EVALUATION OF A MICROWAVE RESONATOR FOR PREDICTING GRAIN MOISTURE INDEPENDENT OF BULK DENSITY

M. F. Digman, S. P. Conley, J. G. Lauer

ABSTRACT. *This work evaluated the utility of a planar resonator to predict moisture considering moisture and densities expected in an on-harvester application. A calibration model was developed to accurately predict moisture over the moisture, density, and temperature ranges evaluated. This model, comprised of bandwidth and center frequency of a resonance peak at 2.38 GHz, predicted moisture content compared to oven moisture reference data with an r^2 of 0.996 and a root mean square error (RMSE) of 1.32. When bulk density was added to the moisture prediction model, no statistically significant improvement was obtained.*

Keywords. *Soybean,* Glycine max *L., Merr., Corn,* Zea mays *L., Microwaves, Microwave moisture sensor, Dielectric constant, Permittivity, Bulk density, Moisture content, Attenuation, Frequency shift, Bandwidth shift.*

Prediction of grain moisture on the harvester is essential for developing accurate yield maps. Furthermore, a sensor located in-line, without the need for a separate sample chamber, would reduce the overall complexity of the system, reducing cost and increasing reliability. A microwave moisture measurement technique could meet these requirements.

Energy in the microwave range of the electromagnetic spectrum and its interaction with moist agricultural materials has long been studied (Kraszewski et al., 1977). The specificity of microwave moisture sensing techniques for water is due to the strong interaction of microwaves with polar substances and its insensitivity to ionic conductivity (Nelson et al., 1998). However, as with other electromagnetic-based techniques, the matrix in which the water exists can have a strong influence on the sensor signal. In the microwave technique, the water-crop matrix can directly influence the effective permittivity and subsequent absorption of microwaves. Additionally, when measuring moisture in an agricultural commodity, such as cereal grains, the sensing zone or measurement chamber contains a mixture of air, dry matter, and water. The relative value of each of these components is quantified by density and moisture content. Laboratory work has shown that microwave-based techniques have evolved to predict moisture independent of density, and empirical relationships have been developed for various commodities (Jacobsen et al., 1980; Meyer and Schilz, 1980; King et al., 1992; Trabelsi et al., 1997; Kim et al., 2005; Trabelsi et al., 2008). Complex permittivity has also been observed to be predictably dependent on temperature.

These techniques are based on the complex permittivity of the commodity, which can be measured with both transmission and resonance techniques. With transmission techniques, signal attenuation and phase shift are measured. With resonance techniques, the shift in resonance frequency and bandwidth (quality) are measured.

Forgoing an investigation of permittivity measurement, this work takes an applied approach to understand how a microwave resonator could be implemented to predict moisture in the field. To this end, a commercially available planar microwave resonator was evaluated to determine its utility in predicting moisture given the variability expected in a field-going sensor.

To meet this goal, grain samples were collected in conjunction with the University of Wisconsin agronomic variety trials. These data represent three very different agronomic settings across Wisconsin. This variability may include harvesting conditions [e.g. temperature, material other than grain (MOG), grain damage], variety, moisture content, constituent content, and growing region (e.g. soil, climate, irrigation, etc.).

MATERIALS AND METHODS

The following sections detail the sample collection, hardware and software, moisture, density and temperature measurement, and statistical methodology employed to evaluate a planar microwave resonator's ability to predict moisture in grain samples.

SAMPLE COLLECTION

Corn (*Zea mays* L.) samples were collected in conjunction with the 2009 and 2010 University of Wisconsin-Madison's (UW) growth and development

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hybrid trial. This study investigates the influence of relative maturity on grain yield and moisture in varying agronomic and climatic regions of Wisconsin represented at the Seymour, Marshfield, Arlington, and Lancaster agricultural research stations. Additionally, soybean (*Glycine max* L.) samples were collected in 2009 from the UW conventional soybean cultivar trial at the Arlington, Marshfield, and Lancaster research stations. In each case, this work capitalized on the diverse hybrids and cultivars represented in these studies to gain a variety of moisture and kernel or bean sizes (*viz.* bulk densities) that could be collected on the same harvest day.

Hardware and Software

The planar resonator (Model P145/120*AH, TEWS Elektronik, Hamburg, Germany) evaluated in this work has been developed to predict moisture and density (Tews and Herrmann, 1995; Herrmann and Tews, 1999). The technology utilizes a flat profile in which the resonator encompasses a ceramic dielectric to produce a fringing electric field. The physical dimensions of the sensor are 188 mm diameter × 85 mm in height, including the mounting flange and connectors. The planar sensing face or the face exposed to the material under test (MUT) is 160-mm diameter and protrudes 5 mm from the mounting flange.

A network analyzer (Model 8753D, Hewlett Packard, Santa Rosa, Calif.)was used in place of the signal generator and measurement system provided by the manufacturer (Model MW3250, TEWS Elektronik, Hamburg, Germany). This hardware allowed researchers to collect the S_{21} response to a frequency sweep from 1.7-3.0 GHz, resulting in greater flexibility for calibration development. Peak detection as well as bandwidth, amplitude, and center frequency measurement were automated through the network analyzer IEEE 488.1, general purpose interface bus (GPIB). Data were collected and stored through the GPIB by means of a custom LabVIEW (LabVIEW 2009, National Instruments Corporation, Austin, Tex.) script. The LabVIEW script collected and saved the overall spectrum (1000 points) from 1.7-3.0 GHz to a time-stamped text file. Additionally, the LabVIEW script directed the network analyzer to center on each resonant peak by detecting the local minimums on either side of the peak. This permitted the program to obtain a high-resolution data set for each peak that was then used to determine the center frequency, bandwidth (at -3 dB) and amplitude.

Grain was applied to the sensor using a 160-mm diameter × 100-mm tall polyvinyl chloride (PVC) ring (fig. 1). The ring was machined to fit the outside diameter of the resonator. Grain was poured into the space formed by the ring and was struck level (fig. 1). Extraneous sample was removed by way of a plastic tray placed beneath the resonator.

Resonator, bulk density, temperature, and moisture data were aggregated into a relational database (FileMaker Pro 11, FileMaker Inc., Santa Clara, Calif.). This structure allowed multiple workstations during sample taking as well as streamlined data analysis through relational queuing.

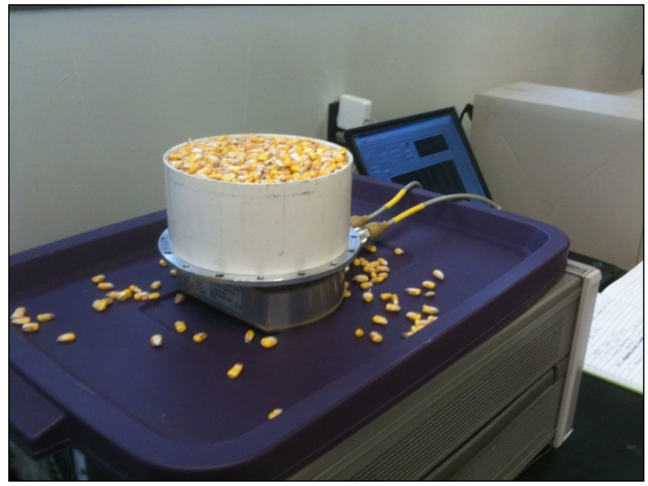

Figure 1. HP 8753D network analyzer, plastic tray, TEWS Model P145/120*AH resonator, and PVC sample ring with a struck-full grain sample.

Moisture and Density Reference

Grain moisture was determined for each sample in triplicate as weight loss on drying in a forced air oven, with a temperature and drying time of 103°C and 72 h, per ASABE S353.2 (*ASABE Standards,* 2008). Moisture content was expressed as percentage of wet sample weight loss by the sample, i.e., wet basis (%w.b.). Grain bulk density was determined by the quotient of the mass of the grain in the sample ring and the ring volume.

Laboratory Protocol

The network analyzer and attached resonator were allowed 30 min to reach steady-state operation. After this time, a through adapter was used to calibrate for cable loss per the procedure outlined in the user's guide (Hewlett-Packard, 1997). Next, three empty and three acrylonitrile butadiene styrene (ABS) standard readings were taken. Empty and a 160-mm diameter × 5-mm thick ABS standard measurement were taken every hour to monitor performance of the measurement system. Resonator temperature was recorded for each series of empty and standard measurements.

The following protocol was followed for individual samples. Each grain sample was analyzed the same day as harvest after being transported from the field in paper bags. First, the sample was emptied into a dish tub and thoroughly mixed by hand. A thermocouple was applied and temperature was recorded after the thermocouple reached equilibrium with the grain. Next, the sample was transferred to the resonator sample ring using a 0.5-L polyethylene cup. After the ring was heaped full, it was struck level onto a tray placed beneath the resonator. Excess sample was discarded. Next, resonance peaks were recorded using the previously described LabVIEW script. Finally, the sample was emptied back into the dish tub, mixed, and replaced into the resonator sample ring. This process was repeated, in total, three times for each grain sample.

After each sample passed the resonator it was mixed, and three 150-g moisture subsamples were taken and placed in covered metal containers for reference moisture measurement. The remaining sample was weighed for density determination and discarded.

ANALYSIS

Amplitude ratio, bandwidth ratio, center frequency ratio and density-independent moisture were computed for each sample reading and resonance peak. Ratios were determined as the quotient of the sample reading and the overall experimental empty average. The density-independent moisture value was computed as the arctangent of the quotient of the bandwidth (B) and resonance peak center frequency ratio (C) (eq. 1). This parameter was modeled after TEWS' mass-independent microwave-moisture-value (Tews and Herrmann, 1995; Schlemm, 2008).

$$\Phi = \tan^{-1}\left(\frac{B}{C}\right) \quad (1)$$

As discussed above, each grain sample was subject to three sensor readings. These readings were averaged for each grain sample before regression. Calibration parameters, including amplitude ratio, center frequency ratio, bandwidth ratio, temperature, bulk density, and their influence on moisture prediction were evaluated using Mathematica (Version 8, Wolfrum Research., Champaign, Ill.). Statistical significance was recognized for $P < 0.05$.

RESULTS AND DISCUSSION

In the frequency range of our 8753D network analyzer (1.7-3.0 GHz) nine resonance peaks were observed for an empty resonator (fig. 2). Resonance peaks identified in the empty resonance spectrum will be referred to from one to nine, labeled from left to right throughout this discussion.

Filling the resonator sample ring with material "detunes" the resonator, moving each resonance peak to a lower frequency while decreasing the amplitude and increasing the width. This phenomenon is the basis for measurement as each of these resonator properties varies depending on the dielectric properties of the material under test (MUT). In general, a shift in a resonator peak's center frequency is related to electric energy (ε'), whereas a shift in amplitude is related to loss (ε''). The presence of water affects both parameters.

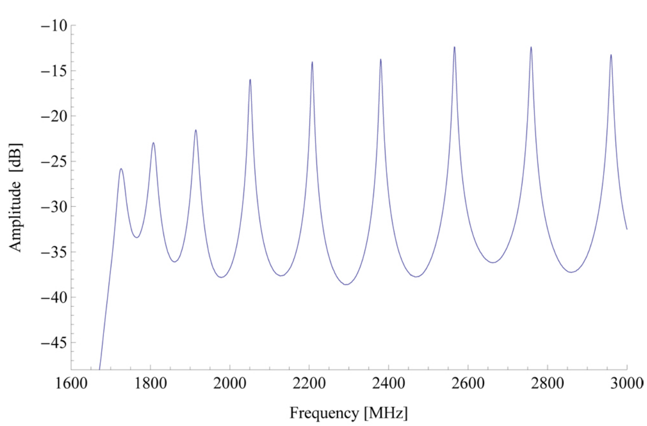

Figure 2. The nine resonance peaks observed for a 1.7-3.0 GHz empty sweep. Peaks were labeled from left (1) to right (9).

SENSOR PERFORMANCE

Temporal stability of the resonator and network analyzer system was monitored via empty and standard readings. Tables 1 and 2 detail the stability of the center frequency, amplitude, and bandwidth parameters averaged across 73 observations taken throughout the testing period. The temperature range in this data set was between 9.5°C and 24.5°C. Exploration of these data reveal that lower frequency peaks were less stable compared to higher frequency peaks across all resonance parameters. Bandwidth was the most stable resonance parameter followed by center frequency and amplitude for empty readings. When applying the acrylonitrile butadiene styrene (ABS) plate, however, bandwidth was less stable than center frequency and exhibited similar stability to amplitude over time (table 2). It must be cautioned that parameter stability alone should not be used to judge appropriate peaks for measurement. A stable peak is desirable so that offsets are not introduced into the calibration over time. However, a very stable peak could indicate that the peak is not sensitive and therefore not appropriate for measurement. Empty and standard data were also compared over time and temperature, but no significant correlations were observed.

Table 1. Center frequency, amplitude, and bandwidth readings for the empty resonator over the testing period.

	Center Frequency (GHz)		Amplitude (dB)		Bandwidth (MHz)	
Peak	Mean	CV[a]	Mean	CV[a]	Mean	CV[a]
1	1.73	8.66E-04	-25.5	-1.49E-04	20.4	5.33E-04
2	1.81	1.07E-06	-23.3	-9.99E-05	17.6	1.33E-10
3	1.91	6.77E-07	-21.5	-4.57E-05	13.1	7.52E-11
4	2.05	2.02E-07	-15.9	-3.21E-05	7.77	6.58E-11
5	2.21	1.25E-07	-14.0	-3.94E-05	6.38	8.62E-11
6	2.38	1.40E-07	-13.7	-3.54E-05	6.84	7.09E-11
7	2.57	1.46E-07	-12.3	-4.73E-05	7.29	7.98E-11
8	2.76	1.50E-07	-12.4	-4.11E-05	7.89	6.45E-11
9	2.96	1.61E-07	-13.2	-2.56E-05	8.20	4.14E-11

[a] CV = coefficient of variation.

Table 2. Center frequency, amplitude, and bandwidth readings for the ABS plate over the testing period.

	Center Frequency (GHz)		Amplitude (dB)		Bandwidth (MHz)	
Peak	Mean	CV[a]	Mean	CV[a]	Mean	CV[a]
1	1.68	8.05E-06	-28.8	-3.03E-04	19.2	1.05E-03
2	1.77	2.44E-06	-25.7	-6.71E-05	21.6	2.04E-04
3	1.87	1.86E-06	-24.3	-5.30E-05	16.8	2.34E-04
4	2.01	1.70E-06	-18.4	-3.84E-05	9.44	8.15E-05
5	2.17	1.61E-06	-15.0	-4.62E-05	6.88	3.62E-05
6	2.35	1.51E-06	-14.9	-5.23E-05	7.18	4.99E-05
7	2.54	1.41E-06	-13.2	-6.98E-05	7.54	4.52E-05
8	2.73	1.33E-06	-13.0	-7.71E-05	8.22	3.93E-05
9	2.93	1.23E-06	-13.7	-5.58E-05	8.43	4.32E-05

[a] CV = coefficient of variation.

Crop Variability

As previously mentioned, variability was entered into the trial by collecting samples from the multi-location hybrid and cultivar trials. In total, 150 grain samples were collected, however, some samples represented extreme moisture contents (greater than 35% w.b.) and were removed from the calibration data set, resulting in a total of 101 samples. Grain samples from the field varied in temperature from 9.5°C to 24.5°C. The moisture of the samples varied from 11.3% to 48.0% w.b. with most samples occurring between 20% and 25% w.b. for corn, and 11.3% to 18.6% w.b. with a majority of samples less than 15% w.b. for soybean (fig. 3). Corn moistures were quite high because the 2009 harvest season was very wet. On the other hand, the 2010 season was very dry and as a result many of the drier corn samples, those less than 15% w.b., were obtained during the 2010 harvest. In the sample ring, grain bulk density varied between 452 and 792 kg/m^3 (fig. 2). No effort was made to artificially increase the bulk density and therefore any variation was a result of the packing density exhibited by the kernel (bean) size, weight, and shape of specific hybrids at the time of harvest.

Reference Moisture

Each sample passing the resonator was sub-sampled and dried in triplicate as previously described. The reference moisture utilized for calibration was computed as the average of these sub-samples. The combined variability of the sub-samples and the drying technique is exhibited by the standard deviation $\sigma = 0.32$, which in the case of our data set was determined to be less than 1% of the average sample moisture content.

Calibration

As previously established, the tested sensor geometry exhibited nine resonance peaks across the observed frequency range (1.7 to 3 GHz) and each peak had varying empty stability. It was further discovered that each peak also had variable susceptibility to the moisture content of the material under test (MUT). It was found that lower frequency peaks were more susceptible to moisture than higher frequency peaks. In fact, each peak exhibited a maximum moisture content in which resonance parameters could no longer be measured by the network analyzer

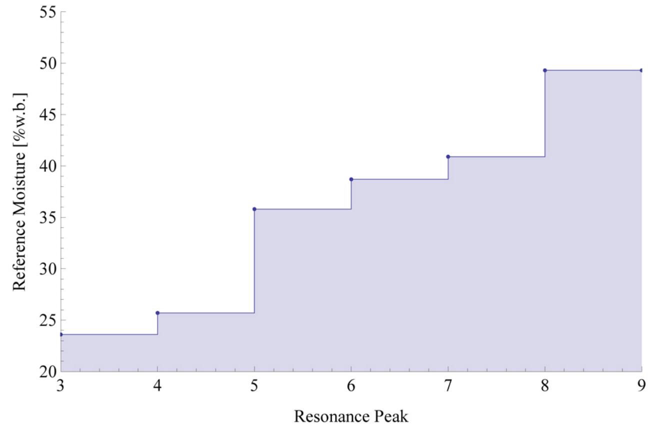

Figure 4. Grain moisture contents at which resonance peaks were no longer observable

(fig. 4). In light of this finding, resonance peak six was chosen for calibration as it would represent the entire moisture range expected during grain and high-moisture corn harvest. However, it was a concern that while this peak would best represent the range of moistures, it may lack the sensitivity to accurately predict moisture at lower grain moisture contents. As a result, developing separate calibration models utilizing the peak most sensitive for the range of moistures expected would be the most appropriate approach. This strategy was not investigated initially but was explored later in the calibration process.

The first step in the calibration development was to explore the center frequency ratio, amplitude ratio, bandwidth ratio, and density-independent moisture (DIM) for peak six (2.38 GHz) graphically (fig. 5). Each resonance parameter was explored through multiple linear regression with and without grain temperature and bulk density. The goal was to achieve a model that predicted moisture accurately with the fewest parameters and data transformations so that over-fitting and subsequent sensor performance assessments would be accurate but conservative. These models seemed appropriate for amplitude ratio, center frequency ratio, but bandwidth shift and DIM exhibit non-linearity, especially at higher moistures. Initial multiple linear regressions revealed that this variability could not be accounted for by the addition of grain bulk density or temperature to the model, so a

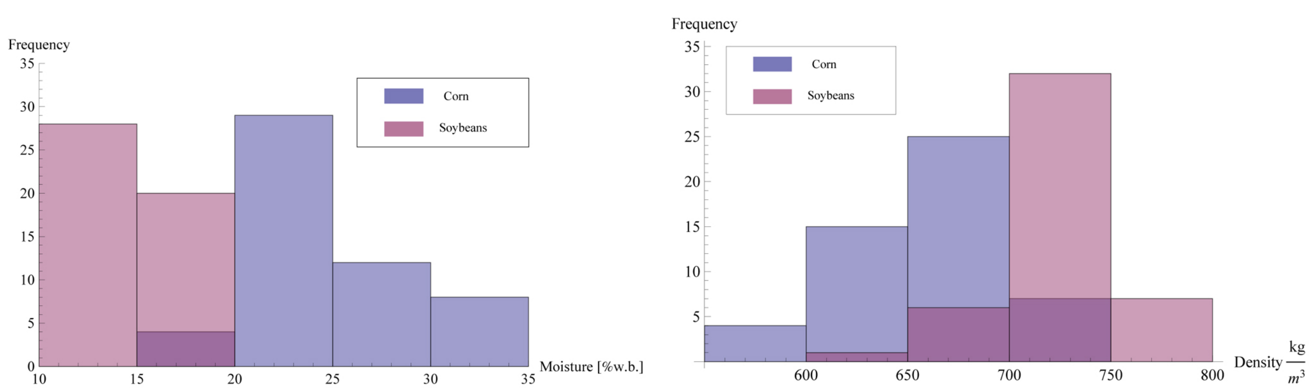

Figure 3. Moisture (left) and density (right) distributions of grain samples collected from the University of Wisconsin-Madison's 2009 and 2010 hybrid trials. Corn samples are depicted in blue (darker color) and soybean red (lighter color).

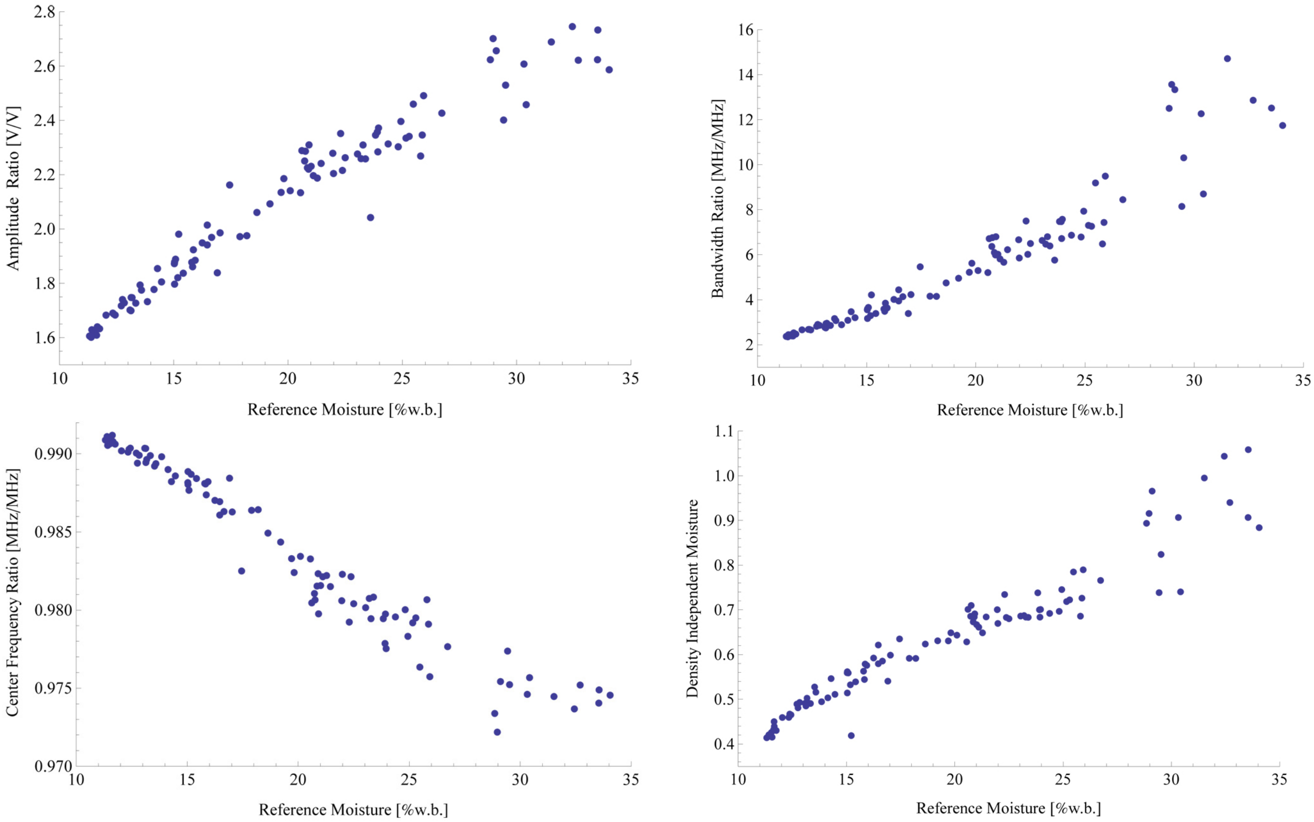

Figure 5. Amplitude ratio (top, left), bandwidth shift (top, right), center frequency shift (bottom, left) and density-independent moisture (bottom, right) resonance parameters for resonance peak six (2.38 GHz) plotted against the average of oven reference moisture replicates.

logarithmic transformation of the data and introduction of quadratic terms were attempted. However, model performance was not significantly improved, so these calibrations were not considered further.

Exploring non-linear regression models employing the sixth resonance peak revealed the best performing model to be one that included DIM (Φ) (eq. 2, fig. 6). The model predicted the calibration data set with an r^2 of 0.996 and a root mean square error (RMSE) of 1.32.

$$MC\ \Phi = 6.70 + 0.334e^{1.92\Phi^2} \tag{2}$$

The intercept, linear, and quadratic (DIM) regression parameters were statistically significant with p-values of 1.99×10^{-7}, 0.031, and 3.69×10^{-17}, respectively. Addition of temperature or density into the model slightly improved regression performance, but neither term was statistically significant.

Exploring the residual plots for the calibration model reveals that model prediction accuracy decreases with increasing moisture content (fig. 7). Specifically, prediction error becomes considerable beyond a moisture content of 20% w.b. Additionally, grain bulk density model prediction error was biased toward lower grain densities.

As previously discussed, all calibration work reported up until now was based on the amplitude ratio at resonance peak six. Although peak six was the most stable across the moisture range expected for harvest, it may not be as sensitive at lower moisture values. Therefore, it can be hypothesized that multiple calibrations up to a specific cut-off frequency would result in higher prediction accuracy. This concept was explored by partitioning the data set into moisture ranges that enveloped particular resonance peaks. Then, calibration models were developed for the resonance peak most sensitive in the range (native peak) as well as for peak six (table 4).

Exploring the data subset for peaks three and four revealed that a linear model with temperature was the best fit. A linear fit is recommended when employing the mass-independent microwave-moisture-value, DIM in our case, over a narrow range of moisture values (Schlemm, 2008).

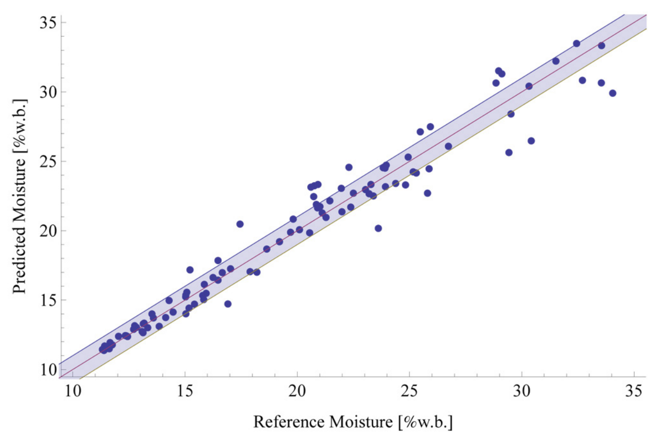

Figure 6. Predicted vs. oven reference moisture for non-linear regression where density independent moisture at peak six (2.38 GHz) is the independent variable. Shaded area represents ±1 moisture percentage point.

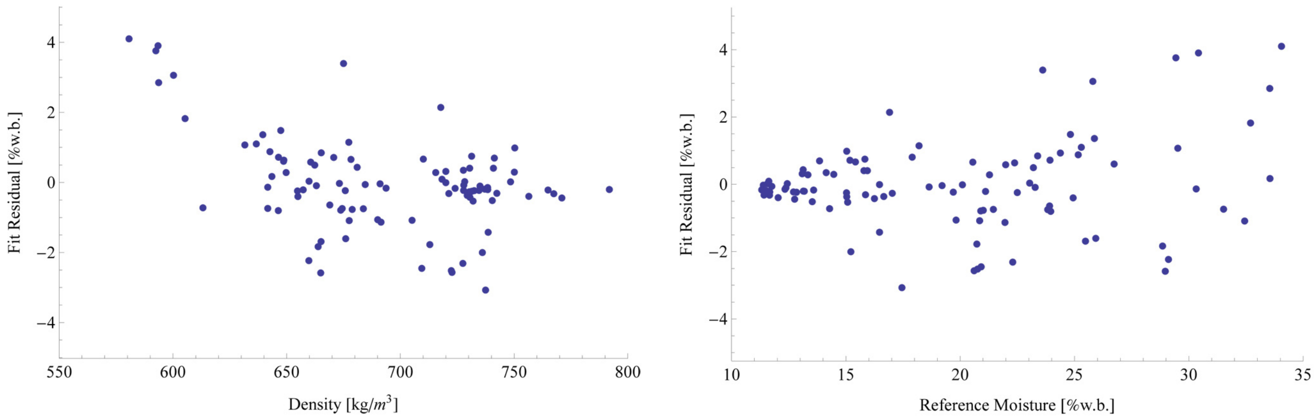

Figure 7. Fit residuals vs. oven reference moisture (left) and density (right) for multiple linear regression model where amplitude ratio at peak six (2.38 GHz) and temperature are dependent variables.

Table 4. Model performance for a model developed for peak six vs. the peak bordering the moisture range subset (native peak).

Peak	Moisture (% w.b.)	Native Peak RMSE	Native Peak r^2	Peak Six RMSE	Peak Six r^2
3[a]	< 23.6	0.854	0.997	0.799	0.951
4[a]	< 25.7	1.29	0.995	1.17	0.932
5	< 35.0	1.73	0.993	1.32	0.996

[a] Linear model best fit.

Our data would support their findings. Unexpectedly, it was observed that the native peak's performance was slightly worse than that of peak six on the basis of RMSE values. Therefore a model at peak six could perform adequately while forgoing the need to maintain multiple calibrations. It was therefore concluded that the single calibration approach presented above is most appropriate.

Future Work

Future work on this project should consist of independent validation either by collecting predicting samples for a third season at our laboratory or by a prospective end user. Additionally, the data set should be expanded to include other commodities such as wheat and oats. The resonator should be tested to evaluate accuracy in flowing grain. If the resonator could be used in such a manner the need for a static sample column could be eliminated, simplifying combine moisture sensor design. Finally, different resonator geometries should be evaluated to exploit the technique's efficacy at high moisture content.

Conclusion

Over the temperature range from 9.5°C to 24.5°C, the moisture range from 11.3% to 35.0% w.b. and grain bulk densities of 452 and 792 kg/m^3, a calibration model for planar microwave resonator was developed to accurately predict moisture in corn grain and soybean. Amplitude ratio, bandwidth ratio, center frequency ratio, and a density-independent moisture parameter, grain bulk density and temperature were evaluated as regression variables. Furthermore, data transformations, resonance parameters at specific resonance peaks, and non-linear regression models were evaluated. The most promising regression model as selected by regression statistics r^2 and root mean standard error (RMSE), and minimal use of data transformation and regression parameters was a model comprised of bandwidth and center frequency at the sixth resonance peak centered at 2.38 GHz. This model predicted the oven moisture reference data with an r^2 of 0.996 and a RMSE of 1.32.

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