SIMPLE GRAIN MOISTURE CONTENT DETERMINATION FROM MICROWAVE MEASUREMENTS

A. W. Kraszewski, S. Trabelsi, S. O. Nelson

ABSTRACT. *Moisture content of wheat,* Triticum aestivum *L., is expressed as a function of the ratio of microwave attenuation and phase shift, measured at 16.8 GHz, and grain temperature. Validation of the calibration equation indicated that moisture content was obtained with an uncertainty less than ±0.45% moisture at the 95% confidence level, independent of density variation, at temperatures from –1°C to 42°C, and moisture contents from 10% to 19%. Moisture determination does not depend on the layer thickness of the wheat nor its bulk density. No differences between two wheat cultivars were observed in the measurement data.* ***Keywords.*** *Moisture measurement, Microwave techniques, Wheat.*

Moisture content is one of the most important factors determining grain quality during harvesting, storage, trading, processing, and transportation. The moisture content, M, (%, wet basis) is defined as:

$$M = \frac{m_w}{m_w + m_d} \times 100 \quad (1)$$

where m_w = mass of water, and m_d = mass of dry material. For a given volume of material, v, equation 1 may be rewritten in the following form:

$$\frac{M}{100} = \frac{\frac{m_w}{v}}{\frac{m_w}{v} + \frac{m_d}{v}} = \frac{k}{\rho} \quad (2)$$

where k is the water concentration in mass per unit volume, and ρ is the bulk density of the moist material.

Standard methods for moisture content determination by oven drying are based on the definition equation 1, and require knowledge of both components, m_w and m_d. The oven drying procedure is time consuming, and results are obtained for several samples of 2 to 10 g each. For large quantities of grain of nonuniform moisture distribution which are often found in elevators, ships, or mill storage, sampling and moisture content testing is a routine operation, most often performed manually. By necessity, for practical purposes, indirect electrical moisture content measurement methods have been developed that are based on correlations between electrical properties of grain and its moisture content (Nelson, 1977, 1991). Early efforts began with dc measurement of grain resistivity, and radio-frequency dielectric type moisture testers have been highly developed since then. Use of microwave measurements for moisture content determination has been considered for some time, and these efforts were summarized previously (Kraszewski, 1988; Nelson and Kraszewski, 1990; Kraszewski, 1991). The influence of ionic conductivity on the dielectric properties of grain can largely be avoided by measurements at microwave frequencies. Thus potential problems with variation in ionic conductivity among lots from different sources that may occur at lower frequencies should cause little trouble for microwave moisture determination. Also, physical contact between the microwave equipment and the material under test is not required, which makes on-line, nondestructive, rapid moisture measurement possible. Results of recent studies on microwave measurements for determination of moisture content in hard red winter wheat are reported in this article.

PHYSICAL PRINCIPLES

It is evident from equation 2 that, even if the water concentration in the material is determined from electrical measurement, the determination of moisture content requires the bulk density of the wet material, ρ, to be known, and that any variations in the density will produce results similar to changes in the water content. Various ways of limiting the density effect in grain moisture content measurements were discussed previously (Kraszewski, 1988). Methods include mechanical density stabilizing means and independent density determination, but a more effective solution is the use of a *density-independent function*, i.e., a relationship between electrical properties of grain and its moisture content that eliminates or limits the effect of density variations.

A simple block diagram of a microwave measuring arrangement is shown in figure 1. According to previous reports (Kraszewski et al., 1977; Powell et al., 1988; King et al., 1992), the most descriptive parameter for the material in free space is its *complex transmission coefficient*, given as $\tau = |\tau| \exp j\phi$, where ϕ is the phase

Article was submitted for publication in January 1997; reviewed and approved for publication by the Food & Process Engineering Inst. of ASAE in October 1997.

The authors are **Andrzej W. Kraszewski,** Research Electronics Engineer, **Samir Trabelsi,** Visiting Scientist, and **Stuart O. Nelson,** ***ASAE Fellow Engineer,*** Research Agricultural Engineer, USDA-ARS, Russell Research Center, Athens Ga. **Corresponding author:** Stuart O. Nelson, USDA ARS, Russell Research Center, PO Box 5677, Athens, GA 30604; tel: (706) 546-3101; fax: (706) 546-3607; e-mail sonelson@bae.uga.edu.

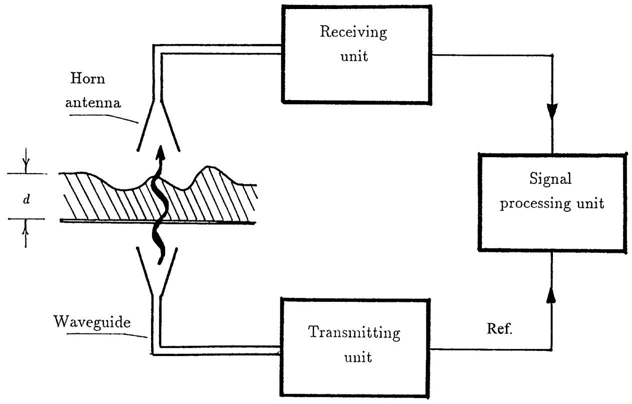

Figure 1–Experimental setup for microwave variables measurement.

delay. The practical measure of the change in wave magnitude is called an insertion loss or attenuation and is given as:

$$A = -20 \log|\tau| = -10 \log \frac{P_{out}}{P_{in}} \quad \text{(dB)}$$

where P_{out} and P_{in} are microwave power levels measured at the output and the input of the respective antennas. Phase delay may be expressed in radians or degrees, and is usually defined as:

$$\phi = -\arg \tau + n\,360° \quad (°)$$

where n is an integer. The phase delay ambiguity (finding a proper value of n) can be removed by repeating the measurements for grain samples of different thickness. Some experimental results for hard red winter wheat measured at 16.8 GHz are shown in figures 2 and 3. It has been noted previously (Kraszewski et al., 1977; Kress-Rogers and Kent, 1987) that both the attenuation and the phase shift are distinct functions of the grain moisture content, density, temperature, and layer thickness. The analytical expressions for the parameters of an electromagnetic wave, assuming that a linearly polarized

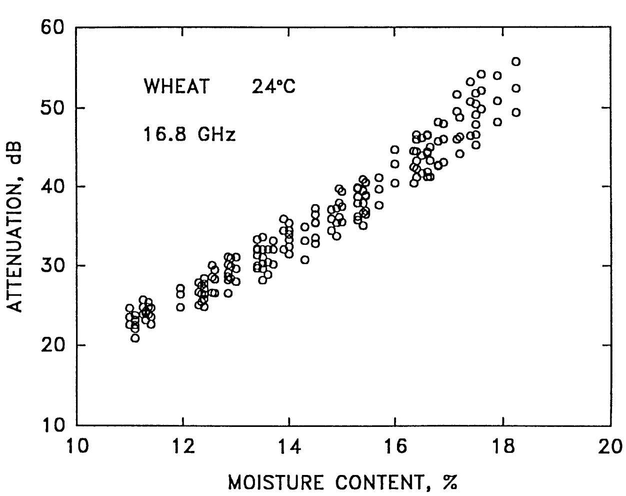

Figure 2–Attenuation of a layer of wheat (d = 10.4 cm) at 24°C as a function of moisture content for varying density.

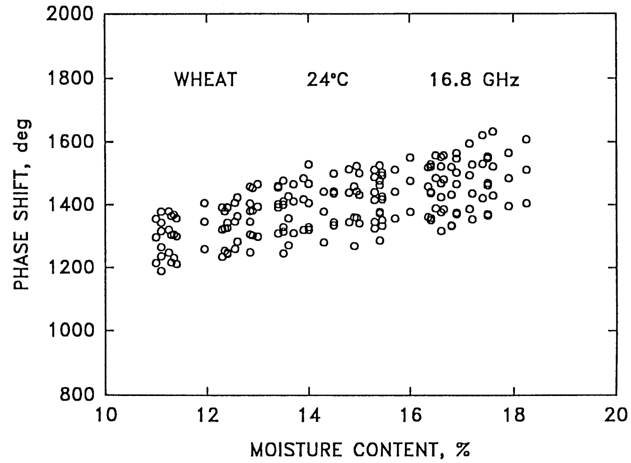

Figure 3–Phase shift of a layer of wheat (d = 10.4 cm) at 24°C as a function of moisture content for varying density.

plane wave is normally incident on the flat surface of a homogeneous layer of material and that the planar sample is of infinite extent laterally so diffraction effects at the edges can be neglected, can be written as:

$$A \cong 8.686\,\pi \frac{d}{\lambda_0} \frac{\varepsilon''}{\sqrt{\varepsilon'}} \quad \text{(dB)} \qquad (3)$$

$$\phi \cong 360 \frac{d}{\lambda_0} \left(\sqrt{\varepsilon'} - 1\right) \quad (°) \qquad (4)$$

where $\varepsilon = \varepsilon' - j\varepsilon''$ is the material relative permittivity, with ε' being the dielectric constant and ε'' the loss factor of the material, d is the layer thickness, and λ_0 is the free-space wavelength. Approximations in equations 3 and 4 are valid for $\varepsilon'^2 >> \varepsilon''^2$ (Kraszewski, 1996), which is true for most cereal grains. The material permittivity, ε, is a function of its moisture content, density and temperature (Kraszewski et al., 1996).

Different combinations of the components of the material permittivity have been proposed as density-independent functions (Kraszewski and Kulinski, 1976; Kraszewski et al., 1977; Jacobsen et al., 1980; Meyer and Schilz, 1981; Kent and Kress-Rogers, 1986; Powell et al., 1988; Kraszewski and Nelson, 1992; McLendon et al., 1993; Trabelsi et al., 1997). Most often, however, a simple ratio of the two measured quantities, equations 3 and 4, was found to be a well-defined function of moisture content, which was, to a great extent, independent of the material density, at least in the range of practical interest (Kress-Rogers and Kent, 1987; Kraszewski and Nelson, 1991). The ratio of these two quantities may be expressed as:

$$R = \frac{A}{\phi} = c \frac{\varepsilon''}{\varepsilon' - \sqrt{\varepsilon'}} = c \tan\delta \left(\frac{\sqrt{\varepsilon'}}{\sqrt{\varepsilon'} - 1}\right) = c\eta \tan\delta \qquad (5)$$

where $\tan\delta = \varepsilon''/\varepsilon'$ is the tangent of the loss angle, and c is a constant numerical coefficient, c = 0.0758. In the study of equation 5, the permittivity data for wheat (Kraszewski et al.,

1996) were used for computation of the loss tangent and the permittivity function $\eta = \sqrt{\varepsilon'} / (\sqrt{\varepsilon'} - 1)$. These quantities, tan δ and cη, are shown as a function of moisture content in figure 4. Comparison of the ratio R as a function of moisture content and tan δ, shown in figure 5, where R is expanded four times to provide better comparison, indicates that R has less pronounced dependence upon the material density than tan δ. This observation indicates the importance of the permittivity function, η, in equation 5. Results of new measurements on wheat and the usefulness of the ratio R in determining moisture content of wheat at different temperatures are reported in this article.

Materials and Methods

Two cultivars of hard red winter wheat, *Triticum aestivum* L., 'Karl' and 'Arapahoe', grown in Nebraska in 1992 and 1994, respectively, were used for measurements. Sample moisture content ranged from about 10% to 19%, wet basis. A sample holder of rectangular cross-section providing a sample thickness of 10.4 cm, was filled with grain and located between two horn antennas, and the two microwave parameters were measured as described elsewhere (Kraszewski et al., 1996). The frequency of 16.8 GHz was chosen as being one of the frequencies at which performance of the horn antennas is best (low standing wave ratio). Starting from a loosely filled sample holder, the measurement of attenuation and phase shift were repeated for samples of gradually increased density. To study the temperature effect on the measured quantities, samples were conditioned in a chamber at five different temperatures, –1, 9, 17, 34, and 42°C. Samples of various moisture content levels were allowed to stabilize for three days at each temperature. The temperature at different locations inside the sample was measured before and after the microwave measurements. In all instances, the temperature remained constant during the measurements, which typically lasted less than one minute. Moisture content of each sample was determined by a standard oven method (ASAE, 1996) just after the microwave measurements were finished. This standard specifies drying unground 10 g samples of wheat for 19 h at 130°C. Altogether, 373 data points for the two wheat cultivars were collected during the study.

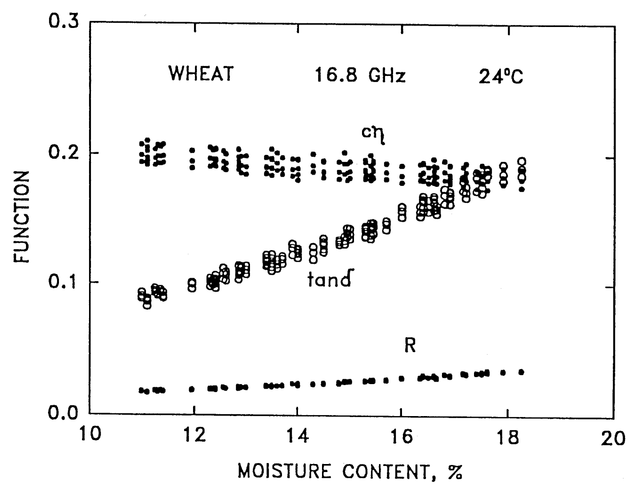

Figure 4–Loss tangent, function η, and ratio R for wheat at 24°C as a function of moisture content for varying density.

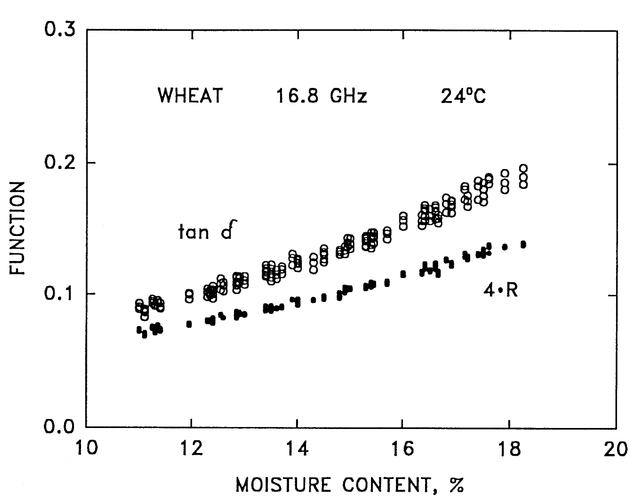

Figure 5–Loss tangent and expanded values of ratio R from figure 4.

Experimental Results

Experimental results obtained for the two wheat cultivars at room temperature (24 ±1°C) are shown in figures 2 and 3. The attenuation and phase shift as a function of moisture content for wheat at three different temperatures are shown in figure 6 and 7, respectively. No differences between the measured data for the two wheat cultivars were observed in careful comparisons. The ratio R of these two quantities for the same conditions is shown in figure 8.

To develop the calibration equation for moisture content determination from the measured microwave parameters, the whole set of experimental data containing points for all moisture contents from 10% to 19%, and for all temperatures from –1 to 42°C, was divided into two subsets, a calibration set (186 even points) and a validation set (187 odd points). The ratio R was calculated for the calibration set and the regression analysis was performed to find expressions best fitting the experimental data. The following was the best linear relation for R as a function of moisture content M and temperature T:

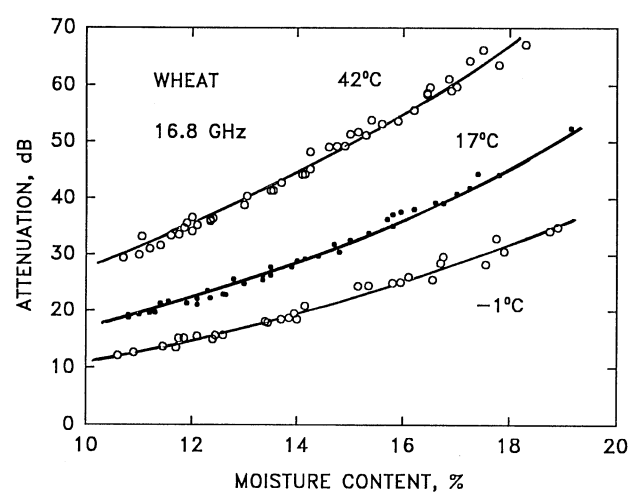

Figure 6–Attenuation of wheat at three different temperatures as a function of moisture content for varying density.

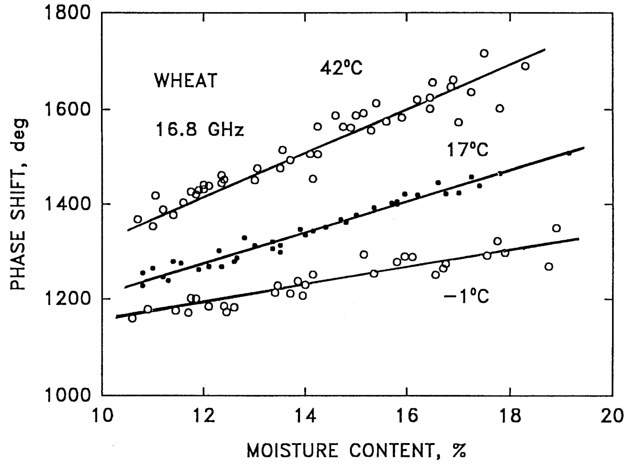

Figure 7–Phase shift of wheat at three different temperatures as a function of moisture content for varying density.

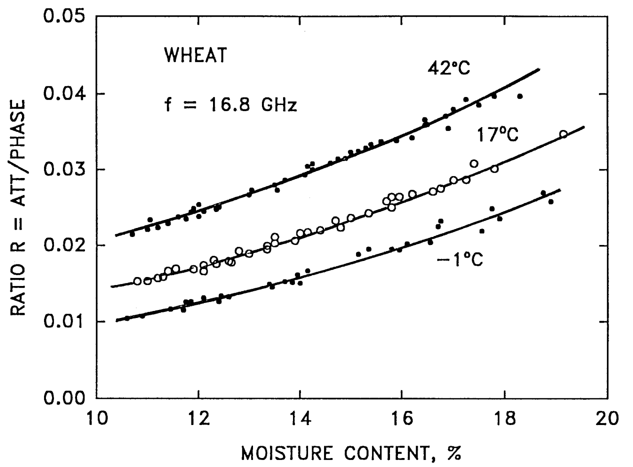

Figure 8–Ratio R for wheat at three different temperatures as a function of moisture content for varying density.

$$R = 0.0021M + 0.00001185MT + 0.000144T - 0.01277$$

$$\text{with } r = 0.9943$$

where r is the correlation coefficient. For a quadratic equation of very similar statistical significance,

$$R = 0.000071M^2 + 0.0000137MT + 0.0001177T$$

$$+ 0.002446 \text{ with } r = 0.9960$$

To avoid truncation errors, both sides of the two equations were multiplied by 10^3. The following two respective calibration equations were obtained:

$$M = \frac{(10^3 R + 12.768) - 0.1438T}{0.01185T + 2.1003} \quad (6)$$

and

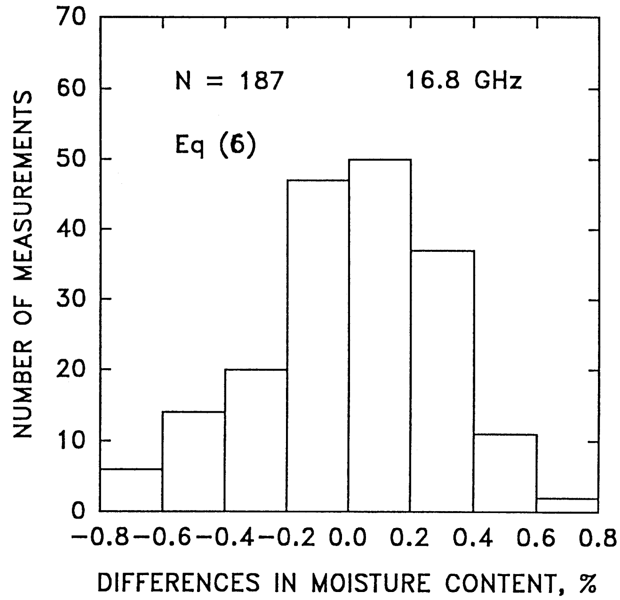

Figure 9–Distribution of differences between oven moisture content determination and moisture content calculated for two cultivars of wheat from equation 6.

$$M = \frac{\sqrt{283.76R + 0.00019T^2 - 0.0334T - 0.6941}}{0.1419} - 0.0964T \quad (7)$$

where M is in percent and T is in °C.

Validity of the calibration equations 6 and 7 was checked with the validation set of 187 data points used to predict moisture content. These values were compared with oven moisture determinations. The histogram presented in figure 9 shows the distribution of differences between oven moisture content determination and moisture content calculated from equation 6. The mean value of differences (bias) was 0.006% moisture, while the standard deviation of differences (standard error of performance, SEP) was 0.285% moisture. The bias and SEP for the data from the quadratic equation 7, shown in figure 10, were 0.01% and 0.239%, respectively.

Repeatability and Uncertainty

Repeatability of the measurement system was checked experimentally by remeasuring two samples of wheat 12 times each. The results of the measurements are listed in table 1. The repeatability of phase shift measurement does not depend upon the wave magnitude, while that of attenuation measurement is related to the wave magnitude. The uncertainties specified for the type of the instrument used in this study are as follows: uncertainty in attenuation measurement $\Delta A = 0.06$ dB for $A < 10$ dB, $\Delta A = 0.07$ dB for $A \leq 20$ dB and $\Delta A = 0.1$ dB for $A \leq 45$ dB; phase shift $\Delta\phi = \pm 3°$ for the whole range, $-180° \leq \phi \leq 180°$. Those numbers translated into moisture content through the calibration equations 6 or 7 provide repeatability better than ±0.015% for M≅12% and ±0.1% for M≅18.5%, at the 95% confidence level. Those values are also listed in table 1, together with the values of $R = A/\phi$. One should keep in mind that the average spread of moisture content in triplicate samples determined by the standard oven method was 0.176% moisture with a standard deviation of ±0.077% moisture.

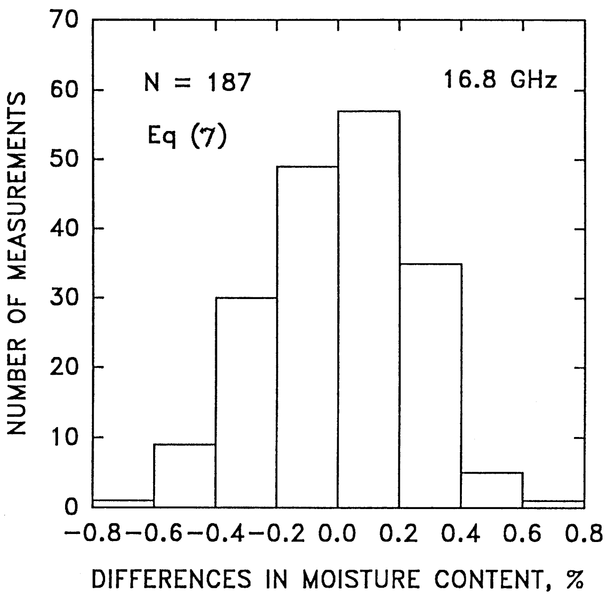

Figure 10–Distribution of differences between oven moisture content determination and moisture content calculated for two wheat cultivars from equation 7.

Table 1. Repeatability of measurements for two wheat samples

	Atten. (dB)	Phase (°)	R × 10^3	M (from eq. 6)	M (from eq. 7)
(a) M = 11.8%; T = 24°C; d = 10.4 cm; f = 16.8 GHz					
	26.552	1369.1	19.394	12.039	11.985
	26.537	1370.3	19.366	12.028	11.972
	26.588	1371.0	19.393	12.039	11.985
	26.578	1371.5	19.379	12.033	11.978
	26.571	1371.5	19.373	12.031	11.975
	26.557	1371.2	19.368	12.028	11.973
	26.582	1372.0	19.375	12.032	11.976
	26.620	1372.5	19.395	12.040	11.986
	26.617	1372.6	19.392	12.039	11.984
	26.582	1373.5	19.353	12.022	11.965
	26.614	1373.9	19.371	12.030	11.974
	26.607	1374.0	19.365	12.027	11.971
Mean:	26.584	1371.9	19.377	12.032	11.977
St.d.:	± 0.027	± 1.5	± 0.014	± 0.006	± 0.007
(b) M = 18.5%; T = 24°C; d = 10.4 cm; f = 16.8 GHz					
	56.224	1592.9	35.296	18.708	18.388
	56.068	1590.3	35.256	18.691	18.374
	56.451	1594.2	35.410	18.756	18.427
	56.082	1591.2	35.245	18.686	18.371
	55.817	1593.5	35.028	18.595	18.297
	56.034	1591.8	35.202	18.668	18.356
	56.232	1589.6	35.375	18.741	18.415
	56.451	1592.6	35.446	18.771	18.439
	56.324	1592.7	35.364	18.736	18.411
	56.373	1593.3	35.381	18.743	18.417
	55.946	1593.5	35.109	18.629	18.324
	56.137	1594.3	35.211	18.672	18.359
Mean:	56.178	1592.5	35.277	18.700	18.381
St.d.:	± 0.20	± 1.5	± 0.127	± 0.053	± 0.043

Discussion and Conclusions

The presented method of moisture content determination in grain is based on simultaneous measurements of two parameters of the electromagnetic wave transmitted through the layer of material. These parameters, attenuation (decrease of the wave amplitude), and phase shift (the phase delay in the material), are directly related to the dielectric properties of the material, its complex permittivity ε. Both components of the permittivity, dielectric constant and loss factor, depend upon the material density (proportions of air and material) and its moisture content (proportions of water and dry material). It was observed empirically for a great number of moist materials and agricultural and food products, including grain, that the ratio of attenuation and phase shift, which both depend on the dielectric properties, provides a density-independent function R, as expressed in equation 5. Since A and ϕ both depend on material layer thickness and density in the same way, their ratio does not depend upon the layer thickness nor the density of the moist material. Taking into account that R can be related in a unique way to the material moisture content and temperature, as expressed in equation 6 or 7, one can conclude that R is a convenient parameter for use in measuring moisture content.

The operating frequency chosen for this study is higher than usually considered for moisture measurement (Kraszewski, 1996). The rationale for this is that at higher frequency the equipment can be smaller and the material layer thickness can be thinner than required at lower frequencies. It can provide better sensitivity to moisture variation along the layer of material. However, this technique is by no means limited to the frequency reported in this article. It can be applied for much lower frequencies, as long as the ionic conductivity of the material is not a factor (usually below 1-2 GHz).

Use of equation 5 is limited to the practical range of variables included and may be less effective for very dry material, when decreasing slope of the relationship $R = \Phi(M)$, as in figure 8, results in decreased accuracy of moisture determination. It may also be less accurate for very moist materials for which uncertainty in attenuation measurement may be greater. Although this approach does not provide the bulk density of grain it can be determined from microwave measurements by other approaches (Kraszewski and Nelson, 1992).

However, with a simple equation, 6 or 7, moisture content of hard red winter wheat was determined with an uncertainty less than 0.5% moisture, at the 95% confidence level, in the moisture range from 10% to 19% at grain temperatures between –1°C and 42°C. It can be observed from figures 9 and 10 that the errors have a normal distribution, which means that they are of random character, and they can be attributed to uncertainties in measurement of the variables, attenuation, phase shift and temperature. The advantage of the measurement configuration shown in figure 1 is that it can be easily adapted for dynamic on-line measurement by providing flow of the material between the antennas. As contact between the measuring equipment and the material is not required during the measurement of the microwave parameters, this may be a convenient, fast, accurate and nondestructive way of moisture content determination in flowing material. It may also be useful for many materials other than grain, such as powdered, granulated, or semiliquid materials.

References

ASAE Standards, 43rd Ed. 1996. S352.2. Moisture measurement—Unground grain and seeds. St. Joseph, Mich.: ASAE.

Jacobsen, R., W. Meyer, and B. Schrage. 1980. Density-independent moisture meter at X-band. In *Proc. 10th European Microwave Conf.*, 216-220, Warsaw, Poland. Seven Oaks, Kent, England: Microwave Exhibitions and Publishers Ltd.

Kent, M., and E. Kress-Rogers. 1986. Microwave moisture and density measurements in particulate materials. *Trans. Inst. M.C.* 8(3):161-168.

King, R. J., K. V. King, and K. Woo. 1992. Microwave moisture measurement of grain. *IEEE Trans. Instrum. Meas.* 41(1):111-115.

Kraszewski, A. 1988. Microwave monitoring of moisture content in grain—Further considerations. *J. Microwave Power* 23(4): 236-246.

________. 1991 Microwave aquametry—Needs and perspectives. *IEEE Trans. Microwave Theory Techn.* 39(5):828-835.

Kraszewski, A., ed. 1996. *Microwave Aquametry*. Piscataway, N.J.: IEEE Press.

Kraszewski, A., and S. Kulinski. 1976. An improved microwave method of moisture content measurement and control. *IEEE Trans. Industr. Electronics and Control Instrum.* IECI-23(4): 364-370.

Kraszewski, A., S. Kulinski, and Z. Stosio. 1977. A preliminary study on microwave monitoring of moisture content in wheat. *J. Microwave Power* 12(3):241-251.

Kraszewski, A., and S. O. Nelson. 1991. Density-independent moisture determination of wheat by microwave measurement. *Transactions of the ASAE* 34(4):1776-1783.

Kraszewski, A., and S. O. Nelson. 1992. Wheat moisture content and bulk density determination by microwave parameters measurement. *Can. Agric. Eng.* 34(4):327-335.

Kraszewski, A. W., S. Trabelsi, and S. O. Nelson. 1996. Wheat permittivity measurements in free space. *J. Microwave Power & Electromag. Energy* 31(3):135-141.

Kress-Rogers, E., and M. Kent. 1987. Microwave measurement of powder moisture and density. *J. Food Eng.* 6:345-376.

McLendon, B. D., B. G. Branch, S. A. Thompson, A. Kraszewski, and S. O. Nelson. 1993. Density-independent microwave measurement of moisture content in static and flowing grain. *Transactions of the ASAE* 36(3):827-835.

Meyer, W., and W. Schilz. 1981. Feasibility study of density-independent moisture measurement with microwaves. *IEEE Trans. Microwave Theory Techn.* 29(7):732-739.

Nelson, S. O. 1977. Use of electrical properties for grain moisture measurement. *J. Microwave Power* 12(1):67-72.

________. 1991. Dielectric properties of agricultural products—Measurements and applications. *IEEE Trans. Electr. Insul.* 26(5):845-869.

Nelson, S. O., and A. Kraszewski. 1990. Grain moisture content determination by microwave measurements. *Transactions of the ASAE* 33(4):1303-1307.

Powell, S. D., B. D. McLendon, S. O. Nelson, A. Kraszewski, and J. M. Allison. 1988. Use of a density-independent function and microwave measurement system for grain moisture measurement. *Transactions of the ASAE* 31(6):1875-1881.

Trabelsi, S., A. W. Kraszewski, and S. O. Nelson. 1997. Simultaneous determination of density and water content of particulate materials by microwave sensors. *Electronics Letters* 33(10):874-876.