operating at a single frequency is discussed through measurements performed on cereal grain and seed.

The sensor principle relies on measurement of material parameters affecting the interaction of an electromagnetic wave with the material at a single microwave frequency and identifying correlations between these parameters and physical properties of interest. In this instance, attenuation, phase shift, and dielectric properties of a layer of grain or seed are correlated with its bulk density and moisture content. Attenuation and phase shift are attributed to the energy loss and propagation delay that the electromagnetic wave undergoes when propagating through the layer of material. The dielectric properties are intrinsic properties often represented by the relative complex permittivity $\varepsilon = \varepsilon' - j\varepsilon''$, where the real part ($\varepsilon'$), or dielectric constant, characterizes the ability of a material to store electric−field energy, and the imaginary part (ε''), the dielectric loss factor, reflects the ability of a material to dissipate electric energy in the form of heat. Both ε' and ε'' are dependent on frequency, temperature, and composition (Hasted, 1973). For granular materials, they also depend on bulk density.

Article was submitted for review in September 2003; approved for publication by the Food & Process Engineering Institute Division of ASAE in September 2004. Presented at the 2003 ASAE Annual Meeting as Paper No. 036129.

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Very often, the sensor operating frequency is selected within a range where effects of ionic conductivity are negligible and away from any relaxation phenomenon that may alter the monotonic variation of the dielectric properties with the physical properties of the material. At microwave frequencies, above 3 GHz, the ionic conductivity has no effect (Meyer and Schilz, 1981) and there are no bound−water−related relaxations, which are expected to take place at much lower frequencies (Hasted, 1973). Historically, many of the sensing applications were conducted in the X−band (8 to 12 GHz) (Jacobsen et al., 1980; Kent and Meyer, 1982; Kraszewski and Kulinski, 1976; Meyer and Schilz, 1980). In this study, a frequency of 10 GHz was selected.

As in all indirect methods, widespread and successful use of such a sensor relies on effective stable calibration and accurate determination of desired physical properties. Performance of two calibration methods for predicting bulk density and moisture content in grain and seed is compared. The data used were obtained by measurements in free space for materials presenting significant structural and compositional differences, namely, wheat, corn, and soybeans (Trabelsi and Nelson, 2003). For the first calibration method, and the most straightforward, attenuation and phase shift measured for each material are used to determine simultaneously the material bulk density and moisture content. In addition, the ratio of attenuation and phase shift is used to determine moisture content in each material independent of bulk density changes (Kraszewski and Kulinski, 1976). For the second calibration method, correlations are established between the dielectric properties and bulk density and moisture content. These correlations allow simultaneous determination of bulk density and moisture content, bulk density determination independent of moisture content and temperature (Trabelsi et al., 2000a), and moisture content determination independent of bulk density (Meyer and Schilz, 1981; Trabelsi et al., 1998b). For each calibration method, bulk density and moisture calibration equations are given for each material at 10 GHz and room temperature along with corresponding standard errors of calibration (*SEC*).

Basic Definitions and Physical Background

Bulk Density and Moisture Content

Granular solids are commonly encountered in nature and in different industries, including food and agriculture, pharmaceutical, mining, and construction materials. Sometimes they are referred to as the fourth state of matter besides liquid, solid, and gas. Therefore, a better understanding of these materials through their characterization is needed. In agriculture, physical properties of grain and seed such as bulk density and moisture content are required for their optimum processing, safe storage, and in trade.

The bulk density is defined on a gravimetric basis as:

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

where m_w is the mass of water, m_d is the dry mass, and V is the bulk volume of the material. In general, ρ is expressed in g/cm^3 or kg/m^3.

The moisture content, in percent, is defined on a wet basis as:

$$M = \frac{m_w}{m_w + m_d} 100 = \frac{m_w / V}{\rho} 100 \tag{2}$$

Another physical parameter that describes the state of a given material is temperature. Temperature can be measured with inexpensive devices and is expressed in degrees Celsius. In this study, bulk density, moisture content, and temperature are assumed to be uniform throughout the sample. Table 1 summarizes the physical properties of the cereal grain and seed used in this study.

Free−Space Measurement

Measurements of the dielectric properties of materials in free space can be carried out in reflection or transmission mode, or both, depending on the number of unknown properties to be determined. Because of the nonmagnetic nature of cereal grain and seed, measurement of either the reflection coefficient or the transmission coefficient is sufficient for determining the dielectric constant (ε′) and the dielectric loss factor (ε″). A free−space transmission technique was used in this study. The measurement system consists of two antennas facing each other with the transmitting antenna connected to a source that generates the electromagnetic wave and the receiving antenna connected to a detector that compares the incident and transmitted signals. The sample is usually placed between the two antennas and transmission measurements are performed (Musil and Zacek, 1986; Trabelsi and Nelson, 2003). In this study, the scattering transmission coefficient (S_{21}) was measured with a Hewlett−Packard 8510C vector network analyzer (VNA). Samples of wheat, corn, and soybeans were poured into a Styrofoam box of rectangular cross−section and placed between two linearly polarized horn/lens antennas (model AHO−2077−N, BAE Systems). Special precautions were taken to ensure accurate measurements. For each sample, the sample thickness was selected to ensure at least 10−dB one−way attenuation without exceeding the VNA dynamic range. In this way, undesirable effects of multiple reflections within the sample were minimized and the VNA capabilities were used properly. Another feature available in the VNA is time−domain gating. It was used to filter out effects of residual post−calibration mismatches and possible multiple−path transmission. For each material of given moisture content, measurements were carried out at three different bulk densities covering the range from loosely

Table 1. Physical characteristics of cereal grain and oil seed samples.

Material	Sample Thickness (cm)	Temperature (°C)	Density Range (g/cm^3)	Moisture Content Range (% w.b.)	Kernel Length (mm)
Wheat	6.3, 10.1, 12.8	21 − 24	0.74 − 0.89	10.0 − 18.0	5 − 7
Corn	4.1, 6.3, 10.1	23 − 24	0.69 − 0.88	10.8 − 25.0	8 − 12
Soybeans	4.1, 6.3, 10.1, 12.8	22 − 24	0.71 − 0.82	7.1 − 20.3	5 − 7

packed to well settled. More detailed descriptions of the measurements are reported elsewhere (Trabelsi and Nelson, 2003).

Attenuation and Phase Shift

Attenuation describes the power loss an electromagnetic wave undergoes when propagating through a medium. For the attenuation to be measured accurately, effects of multiple reflections, interference with the surroundings, and post−calibration mismatches should be minimized. This can be achieved by properly calibrating the measurement system, choosing the thickness that limits the effect of multiple reflections, isolating the sample from the environment with a radiation absorbing material, and applying time−domain gating if the VNA is used (Trabelsi and Nelson, 2003). In general, the attenuation is the difference between the power levels without the sample (A_0) and with the sample (A) placed between the transmitting and receiving antennas. It is expressed in decibels (dB) as:

$$\Delta A(dB) = A - A_0 = 20 \cdot \log\left| S_{21} \right| \tag{3}$$

where $| S_{21} |$ is the modulus of the complex scattering transmission coefficient S_{21}.

The phase shift describes the delay in propagation caused by the slowing of the speed of propagation of the wave in the medium. The phase shift is less sensitive to the causes of errors mentioned above for attenuation. However, all the precautions recommended for accurate measurement of attenuation can only increase the phase−shift measurement accuracy (Trabelsi et al., 1998a). The phase shift is the difference between the phase measured without the sample (Φ_0) and with the sample (Φ) placed between the transmitting and receiving antennas. It is expressed in degrees as:

$$\Delta\Phi = \Phi - \Phi_0 = \varphi - 360 \cdot n \tag{4}$$

where φ is the argument of the complex scattering transmission coefficient, and n is an integer to be determined. With a VNA, φ can only be measured between −180° and 180°. Hence, when the sample thickness (d) 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 (Trabelsi et al., 2000b). It can also be obtained by repeating the measurements with samples of different thickness (Musil and Zacek, 1986).

Dielectric Properties

The dielectric properties are intrinsic properties that characterize the electric field/material interaction (Von Hippel, 1954). They constitute the electrical signature of a material. In general, they are dependent on the physical properties defining the state of a given material. For granular materials, moisture content, bulk density, and temperature are the most influential properties (Nelson, 1973, 1981, 1983, 1988). At microwave frequencies, the complex permittivity of water is much greater than that of dry matter. Therefore, water dominates the dielectric response of moist materials (Hasted, 1973). Analysis of effects of both bulk density and temperature on dielectric properties shows that both are water−related effects (Trabelsi et al., 1999). The dielectric properties can be calculated from the measured attenuation and phase shift. Assuming a plane wave is propagating through a low−loss material ($\varepsilon'' << \varepsilon'$), the dielectric properties are determined as follows (Nyfors and Vainikainen, 1989; Trabelsi et al., 1998a):

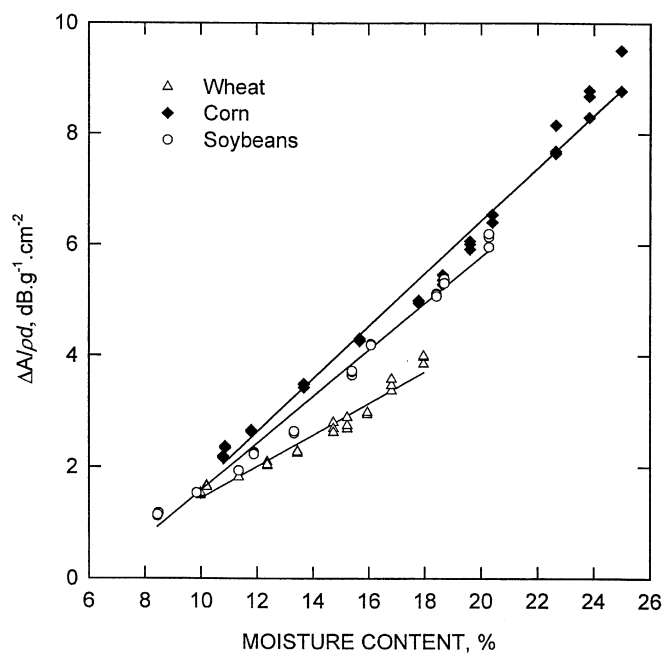

Figure 1. Attenuation divided by sample thickness and sample bulk density as a function of moisture content at 10 GHz and room temperature for wheat, corn, and soybeans.

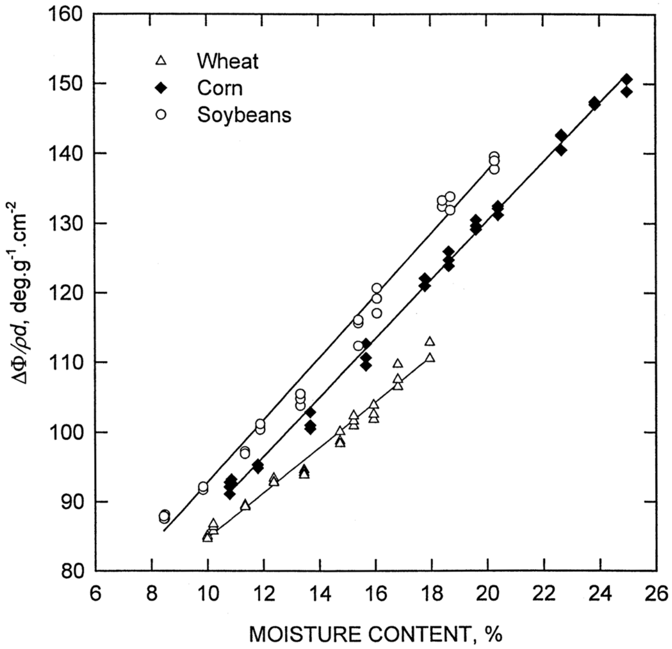

Figure 2. Phase shift divided by sample thickness and sample bulk density as a function of moisture content at 10 GHz and room temperature for wheat, corn, and soybeans.

$$\varepsilon' = \left[1 + \frac{\Delta\Phi}{360d}\frac{c}{f}\right]^2 \tag{5}$$

$$\varepsilon'' = \frac{\Delta A}{8.686\pi d}\frac{c}{f}\sqrt{\varepsilon'} \tag{6}$$

where c is the speed of light, and f is the frequency. Both the attenuation and phase shift are taken as positive numbers.

Calibration Methods for a Multiparameter Microwave Sensor

Method 1: Use of Attenuation and Phase Shift

Simultaneous Determination of Bulk Density and Moisture Content

Since attenuation and phase shift are the microwave parameters directly measured, it is of interest to investigate the possibility of their use to determine simultaneously bulk density and moisture content (Kraszewski, 1988). Dependence of attenuation and phase shift on bulk density and moisture content in wheat, corn, and soybeans are presented in figures 1 and 2 at 10.0 GHz and room temperature. Only data that fulfill the minimum one−way attenuation of 10 dB and remain within the dynamic range of the VNA are presented.

Figures 1 and 2 show that both attenuation and phase shift, each divided by bulk density and the sample thickness, increase linearly with moisture content. Analytically, they can be fitted by linear regressions of the form:

$$\frac{\Delta A}{\rho d} = a_1 M + b_1 \tag{7}$$

$$\frac{\Delta\Phi}{\rho d} = c_1 M + d_1 \tag{8}$$

The regression coefficients and coefficients of determination corresponding to equations 7 and 8 are given in table 2. The high correlation between $\frac{\Delta A}{\rho d}$, $\frac{\Delta\Phi}{\rho d}$, and M indicates that equations 7 and 8 can be used to determine simultaneously bulk density and moisture content at a given temperature, provided that the material thickness is known. Solving equations 7 and 8 for ρ and M:

$$\rho = \frac{1}{d}\frac{a_1\Delta\Phi - c_1\Delta A}{a_1 d_1 - b_1 c_1} \tag{9}$$

$$M = \frac{d_1\Delta A - b_1\Delta\Phi}{a_1\Delta\Phi - c_1\Delta A} \tag{10}$$

At a given frequency and a given temperature, equations 9 and 10 are attenuation− and phase−shift−based calibration equations for bulk density and moisture content determination in grain and seed. To evaluate the performance of these equations in predicting bulk density and moisture content directly from measured parameters, the standard error of calibration (*SEC*) is calculated. The *SEC* is defined as:

Table 2. Regression statistics corresponding to equations 7 to 10 and the standard error of calibration (*SEC*) for bulk density and moisture content determination for wheat, corn, and soybeans at 10.0 GHz for the physical conditions defined in table 1.

Statistics	Wheat	Corn	Soybeans
a_1	0.283	0.474	0.419
b_1	−1.39	−3.06	−2.60
r^2	0.965	0.984	0.988
c_1	3.25	4.23	4.46
d_1	52.02	45.67	48.14
r^2	0.979	0.996	0.989
SEC_ρ (g/cm^3)	0.012	0.032	0.016
SEC_M (%)	0.62	1.20	0.57

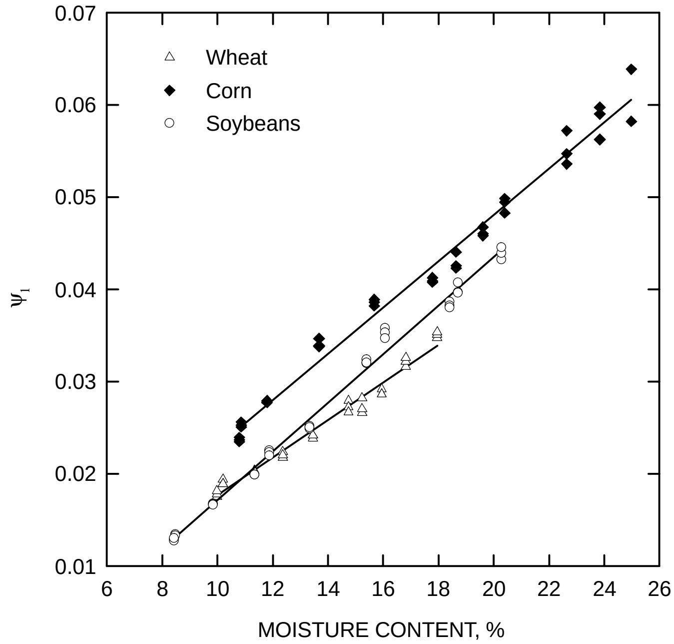

Figure 3. Variation of density−independent calibration function ψ_1 with moisture content in wheat, corn, and soybeans at 10 GHz and room temperature.

$$SEC = \sqrt{\frac{1}{l-p-1}\sum_{i=1}^{l}(\Delta e_i)^2} \tag{11}$$

where l is the number of samples, p is the number of variables in the regression equation with which the calibration is performed, and Δe_i is the difference between the predicted value and that determined by a standard method for the ith sample. Here, the standard technique for bulk density measurement is the gravimetric technique, and for moisture content determination the oven−drying technique was used (*ASAE Standards*, 2000). Table 2 gives the *SEC* values corresponding to equations 9 and 10 for wheat, corn, and soybeans. The *SEC* values for moisture content and bulk density determination of corn are higher than those of wheat and soybeans.

Moisture Content Determination Independent of Bulk Density

Bulk density changes affect the measured microwave parameters in a way similar to that of water. Therefore, when microwaves were considered for moisture sensing in granular materials, it was recognized that there was a need for eliminating the effect of bulk density. The first density−independent entity was introduced in the mid−1970s (Kraszewski and Kulinski, 1976), after it was realized that although the attenuation and phase shift measured at a single frequency through a layer of material were dependent on bulk density, their ratio was not. In this study, the ratio is defined as:

$$\psi_1 = \frac{\Delta A}{\Delta \Phi} \tag{12}$$

Figure 3 shows that for each material, ψ_1 increases linearly with moisture content. Therefore, data for each material can be fitted with a regression equation of the form:

$$\psi_1 = a_{1,m}M + b_{1,m} \tag{13}$$

Regression coefficients and coefficients of determination are given in table 3. A moisture calibration equation is obtained by solving equation 13 for M:

$$M = \frac{\psi_1 - b_{1,m}}{a_{1,m}} \tag{14}$$

SEC values for moisture prediction with equation 14 are given in table 3. The *SEC* values are smaller than those obtained when moisture is predicted with equation 10.

Method 2: Use of Dielectric Constant and Dielectric Loss Factor

Simultaneous Determination of Bulk Density and Moisture Content

This method is based on finding relationships between the dielectric properties and bulk density and moisture content. The dielectric properties of each sample are computed from measured attenuation and phase shift using equations 5 and 6. Figures 4 and 5 show ε'/ρ and ε''/ρ as a function of moisture content in wheat, corn, and soybeans at 10.0 GHz and room temperature.

Both ε'/ρ and ε''/ρ increase linearly with moisture content for each material. Linear regressions of the form:

$$\frac{\varepsilon'}{\rho} = a_2 M + b_2 \tag{15}$$

Table 3. Regression statistics corresponding to equation 14 and the *SEC* in moisture content determination for wheat, corn, and soybeans at 10.0 GHz for the physical conditions defined in table 1.

Statistics	Wheat	Corn	Soybeans
$a_{1,m}$	2.035×10^{-3}	2.510×10^{-3}	2.634×10^{-3}
$b_{1,m}$	-2.69×10^{-3}	-2.13×10^{-3}	-9.17×10^{-3}
r^2	0.977	0.984	0.993
SEC_M (%)	0.41	0.60	0.34

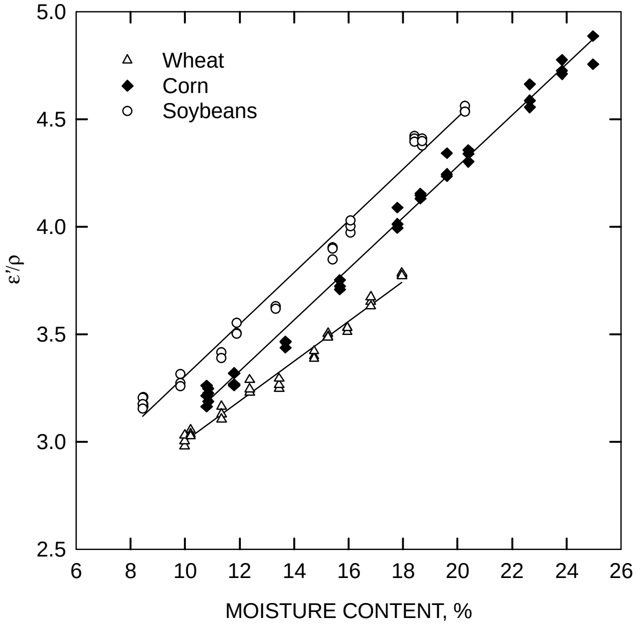

Figure 4. Dielectric constant divided by sample bulk density as a function of moisture content at 10 GHz and room temperature for wheat, corn, and soybeans.

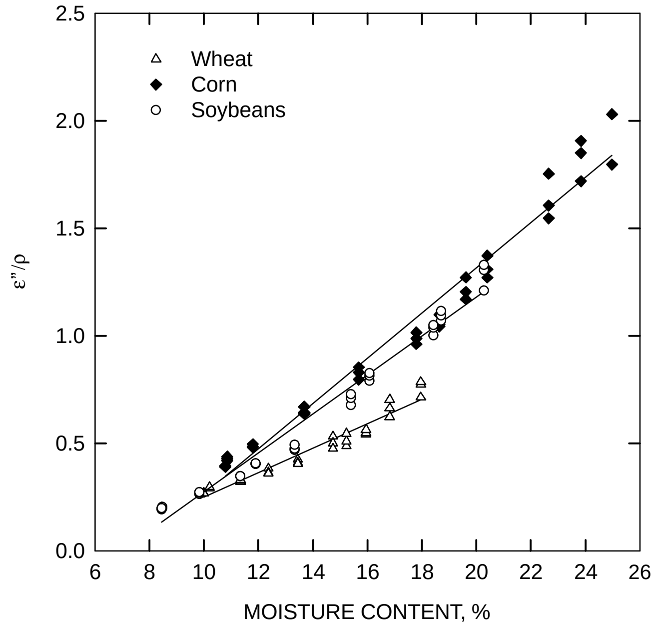

Figure 5. Dielectric loss factor divided by sample bulk density as a function of moisture content at 10 GHz and room temperature for wheat, corn, and soybeans.

$$\frac{\varepsilon''}{\rho} = c_2 M + d_2 \tag{16}$$

provide explicit relationships between the dielectric properties of wheat, corn, and soybeans and the bulk density and moisture content. Equations 15 and 16 allow the simultaneous determination of bulk density and moisture content from measurements of the dielectric properties at a single frequency and at a given temperature. Solving equations 15 and 16 for ρ and M:

$$\rho = \frac{c_2\varepsilon' - a_2\varepsilon''}{b_2 c_2 - a_2 d_2} \tag{17}$$

$$M = \frac{d_2\varepsilon' - b_2\varepsilon''}{a_2\varepsilon'' - c_2\varepsilon'} \tag{18}$$

Equations 17 and 18 are bulk density and moisture content calibration equations. It is also possible to determine calibration equations for the mass of water per unit volume (m_w/V) and the mass of dry matter per unit volume (m_d/V) from these equations and equations 1 and 2.

Table 4 gives the regression coefficients and the coefficients of determination corresponding to equations 15 to 18 as well as the *SEC* values for wheat, corn, and soybeans. For all three materials, correlations between the dielectric properties divided by bulk density and moisture content at a given frequency and a given temperature have high coefficients of determination. As observed in method 1, values of *SEC* for moisture content and bulk density determination of corn are higher than those of wheat and soybeans.

Bulk Density Determination

The complex−plane representation (Argand diagram) of the dielectric properties, also known as a Cole−Cole plot, is often used to analyze the behavior of dielectric materials (Hasted, 1973). In this article, the dielectric loss factor divided by bulk density is plotted against the dielectric constant divided by bulk density for samples of different moisture contents. Figure 6 shows Argand diagrams for wheat, corn, and soybeans. In this representation, at a given frequency, data collected for each material at different moisture contents are aligned along the same straight line (Trabelsi et al., 2000a, 1998b). The x−axis intercept for each material represents the dielectric properties divided by bulk density for a sample with zero moisture content or that corresponding to a sample of any moisture content at the “freezing” temperature of bound water. At this temperature, the mobility of the water molecule dipoles is almost zero, and thus the electromagnetic wave does not undergo appreciable attenuation. Hence, the dielectric loss factor is nearly zero. The intercept can be determined by extrapolation or by performing measurements on completely dry samples (Trabelsi et al., 1998b). It could also be determined by bringing the sample temperature down to bound−water “freezing” temperature.

For each material, a linear regression provides the following relationship between the dielectric properties and bulk density:

$$\frac{\varepsilon''}{\rho} = a_f\left(\frac{\varepsilon'}{\rho} - k\right) \tag{19}$$

Table 4. Regression statistics corresponding to equations 15 to 18 and the *SEC* for bulk density and moisture content determination for wheat, corn, and soybeans at 10.0 GHz for the physical conditions defined in table 1.

Statistics	Wheat	Corn	Soybeans
a_2	0.093	0.119	0.120
b_2	2.08	1.90	2.10
r^2	0.981	0.993	0.986
c_2	0.057	0.105	0.090
d_2	−0.322	−0.783	−0.631
r^2	0.947	0.972	0.976
SEC_ρ (g/cm^3)	0.017	0.034	0.016
SEC_M (%)	0.82	1.45	0.57

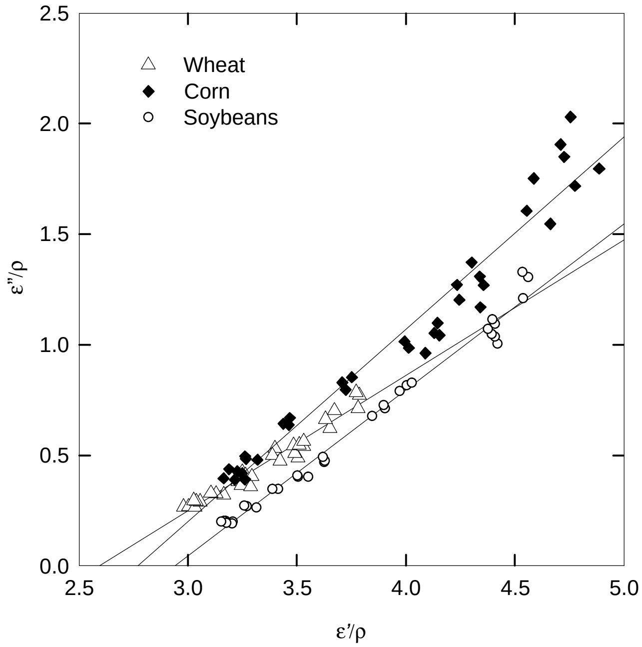

Figure 6. Complex−plane representation of complex permittivity divided by density for wheat, corn, and soybeans of different moisture contents at 10 GHz and room temperature for the physical conditions defined in table 1.

where a_f is the slope of the line, and k is the x−axis intercept. The value of a_f is dependent on frequency alone (Trabelsi et al., 1998b). At a given frequency, bulk density can be determined from measurement of the dielectric properties directly from equation 19 as follows:

$$\rho = \frac{a_f \varepsilon' - \varepsilon''}{k a_f} \tag{20}$$

Along with the bulk density calibration equations (eqs. 9 and 17), equation 20 constitutes the third possible way to determine bulk density of grain and seed from measurement of their dielectric properties. However, equation 20 has the advantage of providing the bulk density regardless of moisture content and temperature of the sample (Trabelsi et al., 1998b).

Table 5 gives the regression coefficients and the coefficients of determination corresponding to equation 20 and corresponding *SEC* values from calibration equations for wheat, corn, and soybeans. The *SEC* values are of the same order as those found with equations 9 and 17.

The values of x−axis intercepts found here by extrapolation do not match the intercepts at the origin from equation 15 with M set equal to zero. This might be related to a slope change at lower moisture levels in a plot of the type shown in figure 4, as was shown by measurements (Nelson and Stetson, 1976), or a rather quadratic variation of ε'/ρ with moisture content over a wider moisture range.

Table 5.Regression statistics corresponding to equations 19 and 20 and the *SEC* for bulk density determination for wheat, corn, and soybeans at 10.0 GHz for the physical conditions defined in table 1.

Statistics	Wheat	Corn	Soybeans
a_f	0.613	0.870	0.751
k	2.596	2.774	2.942
r^2	0.958	0.955	0.987
SEC_ρ (g/cm^3)	0.017	0.035	0.015

Density−Independent Moisture Content Determination

For decades, moisture content determination in granular and other materials from measurement of their dielectric properties at microwave frequencies has been the focus of several studies (Jacobsen et al., 1980; Kent and Kress−Rogers, 1986; Kraszewski, 1996; Kraszewski and Kulinski, 1976; Menke and Knochel, 1996; Meyer and Schilz, 1981; Nyfors and Vainikainen, 1989; Trabelsi et al., 2000a, 1998b, 1999, 2001). The main advantages of such techniques are their nondestructive nature and their suitability for on−line real−time sensing of moisture content. However, although water governs the dielectric response of substances containing water, two major limitations in defining a unique relationship between the dielectric properties and moisture content hindered the anticipated widespread use of these techniques. The first limitation relates to bulk density changes for granular materials, which have an effect similar to that of moisture content on ε' and ε''. The second limitation relates to the need of an individual moisture calibration equation for each material. Figures 4 and 5 illustrate this fact. Both of these limitations complicate the design, cost, and maintenance of a microwave moisture sensor based on the principle of dielectric properties measurement. The first density−independent moisture calibration function expressed in terms of the dielectric properties was introduced in the early 1980s (Jacobsen et al., 1980). It is based on the attenuation−to−phase shift ratio, which was introduced earlier by Kraszewski and Kulinski (1976). This function is defined as:

$$\psi_2 = \frac{\varepsilon''}{\varepsilon' - 1} \tag{21}$$

Figure 7 shows that for each material, ψ_2 increases linearly with moisture content. Therefore, data for each material can be fitted with a regression equation of the form:

$$\psi_2 = a_{2,m} M + b_{2,m} \tag{22}$$

Regression coefficients and coefficients of determination are given in table 6. A moisture calibration equation is obtained by solving equation 22 for M:

$$M = \frac{\psi_2 - b_{2,m}}{a_{2,m}} \tag{23}$$

Values of the *SEC* for moisture prediction with calibration equation 23 are given in table 6. The *SEC* values are smaller than those obtained when moisture is predicted from equation 18.

In recent years, a permittivity−based method for moisture determination in granular materials, independent of bulk density changes and independent of the material, was proposed (Trabelsi et al., 1998a, 1998b, 1999, 2000a). This method allows moisture determination in grain and seed of different geometry, size, and composition from a single moisture calibration equation, hence alleviating the two limitations mentioned above.

The universal permittivity−based calibration function is expressed in terms of ε' and ε'' as follows (Trabelsi et al., 1998b):

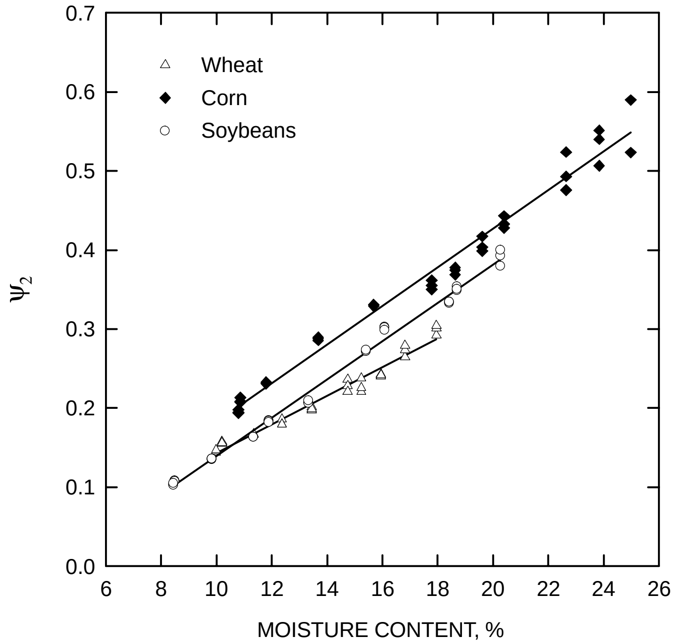

Figure 7. Variation of density−independent calibration function ψ_2 with moisture content in wheat, corn, and soybeans at 10 GHz and room temperature.

Table 6. Regression statistics corresponding to equations 23 and the *SEC* in moisture content determination for wheat, corn, and soybeans at 10.0 GHz for the physical conditions defined in table 1.

Statistics	Wheat	Corn	Soybeans
$a_{2,m}$	0.018	0.024	0.024
$b_{2,m}$	−0.037	−0.061	−0.103
r^2	0.970	0.980	0.994
SEC_M (%)	0.47	0.69	0.33

$$\psi_3 = \sqrt{\frac{\varepsilon''}{\varepsilon'\left(a_f\varepsilon' - \varepsilon''\right)}} \tag{24}$$

Figure 8 shows variation of ψ_3 with moisture content for wheat, corn, and soybeans at 10.0 GHz and room temperature.

For each material, a linear relationship exists between ψ and moisture content, which analytically can be expressed as:

$$\psi_3 = a_{3,m}M + b_{3,m} \tag{25}$$

Table 7 gives the regression coefficients and the coefficients of determination corresponding to equation 25 and the *SEC* values for wheat, corn, and soybeans at 10.0 GHz.

The fact that the data points for all three materials are almost superimposed makes it possible to use a single regression equation. This equation is referred to as a unified or universal calibration equation, since it represents a unique

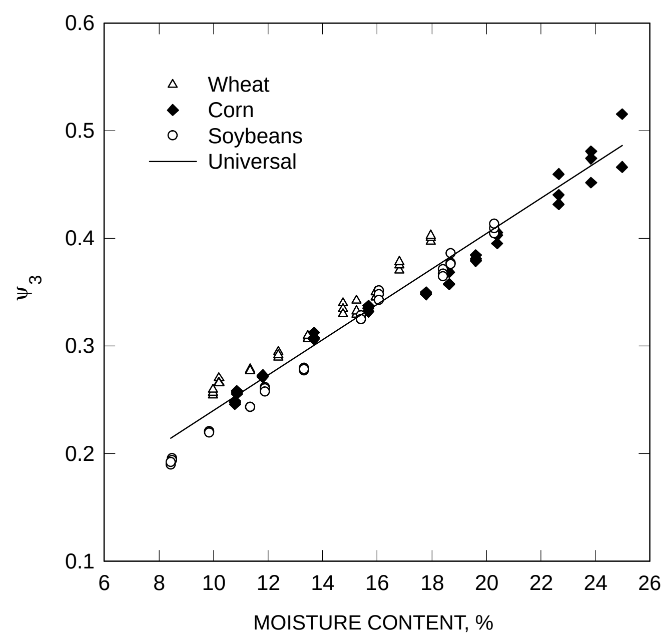

Figure 8. Variation of universal calibration function ψ_3 with moisture content in wheat, corn, and soybeans at 10 GHz and room temperature.

Table 7. Regression statistics corresponding to equation 25 and the *SEC* in moisture content determination for wheat, corn, and soybeans at 10.0 GHz for the physical conditions defined in table 1.

Statistics	Wheat	Corn	Soybeans	Universal
$a_{3,m}$	0.017	0.016	0.018	0.016
$b_{3,m}$	0.087	0.079	0.040	0.075
r^2	0.976	0.974	0.993	0.955
SEC_M (%)	0.42	0.79	0.35	0.93

relationship between ψ and *M* for materials of significant structural and compositional differences. From this equation, a single moisture content calibration equation can be generated:

$$M = \frac{\psi_3 - b_{3,m}}{a_{3,m}} \tag{26}$$

Equation 26 allows moisture prediction with an SEC_M of 0.93% for all three materials. Therefore, it constitutes an important step in universal moisture sensing in grain and seed and provides an incentive for building a new generation of cost−effective microwave moisture sensors.

DISCUSSION AND CONCLUSIONS

The two calibration methods for materials with significant structural and compositional differences that were reviewed and compared in this article constitute the basis for developing calibration algorithms for nondestructive, real−time sensing of bulk density and moisture content of grain and seed with a single−frequency microwave sensor. They can be used in combination or separately, depending on the application type and desired level of accuracy.

Calibration method 1 has the advantage of using directly measured microwave parameters (attenuation and phase shift) but has the shortcoming of being instrument−related. Calibration method 2 depends on the dielectric properties and thus can be used regardless of the measurement technique (reflection−, transmission−, or cavity−based sensor).

Statistical analysis shows high coefficients of determination for the correlations between measured microwave parameters and bulk density and moisture content in grain and seed for both calibration methods. For both calibration methods, values of *SEC* for bulk density and moisture content determination in corn are higher than those of wheat and soybeans. Based on the *SEC* values, performance of both calibration methods for bulk density prediction is equivalent. For moisture content determination, density−independent calibration functions performed better than direct correlations between moisture content and attenuation and phase shift or between moisture content and the dielectric properties. Moisture calibration functions ψ_1 and ψ_2 require individual calibration equations for each material. In contrast, ψ_3 offers the promise of a universal moisture calibration that remains valid across instruments of different designs for materials of different structure and composition.

Calibration method 2 seems to combine the features expected in a cost−effective microwave sensor: bulk density can be determined without the knowledge of moisture content or temperature, and moisture content can be determined independent of bulk density from a single universal calibration equation.

Both calibration methods are based on measurements at a single microwave frequency, which simplifies considerably the design of the sensor and allows stable calibration for better repeatability of the measurements. The accuracy with which bulk density and moisture content can be determined is dependent on the accuracy with which attenuation and phase shift can be measured, the validity of the equations used to compute the dielectric properties, and to some extent on the accuracy of the standard techniques for moisture content and bulk density determination.

Although a vector network analyzer was used here, in principle, these calibration methods can be utilized in a microwave sensor comprising a single−frequency microwave source, a pair of inexpensive antennas (microstrip antennas), a detector, and a microprocessor. With the advent of microwave components of small size and reduced price, the cost of such a sensor would be a small fraction of the cost of the measurement system used in this study.

The principles of a multiparameter microwave sensor presented here for grain and seed can be applied to other granular and particulate materials.

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