New Dielectric Moisture Measurement Technologies

D. B. Funk[1] , P. Meszaros[2], Z. Gillay[2], J. H. Rampton[1], L. D. Freese[1]

Abstract

Moisture content is one of the most important quality factors in marketing grain, since it determines both the quantity of dry matter traded and the storability of the grain. Its significance is heightened rather than diminished when dealing with high-value specialty crops. The National Type Evaluation Program for grain moisture meters facilitates the development of accurate moisture meter calibrations for commercial moisture meters for the fifteen major grain types in the United States, but that process is too slow and expensive to provide timely moisture meter calibrations for emerging specialty crops.

Research performed by USDA-Grain Inspection, Packers and Stockyards Administration (GIPSA) and USDA-Agricultural Research Service (Athens, GA) (ARS) has created a new dielectric moisture measurement technology that provides improved accuracy and greatly simplifies the calibration development process. In this method, many similar types of grains (such as wheat classes, rough rice classes, edible beans, processed rice, etc.) can be grouped together to use exactly the same calibrations. Furthermore, distinctly different types of cereal grains and oilseeds can be combined into one single calibration by the use of a few "unifying parameters."

The accuracy of the method, with a single unified calibration, is substantially better than what is achievable with current grain moisture meters using separate calibrations for each distinct grain type. Therefore, it appears that the differences between commodity grain types and similar specialty grains should not require separate calibrations. This could remove the development of moisture meter calibrations as an impediment to marketing new specialty grains.

Introduction

Uniformity in dielectric grain moisture measurement is just as much an issue today as it was at the 1990 "Uniformity by 2000" conference. (Funk, 1990) The emergence of high-value differentiated products demands even greater moisture measurement accuracy and uniformity and presents new challenges. Moisture content is one of the most critical grain quality measurements because of the direct economic significance of the fraction of the total product weight that is water and because moisture content largely determines the rate at which the grain will degrade during handling and storage. Because of its significance, moisture content is measured and used to compute the price virtually every time grain is sold.

[1] U. S. Department of Agriculture (USDA), Grain Inspection, Packers and Stockyards Administration (GIPSA), Kansas City, Missouri, USA

[2] Faculty of Food Science, Physics and Control Department, BKAE University, Budapest, Hungary

E-mail of the primary author: david.b.funk@usda.gov

The radio-frequency (RF) dielectric method measures moisture content in grain by sensing the dielectric constant of grain samples. The RF dielectric method presents an attractive combination of good accuracy, close matching (standardization) among instruments within a model, relatively simple calibration development (as compared to other alternative methods), and moderate manufacturing cost. Because of these advantages, grain moisture meters based on the RF dielectric method are used widely around the world—including in the United States, where the USDA-Grain Inspection, Packers and Stockyards Administration (GIPSA) (and its predecessor agencies) has specified the use of RF dielectric-type moisture meters for official inspection for over forty years.

Overview of the RF Dielectric Method

Permittivity is a measure of the ability of a material to store and dissipate energy when subjected to an electric field. The relative permittivity of a material is the ratio of the permittivity to the permittivity of vacuum. The relative permittivity (Equation 1) is made up of a real part, the dielectric constant, which relates to energy storage, and an imaginary part, the loss factor, which relates to energy dissipation. The dielectric constant and loss factor are dimensionless quantities because they are relative values. The dielectric constant of a material is always greater than or equal to 1.0, and the loss factor is always greater than or equal to zero.

$$\varepsilon_r^* = \varepsilon_r' - j \cdot \varepsilon_r'' \tag{1}$$

The loss tangent is the ratio of the loss factor to the dielectric constant. In general, both the real and imaginary parts of the permittivity of a material are dependent on the measurement frequency—the frequency of the applied electric field. At a given measurement frequency, the loss tangent is equal to the ratio of the amount of energy dissipated per cycle of the driving electric field to the amount of energy stored per cycle. Materials with low loss tangent values (very near zero) are “good” dielectrics and materials with loss tangent values significantly higher than zero are “lossy” dielectrics. In general, grains are lossy dielectrics, with loss tangent values varying from less than 0.1 up to 1 or even higher, depending on the measurement frequency, grain type, and moisture content.

Water is a polar molecule (the center of charge is not at the geometric center of the molecule) because the angle between the two oxygen-hydrogen bonds is much less than 180 degrees and the oxygen atom has a greater electron affinity than hydrogen. Therefore, the oxygen atom has a net negative charge and the two hydrogen atoms have net positive charges. Because of the displacement of charge from the geometric center, the water molecule experiences a torque when placed in an electric field. Rotation of the molecule in response to the electric field stores energy. The magnitude of the energy storage of polar molecules is much greater than that for non-polar molecules, which store energy only due to distortion of the electron “cloud” around the molecule.

The dielectric constant of pure water at room temperature is about 80, whereas the dielectric constants of dry (generally non-polar) grain constituents are approximately 2 to 3. The wide difference between the dielectric constants of water and other grain constituents is the basis for successful moisture measurement by the dielectric method. However, the measured dielectric constants of grains are dependent on many other factors that complicate the RF dielectric method.

Water molecules are in liquid water or grain are never “free” but are always electrostatically associated with one or more other water molecules and/or other polar molecules through hydrogen bonds. Those hydrogen bonds affect both the magnitude and the frequency dependence of the water molecules’ capacity to store energy in an electric field. The hydrogen bonds between water and different types of molecules have different strengths; weaker bonds allow the water molecules to rotate more freely. Also, different grain constituents have different numbers of potential hydrogen-binding sites. Therefore, the varying chemical compositions of grains are expected to affect their dielectric characteristics.

Grain is not a homogeneous material, of course. In addition to the microscopic and macroscopic differentiation of structures (and chemical composition) within the kernel, bulk grain is a mixture of two phases—grain and air. Dielectric constant is a volume-based parameter. Since air has a dielectric constant of approximately 1.00, the dielectric constant of a mixture of grain and air depends in a complex way on the relative fractions of air and grain in the bulk sample. Different kernel shapes and densities, different test cell shapes, and different methods for filling the test cell all affect the bulk density of the grain in the test cell and the dielectric constant that is measured.

Temperature also affects the measured dielectric constant. The dielectric constant of pure water decreases with increasing temperature in the range of 0 to 100 Celsius, but the dielectric constant of water that is absorbed in grain and more or less bound to grain constituents increases with increasing temperature. The dielectric constant of pure water, as measured at radio frequencies and above, decreases abruptly to a much lower value if the temperature goes below 0 Celsius; but the dielectric constant of grain shows no such abrupt transition at the freezing point of water. (Mészáros and Funk, 2003). Accurate grain moisture measurements over a range of temperatures require precise determination of grain temperature and the application of suitable correction functions.

Calibrations for RF Dielectric Grain Moisture Meters

Developing calibrations for grain moisture meters requires measuring dielectric characteristics, density, temperature, and the “true” (reference) moisture for a representative set of grain samples for each grain type. Multiple linear regression or other mathematical procedures are used to determine the optimum mathematical relationships (functional forms and calibration coefficients) between the measured instrument parameters and the true moisture content. Those relationships are then applied when measuring the moisture contents of “unknown” samples. There has been no standardization among different manufacturers of moisture meters; virtually every manufacturer measures slightly different parameters in different ways and applies unique calibration functions to predict moisture contents. These differences in measurement technologies cause significant inconsistencies between different moisture meter types even if the moisture meter calibrations are optimized with respect to average error.

Although developing the mathematical relationships between RF dielectric parameters and moisture content is a fairly simple process for a single grain type, the total calibration development effort is staggering in magnitude because of the number of grain moisture meter models and the number of grain types involved. The most recent list of U.S. official moisture meter calibrations (GIPSA, 2003) includes sixty-one different calibrations. One instrument support company claims over 450 calibrations on file for GIPSA’s current official grain moisture meter type. (Calibration Plus, 2004) Creating that many calibrations has required decades of effort.

Since the relationships between measured dielectric parameters and moisture (as determined by air oven methods) have not proven to be very stable over time, calibration equations are routinely evaluated and adjusted to maintain accuracy. Thus the cost of developing and checking moisture meter calibrations goes on and on. The calibration development cost over the life of an instrument model can be several times the cost of the initial design of the instrument. Therefore, calibration development has been a tremendous impediment to introducing new moisture measurement algorithms since changing the measurement technique renders all existing calibrations obsolete.

National Type Evaluation Program

As projected at the "Uniformity by 2000" conference (Funk, 1990), GIPSA and the National Conference on Weights and Measures have developed a National Type Evaluation Program for grain moisture meters. (NIST, 2000) This program has contributed significantly to improving the accuracy and consistency of grain moisture measurements in the United States by: 1) establishing criteria for grain moisture meters to be used for commercial purposes, 2) evaluating new instrument models' compliance with those requirements, and 3) establishing and conducting an on-going program for evaluating the accuracy of moisture meter calibrations and providing data to help manufacturers improve their calibrations.

Moisture Calibrations for Minor Grains and Specialty Grains

The ongoing calibration program for commercial moisture meters involves only the fifteen most significant grain types in the United States. GIPSA tests many other grain types, in addition to the fifteen "major" grains, to establish official calibrations for its official moisture meter, but the costs of testing those other grain types on all NTEP-certified moisture meters are greater than moisture meter manufacturers are willing to bear. No other source of funding has been found to support that effort. Therefore, the need for accurate and consistent moisture measurements for "minor" grains and for emerging specialty grains is not being fully addressed.

Because of the instability (over time) of the observed relationships between measured parameters and moisture content, two or three years' data for each grain type are considered necessary to create valid calibrations for the official moisture meter. This process is too slow to respond effectively to new grain types whose moisture contents may or may not be measured accurately with grain moisture meter calibrations based on commodity grains. While accurate moisture calibrations are being developed, moisture inaccuracy caused by using generic calibrations could discourage production of the crop.

High-oil corn is an example of this problem. For some time after high-oil corn began to be marketed, only generic corn calibrations were available for moisture measurements. After a considerable quantity of calibration data was accumulated, it was found that a different calibration was needed to improve moisture measurement accuracy for that special grain type. The current list of official moisture meter calibrations lists high-oil corn separately from generic corn. (GIPSA, 2003)

Dry-Basis Marketing

Current marketing practices for commodity grains usually penalize producers for overly dry grain because no premium is paid for grain at moisture levels below the "market" moisture value—and adding water to overly dry grain to adjust the moisture content is illegal in the United States. Producers are also penalized for delivering grain above the market moisture value. Though some have advocated dry-basis marketing of grain, the practice has been generally resisted. Blending wet grain with overly dry grain is a significant profitability factor for those who have access to overly dry grain to blend with wet grain. For specialty grains, however, blending is less likely to be practiced. It may be necessary to use dry-basis marketing to encourage production of some specialty grains.

Perhaps the most common argument against dry-basis marketing of grain (other than greater breakage susceptibility of overly dry grain) is that grain moisture meters are less accurate at low moisture levels than at normal market moisture levels. Improvements in moisture meter accuracy for very dry grain could make dry-basis marketing of specialty grains more attractive.

Summary of Improvements Needed

- Standardized moisture measurement technology could improve measurement consistency among moisture meters from different manufacturers and dramatically reduce the total cost of calibration development—and the costs that are passed on to moisture meter users.
- Measurement technology that minimizes differences among different grain types could greatly reduce the number of separate moisture calibrations to be developed and maintained and simplify moisture meter use.
- Measurement technology that is less affected by differences among similar grain types could minimize crop year calibration differences and reduce or eliminate the need for data from multiple crop years to establish valid calibrations, reduce the total number of samples required to establish calibrations, and permit more rapid development of accurate calibrations for new grain types.

Materials and Methods

In response to these needs and with the belief that it was possible to substantially improve the RF dielectric moisture method, USDA-GIPSA and USDA-Agricultural Research Service (Athens, GA) initiated a collaborative research project in 1995. The primary goals of that research were to achieve a better understanding of the physical processes involved in the dielectric response of cereal grains and oilseeds and, based on that understanding, to create a new algorithm that would warrant a new generation of moisture meters.

Several researchers had previously studied the dielectric properties of cereal grains and oilseeds and had attempted to optimize parameters for using the RF dielectric method for grain moisture measurements. However, their results had had limited impact on grain moisture meter design. Until recently, making precise, wide frequency range measurements of the dielectric constant of grain was far too slow to be practical for characterizing hundreds of samples during or shortly after harvest. Also, obtaining samples that were representative of diverse growing regions, varieties, and moisture levels and determining the “true” moisture contents of those samples by a well-controlled reference method were very difficult and expensive.

This research overcame those limitations by using the same samples and reference analyses as the GIPSA Annual Moisture Survey.(GIPSA, 1999) This program involves collecting and testing about 1200 grain samples per year that represent all significant growing areas for all US grain crops that are assigned to GIPSA for quality certification. The purpose of the Annual Moisture Survey is to ensure that official moisture meters (used by the US Official Inspection Service) are calibrated to provide the best accuracy possible with respect to the USDA air oven method. This RF dielectric research project was a logical and effective extension of the Annual Moisture Survey.

During the initial research period of 1997 to 2000, dielectric characteristics were measured for 3,371 individual grain samples representing 41 US grain types. The primary dielectric measurement system consisted of a Hewlett-Packard HP-4291A RF Material/Impedance Analyzer and a special transmission line test cell that was developed and calibrated by Dr. Kurt Lawrence and Dr. Stuart O. Nelson, ARS. (Lawrence et al, 1999) (Figure 1.) Funk (2001) provides details of the measurement method.

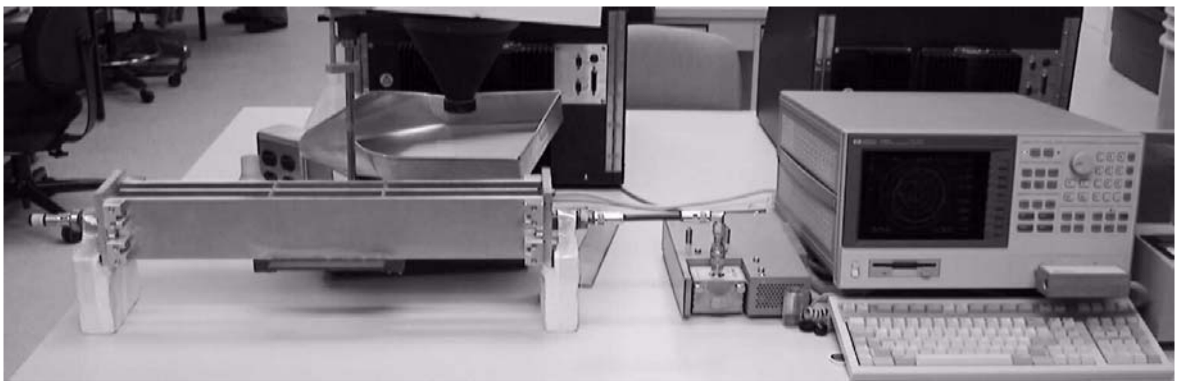

Figure 1. Transmission line test cell and HP-4291A RF Material/Impedance Analyzer

Results and Discussion

<u>The Nature of the Dielectric Response in Grain</u>

That research led to several conclusions regarding the nature of the dielectric response in the kilohertz and low-megahertz regions. (Funk, 2001)

- The large dielectric loss peaks and steep slopes and the unusually high dielectric constant values observed in the kilohertz region are due to conductivity effects—Maxwell - Wagner relaxations and electrode polarization—and not to bound water. These conductivity effects are extremely sensitive to the distribution of moisture within kernels and subtle differences in kernel morphology—contributing significantly to moisture meter calibration instability.
- Moving the measurement frequency for dielectric moisture meters from the 1 to 20 MHz range to about 150 MHz dramatically reduces the influence of conductivity effects on moisture measurements and improves calibration accuracy and stability. It is unnecessary to go to much higher frequencies (microwave range) to avoid conductivity effects in grain.
- For grain, the Landau-Lifshitz, Looyenga density correction (Nelson, 1992) effectively normalizes grain samples to a common density—thereby minimizing density-induced

errors from test cell filling methods, grain moisture level, and kernel density and shape. The Landau-Lifshitz, Looyenga density correction reduces the achievable moisture measurement error to less than one third of the error observed without density correction.

- Most water in grain appears to be "bound" in the sense that it does not freeze at 0 °C, but there is a difference in the dielectric behavior of "tightly-bound" or "monolayer" water and the dielectric response of the rest of the water in grain. The linear relationship between dielectric response and temperature extends through the freezing point for all but very wet samples.

Based on these findings, a new unified moisture algorithm (UMA) was developed and tested. The UMA included the following steps:

- Measure the real part of the relative permittivity of grain at a single frequency near 150 MHz.
- Apply the Landau-Lifshitz, Looyenga density correction equation and a few "unifying parameters" to superimpose the dielectric constant versus moisture characteristics for all grain types.
- Fit one polynomial equation to all of the "unified" data to create a calibration that provides excellent accuracy for all grain types.

Table 1 compares the performance achieved with the unified calibration to that of the USDA official moisture meter. Figure 2 shows the results in graphical form.

Table 1. Comparison of moisture measurement accuracy for separate moisture calibrations (various polynomial regression orders), the Unified Moisture Algorithm, and GIPSA's official moisture meter for data from three crop years. (Funk, 2001)

Grain Type	Separate Moisture Calibrations	Poly. Regr.	Unified Moisture Algorithm	Official Moisture Meter
	SDD	Order	SDD	SDD
Six-Rowed barley				0.35
Two-Rowed barley				0.46
Combined barley	0.21	3	0.23	
Low-moisture corn (< 20%)				0.38
High-moisture corn (> 19 %)				0.90
Combined corn	0.33	4	0.36	0.60
Oats	0.23	1	0.25	0.34
Long Grain Rough rice				0.34
Medium Grain Rough rice				0.45
Combined rice	0.34	3	0.38	
Sorghum	0.13	3	0.15	0.38
Soybeans	0.16	3	0.23	0.43
Sunflower seeds	0.32	3	0.35	0.67
Durum wheat				0.32
Hard Red Spring wheat				0.35
Hard Red Winter wheat				0.39
Hard White wheat				0.28
Soft Red Winter wheat				0.35
Soft White wheat				0.28
Combined wheat	0.23	3	0.23	
Combined all grains			**0.29**	

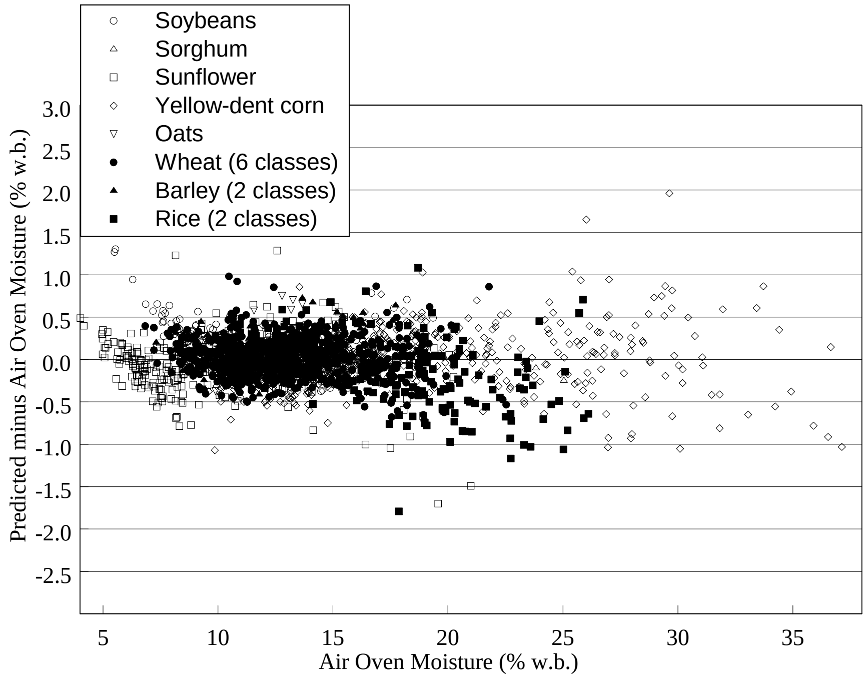

Figure 2. Predicted moisture measurement error for 15 grain types and 3 crop years with the unified moisture algorithm. (Funk, 2001)

Public Algorithm

In the interest of promoting standardization in commercial grain moisture measurement, GIPSA decided to publish the UMA as a public algorithm rather than to seek patent protection and exclusive licensing. GIPSA has been working with several manufacturers to share technical details of the method and to assist in the development of commercial instruments. During one such information-sharing meeting in August 2001, attendees from industry and academia raised several important technical questions that are summarized below.

1) Is it possible with practical, cost-effective electronic circuitry to duplicate the dielectric measurements made with GIPSA's expensive research-grade instrument?
2) To what extent can the dimensions and shape of the test cell be changed from that used in the original research and still yield compatibility with the unified calibrations?
3) What tolerances (mechanical, electrical, and mathematical) and test cell materials are required to achieve conformity with unified moisture algorithm?
4) How can unifying parameters for additional grain types be developed most efficiently and effectively?
5) What functional form and specific coefficients should be used for temperature corrections to achieve excellent accuracy over wide temperature and moisture ranges with the unified moisture algorithm?
6) What are the practical limits for the temperature range for moisture measurements with the unified moisture algorithm?

7) What reference materials, instrumentation, and processes are needed to validate dielectric measurements for commercial moisture meters to ensure compatibility with the unified moisture algorithm?

Practical Instrumentation

GIPSA provided an answer to the first question by creating a simple prototype senor system (Figure 3) based on inexpensive commercially-available components. This was demonstrated for a gathering of interested manufacturers in August 2002.

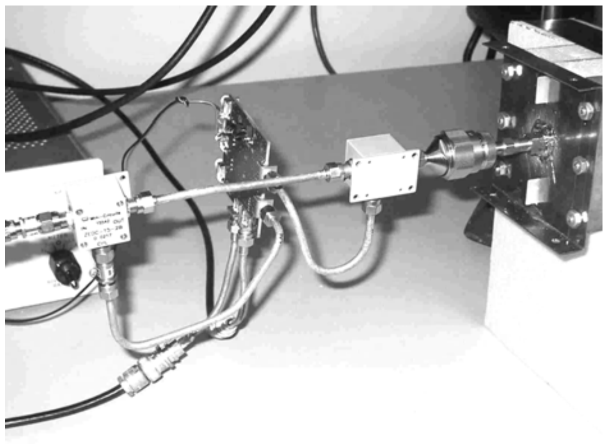

Figure 3. Prototype VHF moisture meter sensor system consisting of two directional couplers and an Analog Devices AD-8302-Eval circuit board. RF connections are made with semi-rigid coax. The signal generator, digital voltmeters for measuring gain and phase voltages, and test cell (on right) are not shown.

GIPSA established a research contract with BKAE University, Faculty of Food Science, Budapest, Hungary, to address several of the other questions that were raised by that initial meeting. That research is still continuing. Some of the results are summarized below.

Modeling Test Cell Characteristics

Mathematical modeling of the test cells by signal flow graphs, ABCD matrices, and finite element analysis has answered many questions regarding how test cell design and tolerances affect the measured dielectric constant of grain in the test cell.(Gillay and Funk, 2003) Figure 4 shows four test cells of different sizes that have been used to experimentally verify the mathematical predictions regarding test cell characteristics. (The largest test cell shown was designed and constructed by ARS-Athens, GA. The others were constructed at BKAE University and GIPSA.)

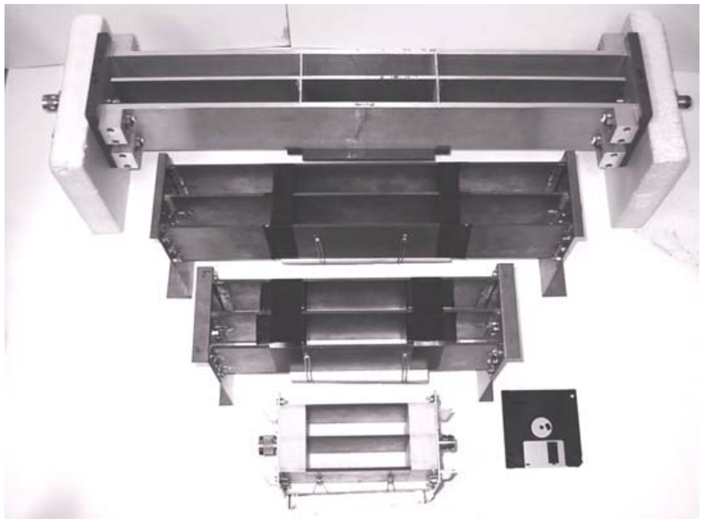

Figure 4. Four prototype test cells that were created to test the feasibility of obtaining compatible results with different sizes of test cells. (with diskette for size comparison)

Temperature Correction

Research on optimizing the temperature correction function and temperature correction coefficients for different grain groups is continuing at BKAE University and results are being prepared for publication. In general, the temperature characteristics of grain are somewhat different at 149 MHz than in the 1 to 20 MHz frequency range. The temperature sensitivity at 149 MHz is lower, especially for high-moisture grains. This may be an important benefit for the unified moisture algorithm for measuring high-moisture grain accurately at temperature extremes.

Unifying Parameters

GIPSA has continued to acquire dielectric measurements for grain samples in the Annual Moisture Survey. Those data have been added to the unified moisture algorithm, bringing the number of samples in the calibration to 5,141 and the number of separate grain types to 53. Those 53 grain types are placed in 19 groups (19 sets of three unifying parameters). Another paper in these proceedings (Mészáros and Funk, 2004) describes the mathematical details of the unified moisture algorithm, the improvements achieved in the process for optimizing the unifying parameters, and the performance achieved. Table 2 and Figure 5 summarize those results.

Table 2. Calibration statistics for the combined grain groups for 1998-2002 crop years.

Group Name	Number of Samples	Types in Group	Error St. Dev. (% M)	Calc. Slope
Soybeans	642	1	0.169	0.996
Sorghum	193	1	0.214	1.022
Sunflower	472	2	0.342	0.995
Corn	926	3	0.365	1.000
Oats	125	1	0.264	0.988
Wheat	1027	5	0.212	0.999
Barley	308	2	0.296	0.954
Rice & Durum	746	4	0.427	1.009
Peas	81	3	0.249	0.995
Mustard	33	2	0.297	0.936
Edible Beans 1	141	9	0.403	0.962
Triticale	12	1	0.171	0.942
Processed Rice	260	11	0.273	0.969
Long-Grain Proc. Rice	56	2	0.228	0.986
Edible Beans 2	30	2	0.416	0.949
Canola	16	1	0.249	1.091
Safflower	12	1	0.450	0.860
Flaxseed	28	1	0.123	0.966
High-Oil Corn	33	1	0.177	0.993
Summary	**5141**	**53**	**0.308**	

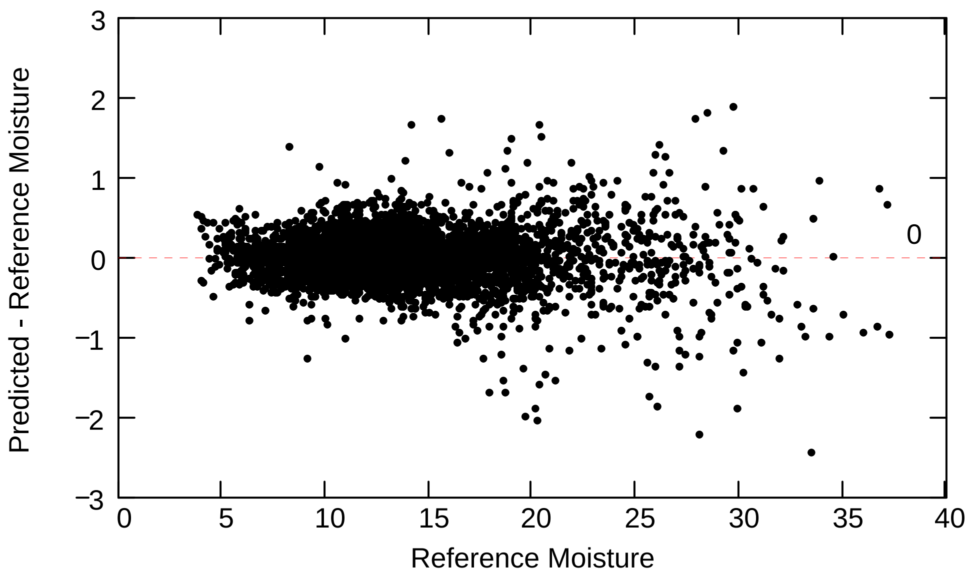

Figure 5. Performance of the Unified Moisture Algorithm (predicted minus reference moisture) for 5,141 samples representing 53 types of U.S. cereal grains, oilseeds, pulses, and processed rices for the 1998-2002 crop years.

The unifying parameters are fairly highly correlated to grain chemical and physical parameters, so it may be possible to select appropriate unifying parameters for new grain types (or types with significantly altered characteristics) without acquiring and testing grain samples having a full range of moisture values.

Low-Moisture Accuracy

The fourth-order polynomial equation that was used in the original description of the unified moisture algorithm was replaced with a fifth-order polynomial equation. This significantly improved moisture prediction accuracy at low moisture levels. Comparing Figures 2 and 5 shows the improvement in accuracy in the 5 to 10 percent moisture region. Also, Figure 5 includes several more grain types with very low moisture levels such as canola, flaxseed, safflower, and sunflower.

Conclusions

This research has produced a unified moisture algorithm that offers important benefits for grain moisture measurement in general and especially for moisture measurement for emerging specialty grains. Moving the measurement frequency from the 1 to 20 MHz region to about 149 MHz dramatically reduced the effects of sample conductivity on moisture measurement results. Effective density correction improved the achievable accuracy and caused all grain types to conform to geometrically similar dielectric constant versus moisture patterns. The dielectric characteristics (versus moisture) for grain types that were physically and chemically similar became indistinguishable and could be treated as groups. Since similar grain types that previously required separate moisture calibrations can be combined, it is unlikely that the much smaller differences within grain types will cause significant moisture errors from region to region or from crop year to crop year.

Processes were developed for optimizing unifying parameters to cause the dielectric characteristics of groups of dissimilar grains to be superimposed so that a single polynomial equation described the common curve shape. The accuracy of the method extends to low moisture levels so that grains can be marketed on dry-basis with confidence. The appropriate unifying parameters can be estimated from grain physical and chemical parameters, so reasonable moisture meter calibrations based on the unified moisture algorithm may be prepared without acquiring large numbers of samples. Thus, the unified moisture algorithm appears to overcome the major limitation of the RF dielectric method—cost, effort, and time delays in developing robust grain moisture calibrations.

Acknowledgements

Dr. Stuart O. Nelson and Dr. Kurt C. Lawrence, USDA-ARS, Athens, GA, developed and calibrated the original test cell used to collect the dielectric data and loaned a second identical test cell to BKAE University to permit comparison tests. They also provided invaluable advice at many points in the research project.

The USDA-GIPSA-TSD-ISE Moisture Group supervised by Dr. Rampton conducted the instrument tests to acquire all of the VHF dielectric data needed to develop the Unified Moisture Algorithm. Special thanks are due Mr. Steven Burton and Ms. Lucille Clark who did the bulk of the instrument tests and to Ms. Patricia Jackson who oversaw and organized the day-to-day operations and data organization in the laboratory.

Ms. Brenda Evans and Mr. Glenn Terrill, USDA-GIPSA-TSD-ARTS performed the reference moisture analyses for all of the grain samples.

Mr. Larry Freese, Mathematical Statistician, USDA-GIPSA-TSD-ISE developed SAS programs to facilitate the compilation and processing of data from thousands of separate data files and provided valuable statistical expertise during the development of the algorithm.

The on-going research regarding the Unified Moisture Algorithm at BKAE University has been supported in part by a grant and equipment loans and donations from USDA-GIPSA-TSD.

The Agilent Technologies E4991A RF Material/Impedance Analyzer used for VHF dielectric measurements at BKAE University was provided by a grant from the Hungarian Ministry of Education.

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