Abstract. Dielectric properties of wheat samples, in which moisture equilibrium was upset by adding water, were tracked versus time in the frequency range between 5 GHz and 15 GHz at room temperature (23 °C). Results presented at 10 GHz show an initial drop in the dielectric constant and loss factor, which reflects the initial stages of water binding, followed by a plateau indicating the final binding level of the water molecules in the wheat kernels. With application of a density-independent calibration algorithm, the apparent moisture content was predicted in each sample from measurement of the dielectric properties. As expected, for each wheat sample, the predicted initial moisture content was higher than the reference oven moisture content and decreased as time increased. This study shows that dielectric-based moisture sensors require correction when used for sensing moisture content in nonequilibrated materials.

Keywords. Moisture content, microwaves, dielectric properties, dielectric constant, loss factor, water binding.
Introduction
Water is an important component of most natural and man-made materials. Understanding water behavior is fundamental in improving and preserving the quality of many of these materials. In particular, it has impact on developing reliable indirect sensing methods for real-time quality control. In the food and agricultural industries, dielectric-based moisture sensors are the most popular example that illustrates such methods. Microwave moisture sensors are based on a phenomenon called orientational dipolar polarization of water molecules (Hasted, 1973). In some instances, such as drying and moistening processes, water is in nonequilibrium status and may be in transient binding modes. As a result, the reading of microwave moisture sensors (Kraszewski, 1996) used to monitor water content in real time in such processes is inaccurate. The main objectives of this study are to investigate experimentally the dielectric behavior of water as it is binding to wheat kernels and to determine the scale of related errors when microwave moisture sensors are used.

There are different degrees of binding, and each water molecule may have up to three bonds (ice), depending on the structure and composition of the material and the amount of water available. One way to examine variations in water binding is to measure the dielectric properties of a system in which equilibrium moisture distribution is upset by adding water (Sokhansanj and Nelson, 1988; Trabelsi and Nelson, 2005). In this study, changes of microwave dielectric properties with time were tracked for wheat samples in which equilibrium moisture content was suddenly increased to different moisture levels. Variations of the dielectric properties with time are shown for three moisture levels at 10 GHz and 23 °C. Similarly, variations of the apparent moisture content in each nonequilibrated wheat sample predicted with a density-independent calibration algorithm (Trabelsi et al., 1998; Trabelsi and Nelson, 2004; Trabelsi and Nelson, 2006) are presented. For each moisture level, an estimate of error related to the nonequilibrium status is given.

Materials and Methods
The experiment consists of adding water to a wheat sample of known moisture content and tracking dielectric properties changes with time at room temperature (23 °C) over the frequency range from 5 to 15 GHz. The wheat sample used in this study was ‘Arapahoe’ hard red winter wheat grown in Nebraska in 1994 and stored at 4 °C and 40% r.h., with an initial equilibrium moisture content of 10.6%, wet basis. In the first measurement series, distilled water was added to a 7-kg wheat sample contained in a plastic bag to increase its moisture content to about 14%. Water was added by spraying the wheat kernels and mixing throughout the sample to distribute the water evenly. Once the mixing was completed, the wheat kernels were poured into a Styrofoam\(^1\) container, which was placed between two horn/lens antennas for free space microwave dielectric measurements with a Hewlett Packard 8510C vector network analyzer (Trabelsi and Nelson, 2003). To track changes in the dielectric properties with time as water was binding with molecules of wheat kernels, measurements were taken every 5 min for about 90 min and then every 15 min for a total time span of 6 hours. The same procedure was repeated when the initial moisture content of the wheat sample was increased from 10.6% (wet basis) to about 17% and 22%, respectively. After each measurement series, three samples of 30 g each were taken out for oven moisture testing (ASAE, 2000). The oven moisture contents were 14.4%, 17.5%, and 22.7%.

\(^1\) Mention of company or trade names is for purpose of description only and does not imply endorsement by the U.S. Department of Agriculture.
The dielectric properties are 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 the electric-field energy, and the imaginary part, $\varepsilon''$, or dielectric loss factor, reflects the ability of a material to dissipate electric energy in the form of heat. At microwave frequencies, the effect of ionic conductivity is negligible, and thus all losses are attributed to water molecule rotation.

Here, the dielectric properties were determined from measurements of the modulus and phase of the scattering transmission coefficient $S_{21}$. Figure 1 shows the measurement setup. Detailed measurement procedures can be found in a previous publication (Trabelsi and Nelson, 2003).

![Diagram of measurement setup.](image)

Assuming that a plane wave is traversing a layer of low-loss material, the dielectric properties, $\varepsilon'$ and $\varepsilon''$, are calculated from the modulus, $|S_{21}|$, and phase, $\varphi$, of scattering complex transmission coefficient $S_{21}$ as follows:

$$
\varepsilon' = \left[1 - \frac{(\varphi - 360n)c}{360df}\right]^2
$$

$$
\varepsilon'' = \frac{-20\log|S_{21}|c}{8.686\pi df} \sqrt{\varepsilon'}
$$

where $c$ is the speed of light in m/s, $f$ is the frequency in Hz, $d$ is the thickness of the layer of material in meters, and $n$ is an integer to be determined (Trabelsi et al., 2000).

**Results and Discussion**

Figures 2 and 3 show variation of the dielectric constant and loss factor with time at 10 GHz and 23 °C. Both $\varepsilon'$ and $\varepsilon''$ decrease sharply and then reach a plateau and remain constant. The decrease in magnitude of $\varepsilon'$ and $\varepsilon''$ is larger for higher moisture contents and takes place over
a longer time interval. This is to be expected, because when more water is added it takes longer for water molecules to reach a final stage of binding in the wheat kernels. In fact, this time interval reveals the changes of activation energy as the binding modes of water molecules change. At microwave frequencies, water in its liquid form has an activation energy of 4.5 kcal/mole and single ice crystals have an activation energy of 13 kcal/mole (Hasted, 1973). In each material, bound water is characterized by a spectrum of activation energies that lie somewhere between that of liquid water and that of ice. This uncertainty constitutes a major obstacle in the modeling of the dielectric response of bound water.

Data in figures 2 and 3 were fitted with functions of the form:

\[ \varepsilon' = A + Be^{-k_1t} \]  
\[ \varepsilon'' = C + De^{-k_2t} \]

where \( t \) represents time after moistening in minutes.

The regression constants and coefficients of determination are shown in table 1. Both equations (3) and (4) have high coefficients of determination, \( r^2 \).

![Figure 2. Dielectric constant at 10 GHz and 23 °C as a function of time for three samples of 'Arapahoe' hard red winter wheat in which equilibrium moisture distribution was upset by adding water. Initial moisture content: 10.6%.](image-url)
Figure 3. Dielectric loss factor at 10 GHz and 23 °C as a function of time for three samples of ‘Arapahoe’ hard red winter wheat in which equilibrium moisture distribution was upset by adding water. Initial moisture content: 10.6%.

Table 1. Regression constants and coefficients of determination corresponding to equations (3) and (4).

<table>
<thead>
<tr>
<th>Moisture content (%)</th>
<th>$A$</th>
<th>$B$</th>
<th>$k_1$</th>
<th>$r_1^2$</th>
<th>$C$</th>
<th>$D$</th>
<th>$k_2$</th>
<th>$r_2^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.4</td>
<td>2.43</td>
<td>0.112</td>
<td>0.033</td>
<td>0.996</td>
<td>0.314</td>
<td>0.068</td>
<td>0.026</td>
<td>0.996</td>
</tr>
<tr>
<td>17.5</td>
<td>2.91</td>
<td>0.155</td>
<td>0.027</td>
<td>0.998</td>
<td>0.577</td>
<td>0.129</td>
<td>0.022</td>
<td>0.998</td>
</tr>
<tr>
<td>22.7</td>
<td>3.90</td>
<td>0.261</td>
<td>0.017</td>
<td>0.997</td>
<td>1.128</td>
<td>0.232</td>
<td>0.015</td>
<td>0.998</td>
</tr>
</tbody>
</table>

In terms of moisture content, the reading of a dielectric-based moisture sensor will track changes in dielectric properties and thus it is expected to provide a higher reading before the water molecules reach a final stage of binding. To calculate the apparent variation in moisture content, a density-independent calibration algorithm was used to determine moisture content in nonequilibrated wheat samples (Trabelsi et al., 1998; Trabelsi and Nelson, 2004). For well-equilibrated wheat samples, moisture content can be calculated from the dielectric properties measured at 23 °C and 10 GHz with the following moisture calibration equation:

$$M = \frac{\psi - 0.088}{0.017}$$

(5)

where $\psi$ is the density-independent calibration function which is expressed in terms of $\varepsilon'$ and $\varepsilon''$. 
\[ \psi = \sqrt{\frac{\varepsilon''}{\varepsilon'(a_f \varepsilon' - \varepsilon'')}} \]  

(6)

where \(a_f\) is the slope in the complex plane of the straight line correlating the loss factor divided by bulk density to dielectric constant divided by bulk density (Trabelsi et al., 1998). At 10 GHz, it has a value of 0.6053. Values of apparent moisture content obtained with (5) for each wheat sample are plotted versus time in figure 4. The trends observed are similar to those of \(\varepsilon'\) and \(\varepsilon''\) in figures 2 and 3. Data in figure 4 can be fitted with a regression of the form:

\[ M_{\text{apparent}} = A_m + B_m e^{-k_m t} \]  

(7)

Regression constants and coefficients of determination are shown in table 2.

Figure 4. Variation of predicted apparent moisture content of nonequilibrated wheat samples with time.

Table 2. Regression constants and coefficients of determination corresponding to equation (7).

<table>
<thead>
<tr>
<th>Moisture content, %</th>
<th>(A_m)</th>
<th>(B_m)</th>
<th>(k_m)</th>
<th>(r^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.4</td>
<td>14.60</td>
<td>1.59</td>
<td>0.0213</td>
<td>0.996</td>
</tr>
<tr>
<td>17.5</td>
<td>19.01</td>
<td>2.32</td>
<td>0.0189</td>
<td>0.997</td>
</tr>
<tr>
<td>22.7</td>
<td>23.51</td>
<td>2.80</td>
<td>0.0140</td>
<td>0.997</td>
</tr>
</tbody>
</table>

Figure 5 shows errors in moisture prediction related to transient binding stages of water. The error attributed to the use of (5) was taken into account in the difference between the apparent...
moisture and oven moisture. As expected, the difference decreases as time increases for each moisture level. However, the difference between the apparent moisture and oven moisture is higher for higher moisture content. In terms of error, for example at \( t = 0 \) min, the relative errors are 11.3%, 13%, and 11.8%, for the 14.4%, 17.5%, and 22.7% moisture content, respectively. These errors are of the order or greater than those related to the use of density-independent algorithms (Trabelsi and Nelson, 2006). Therefore, when microwave moisture sensors are used to monitor moisture content in materials with nonequilibrated water there is a need for a correction of the meter reading.

![Graph showing difference between apparent and oven moisture content over time for three samples of 'Arapahoe' hard red winter wheat.]

Figure 5. Difference between the apparent moisture content and oven moisture content for three samples of ‘Arapahoe’ hard red winter wheat.

**Conclusion**

Study of the dielectric response of nonequilibrated moisture in wheat reveals a first phase of sharp decrease in both the dielectric constant and loss factor, followed by a plateau reflecting the final stage of the binding of water. In terms of moisture content, the apparent decrease of moisture content of nonequilibrated wheat samples with time is mainly related to the binding status of the water molecules rather than a real change in moisture content. It is expected that the water molecules are loosely bound to the kernel molecules in the beginning and then reach a tighter level of binding when they reach the equilibrium stage. In practice, when dielectric-based moisture sensors are used to determine moisture content in a given material during a process in which the water is in nonequilibrium status (drying or adding water for example), there is a need for correction of the reading of the sensor to offset the effects resulting from changes in binding modes of water. Also, a preliminary investigation of the process under consideration could provide the appropriate timing for a correct determination of moisture content with a dielectric-based moisture sensor.

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References


