# UNIFYING PARAMETERS FOR A MORE EFFECTIVE GRAIN MOISTURE MEASUREMENT METHOD


## ABSTRACT

Collaboration between USDA-Grain Inspection, Packers and Stockyards Administration (Kansas City, MO) and USDA-Agricultural Research Service (Athens, GA) resulted in a substantially improved dielectric method for grain moisture measurement. This method effectively combines many diverse grain types into a single "unified calibration" that is capable of moisture measurement accuracy that is as good as or better than what is achievable for grain-specific calibrations with current instruments. In this method, similar grain types (such as different classes of wheat or different types of edible beans) are placed in grain groups that can be measured without knowing the specific grain type. For each of the groups, certain "unifying parameters" are needed to enable all of the grain groups to be combined into a single "unified calibration" that is applicable to virtually all types of cereal grains and oilseeds.

GIPSA has been supporting research at BKAE University, Faculty of Food Science, for the purpose of developing methods for optimizing the necessary unifying parameters. This paper explains the roles of the unifying parameters in the new moisture measurement method and the processes for developing the unifying parameters. Specific optimized values for the unifying parameters for different grain groups are given, and the performance improvements achieved by optimizing the parameters are shown.


## INTRODUCTION

The United States Department of Agriculture—Grain Inspection, Packers and Stockyards Administration has used the radio-frequency (RF) dielectric method to measure moisture content in grain for over forty years. In Hungary and most of the rest of Europe large grain receiving stations are also using this type of technology to measure the moisture content of grain samples because the method presents an attractive combination of good accuracy, relatively simple calibration development (for one grain type), and moderate manufacturing cost. However, the technology is burdened by the need for separate calibrations for each of dozens of grain types and yearly checking of calibrations to ensure continuing accuracy.

Research collaboration between USDA-GIPSA and USDA-Agricultural Research Service (Athens, GA) over the period of 1995 to 2001 resulted in an improved RF dielectric method that effectively combines many diverse grain types into a single "unified calibration." This method is capable of moisture measurement accuracy that is equal to or better than what is achievable for grain-specific calibrations with current instruments. In this method, similar grain types are placed in grain groups that can be measured without knowing the grain type.

GIPSA has been supporting continuing research at BKAE University, Faculty of Food Science, for the purpose of developing methods for optimizing the necessary unifying parameters. This paper is a progress report on that effort. The aims of this study are to explain the roles of the unifying parameters in the new moisture measurement method, to improve the processes for developing the unifying parameters, and to create methods for developing unifying parameters from grain physical and chemical properties—so as to minimize the effort in calibration development.

# MATERIALS AND METHOD

## Grain Samples

More than 5000 grain samples were tested by GIPSA technical staff in the course of this research. Table 1 summarizes the grain types and numbers of samples that were tested during each crop year. This research utilized the samples that were collected through GIPSA's Annual Moisture Calibration Survey in the United States between 1998 and 2002. (USDA-GIPSA, 1999) This program provides a uniquely extensive, broad, and representative sample set to ensure accurate calibrations for official grain moisture measurements—and it is ideally suited for research to investigate dielectric properties that affect moisture measurement and to develop improved moisture measurement algorithms. The reference moisture value for each test sample was determined by GIPSA technical staff using the appropriate USDA standard air oven method. (Burden, 1998)

## Instrumentation

The HP-4291A (Figure 1) is a single-port RF instrument designed to measure and record complex reflection coefficients with high precision from 1 to 1800 MHz. It includes software to calculate correction parameters to calibrate the instrument with standard networks (open, short, and 50-ohm load) at the instrument's test port and to extend that calibration to other reference planes—in this case the grain test cell described below. The instrument has the capability to store data to a floppy disk or send it to an external computer through the GPIB interface.

## Test Cell

The test cell (Figure 1) was constructed as a 50-ohm transmission line. (Lawrence et al, 1999). It consists of three parallel aluminum plates. The ends of the plates are connected to endplates from a Hewlett-Packard 805A Slotted Line. Each endplate contains a machined 50-ohm transition from a Type-N coaxial connector to a threaded stud that is connected directly to the center plate. The test cell was designed to permit transmission coefficient measurements as well as reflection coefficient measurements.

## Test Method

A digital thermometer (Shore Sales Digital Thermometer Model LT-207) for room temperature tests and alcohol-in-glass thermometers for extreme-temperature tests were used to determine sample temperature immediately before pouring the sample into the loading funnel. The sample was loaded into the test cell with a process intended to achieve a moderate packing density. Grain was allowed to flow from the filled funnel into the center of the test cell and completely over-fill the test cell. The excess was removed by striking off the test cell with the type of striker used by the USDA for official test weight determinations. This established a fixed volume for the test. Complex reflection coefficient measurements from 1 and 501 MHz were recorded using the HP-4291A. The test cell was emptied by removing a sliding gate below the grain-holding section, and the sample was weighed. The measured data were converted from complex reflection coefficients to relative complex permittivity by means of an iterative solver in a custom-designed Mathcad program.(Mathsoft, 2000) The conversion was based on a signal flow graph analysis of the test cell.(Funk, 2001) The calibration parameters for the conversion algorithm were determined from the results of tests performed by Dr. Kurt Lawrence, ARS-Athens, GA, using reagent-grade alcohols. Analysis of the data (Funk, 2001) showed that a single frequency, approximately 149 MHz, to be the most suitable for RF moisture measurements. That measurement frequency was used for the work reported in this paper.

**Table 1. Tested Grain Types**

| GRAINS TESTED WITH HP-4291A IMPEDANCE ANALYZER | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Grain group name** | **Grain name** | **1998 Crop** | **1999 Crop** | **2000 Crop** | **2001 Crop** | **2002 Crop** | **Totals** |
| Soybean | Soy | 99 | 137 | 135 | 123 | 148 | 642 |
| Sorghum | Sorghum | 11 | 44 | 54 | 42 | 42 | 193 |
| Sunflower | Oil type | 66 | 137 | 77 | 74 | 69 | 423 |
| | Confectionary | | 49 | | | | 49 |
| Corn | Corn | 115 | 217 | 143 | 179 | 214 | 868 |
| | Waxy corn | | 44 | | | | 44 |
| | Popcorn | | | | | 14 | 14 |
| Oats | Oats | 25 | 19 | 13 | 47 | 21 | 125 |
| Wheat | Hard white wheat | 33 | 68 | 65 | 7 | 26 | 199 |
| | Soft white wheat | 28 | 53 | 46 | 15 | 34 | 176 |
| | Soft red winter wheat | 15 | 55 | 56 | 68 | 70 | 264 |
| | Hard red winter | | | | 48 | 61 | 109 |
| | Hard red spring | 40 | 47 | 55 | 79 | 58 | 279 |
| Barley | Two row barley | 10 | 29 | 32 | 31 | 34 | 136 |
| | Six row barley | 29 | 25 | 39 | 32 | 47 | 172 |
| Rice &Durum | Short grain rough rice | | 25 | | 60 | | 85 |
| | Long grain rough rice | 38 | 33 | 44 | 86 | 43 | 244 |
| | Durum wheat | 4 | 50 | 24 | 50 | 49 | 177 |
| | Medium grain rough rice | 48 | 50 | 37 | 56 | 49 | 240 |
| Peas | Austrian winter peas | | | | 14 | 12 | 26 |
| | Smooth green dry peas | | 42 | | | | 42 |
| | Wrinked dry peas | | | | 4 | 9 | 13 |
| Mustard | Brown mustard seed | | | | | 27 | 27 |
| | Yellow mustard seed | | | | | 6 | 6 |
| Edible beans | Dark red kidney bean | | 12 | | 6 | | 18 |
| | Large lima beans | | | | 1 | | 1 |
| | Light red kidney bean | | 11 | | | | 11 |
| | Split peas | | | | | 16 | 16 |
| | Garbonzo bean | | | | 15 | | 15 |
| | Small red beans | | | | 13 | 17 | 30 |
| | Dark light red kidney bean | | | | 4 | | 4 |
| | Pink beans | 11 | | | 7 | 23 | 41 |
| | Yellow eyed bean | | | | | 5 | 5 |
| Triticale | Triticale | | | | | 12 | 12 |
| Canola | Canola | 16 | | | | | 16 |
| Safflower | Safflower | | 12 | | | | 12 |
| Flaxseed | Flaxseed | | 28 | | | | 28 |
| High-oil corn | High oil corn | 17 | 16 | | | | 33 |
| Edible bean 2 | Great northern beans | 10 | | | | | 10 |
| | Pinto beans | 20 | | | | | 20 |
| Processed rice | Medium grain brown | | | | 30 | 22 | 52 |
| | Long/medium second head milled rice | | | | 16 | 16 | 32 |
| | Brewers milled rice | | | | 6 | | 6 |
| | Short grain second head milled rice | | | | 13 | | 13 |
| | Short grain milled rice | | | | 15 | 12 | 27 |
| | Second head milled rice parboiled | | | | | 10 | 10 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Short grain brown rice | | | | 9 | 8 | 17 |
| | Brewers milled rice parboiled | | | | | 10 | 10 |
| | Medium/short second head milled rice | | | | | 16 | 16 |
| | Medium grain milled rice parboiled | | | | | 14 | 14 |
| | Medium grain milled | | | | 29 | 34 | 63 |
| Long Grain Processed Rice | Long grain milled rice | 10 | 20 | | | | 30 |
| | Long grain brown rice | 10 | 16 | | | | 26 |
| **Total Samples** | | **655** | **1239** | **820** | **1179** | **1248** | **5141** |
| **Total Types** | | **21** | **25** | **14** | **31** | **34** | **53** |

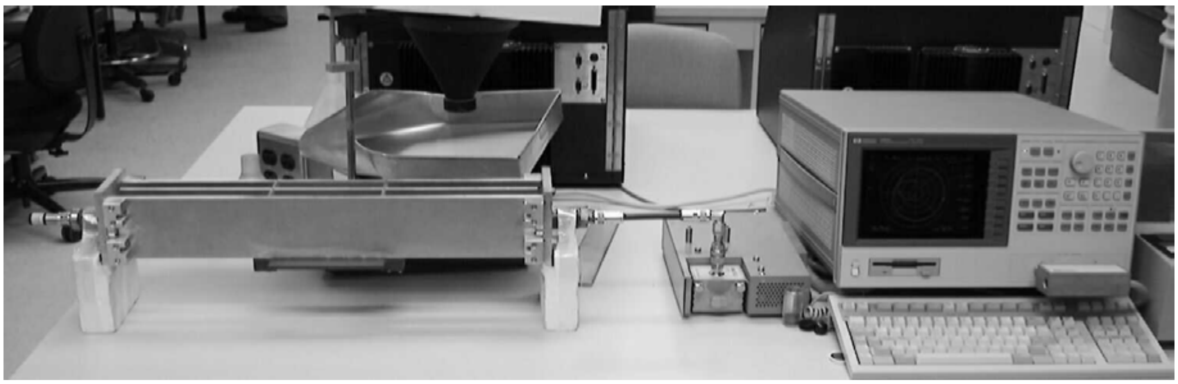

**Figure 1. Transmission line test cell and HP-4291A RF Material/Impedance Analyzer**

## RESULTS AND DISCUSSION

<u>Data Transformations Prior to Applying Unifying Parameters</u>

In addition to the iterative procedure for converting complex reflection coefficients to relative complex permittivity, two other transformations are required to put the data into a form suitable for predicting moisture content in grain.

*Test Cell Standardization*

Other research at BKAE University has shown that the data need to be corrected for two effects that are caused by the test cell design.(Gillay and Funk, 2003) The presence of dielectric materials in proximity to the test cell (specifically the cell "gate") causes the calculated dielectric constant of the empty test cell to be other than 1.000. To correct this, an offset value $\varepsilon_{ec}$ is subtracted from the measured relative complex permittivity as shown in Equation 1. Secondly, the parallel-plate transmission line test cell is does not support a true transverse-electric-magnetic (TEM) mode when grain is in the test cell. A filling factor *FF* is needed to convert the measured relative complex permittivity to actual relative complex permittivity. The real part of the relative complex permittivity $\varepsilon_r$ is used for further calculations.

$$\varepsilon_r = \mathrm{Re}\left(\varepsilon_{meas} - \varepsilon_{ec}\right) \cdot FF + 1 \qquad (1)$$

*Density Correction*

Funk (2001) showed that density-corrected dielectric constant is much more useful for grain moisture measurement than uncorrected dielectric constant. The Landau and Lifshitz, Looyenga dielectric mixture equation as restated by Nelson (Nelson, 1992) was found to be particularly effective for adjusting the dielectric constants of different grain samples to a common density (target density). (Funk, 2001) This correction minimized errors caused by three major sources of density variations: moisture level, filling method, and sample-to-sample variation. Equation 2 is the density correction equation as used in this research.

$$\varepsilon_{dc} = \left[ \left( \varepsilon_r^{\frac{1}{3}} - 1 \right) \cdot \frac{wt_{target}}{wt_{sample}} + 1 \right]^3 \tag{2}$$

$\varepsilon_{dc}$ is the density-corrected dielectric constant
$\varepsilon_r$ is the dielectric constant
$wt_{target}$ is the target weight (g)
$wt_{sample}$ is the sample weight (g)

All three generations of unifying parameters (as discussed below) used the same basic density-correction equation, but the means of selecting the target weights were different for the second and third generation than for the first generation.

*Temperature Corrections*

Temperature significantly influences the dielectric characteristics of grain; the dielectric constant increases with increasing temperature. Funk (2001) found that a simple temperature correction function (Equation 3) was reasonably effective for correcting temperature effects on predicted moisture values.

$$M_{tc} = M_{pred} - Ktc \cdot (T - 25) \tag{3}$$

$M_{pred}$ is the moisture value calculated from dielectric characteristics
$Ktc$ is the temperature correction coefficient (% moisture per degree Celsius)
$T$ is the measured sample temperature
$M_{tc}$ is the predicted moisture content with temperature correction

That is, the temperature correction required is linear with temperature and independent of moisture content (to a reasonable approximation). When developing moisture calibration equations it is advantageous to reverse-correct the reference moisture values for temperature, as shown in Equation 4, instead of forward-correcting the dielectric constant values. This simplifies calibration development, especially when multi-term (polynomial or other) non-linear equations are used to fit dielectric data to air oven results.

$$M_{adj} = M_{ref} + Ktc \cdot (T - 25) \tag{4}$$

$M_{ref}$ is the reference (air oven) moisture value
$M_{adj}$ is the reverse temperature-corrected air oven moisture value

Current research at BKAE University is focusing on further optimizing the temperature correction functional form and the specific correction coefficients for different grain types. The temperature correction values applied in this study are the estimated values by Funk (2001) based on temperature tests performed at USDA-GIPSA.

Processes for Developing Unifying Parameters

Funk (2001) observed that moving the measurement frequency to about 150 MHz (instead of the more usual 1 to 20 MHz) and applying Equation 2 for density correction:1) dramatically reduced the scatter within a grain type, 2) reduced the differences among grain types, and 3) caused the dielectric versus moisture data plots for each of the grain types to assume geometrically similar shapes. The purpose of the unifying parameters is to align those data sets so that a single polynomial equation fits all grain types.

This section is divided four parts: first generation, second generation, and third generation processes for developing unifying parameters. The first generation of unifying parameters were developed at GIPSA (Funk, 2001), and the same methods were used at BKAE University to optimize those parameters and apply the processes to additional grain types. The second and third generations of unifying parameter processes were developed at BKAE University. The third generation processes were used to optimize unifying parameters for several additional grain types based on data provided by GIPSA.

*First Generation Unifying Parameters*

The first generation unifying parameters included different target weights for each of 8 grain groups. The error in the linear fit between density-corrected dielectric constant and adjusted moisture content was independent of the target sample weight chosen for the grain group. Changing the target weight only changed the slope of the linear regression. Therefore, target sample weight ($wt_{targ}$ in Equation 2) was chosen for each grain group to make the linear regression slope (between density-corrected dielectric constant and adjusted moisture content) be exactly 6.000 % moisture per unit of density-corrected dielectric constant. This was a slope adjustment step, but it did not use an explicit slope coefficient. Figure 2a shows the results of this adjustment. It was observed that data for all grain types seemed to coalesce into two groups—soybeans and sunflower seed (oilseeds) in one and all other grains (cereal grains) in the other.

After that slope adjustment it appeared that the differences among the groups were essentially offsets along the vertical (dielectric constant) axis. A separate offset parameter *OP* was applied to the density-corrected dielectric constants in each grain group to minimize the average differences among grain groups. (Equation 5) The results are shown in Figure 2b.

$$\varepsilon_{adj} = \varepsilon_{dc} + OP \tag{5}$$

After applying the offset adjustments, the density-corrected dielectric constant versus moisture curves were very nearly superimposed for all grains. However, some differences were visible in the very low moisture region. Slope changes were observed for each grain group at or below about 10 % moisture. The bend for sunflower seeds occurred at about 7 % moisture, the bend for soybeans was at about 8.5 % moisture, and the bend for the cereal grains was at about 10 % moisture (or slightly higher). It was recognized that these bends were occurring at about the same moisture levels where conductivity caused much more dramatic bends in the dielectric constant versus moisture curves at much lower frequencies. (Funk, 2001) This change in slope was found to be fairly stable over the range of 100 to 250 MHz. It was concluded that this slope change was due to two different water phases (monolayer water and higher layers of water) that have different dielectric constants. This commonality of slopes in both regions suggested one last correction to bring all grain types together in a single prediction equation.

Starting from the condition portrayed in Figure 2b, the data for soybeans were translated along the common line (slope = 6.000) by +1.5 % moisture content and +1.5/6.0 = 0.25 units of dielectric constant; and the data for sunflower seeds were translated by +3.0 % moisture content and +3.0/6.0 = 0.50 units of dielectric constant to get the close agreement among grain groups shown in figure 2c. The translation unifying parameter *TP* was applied according to Equations 6 and 7. No translation unifying parameter was applied to the cereal grains.

$$M_{adj} = M_{ref} + Ktc \cdot (T - 25) + TP \tag{6}$$

$$\varepsilon_{adj} = \varepsilon_{dc} + OP + \frac{TP}{6} \tag{7}$$

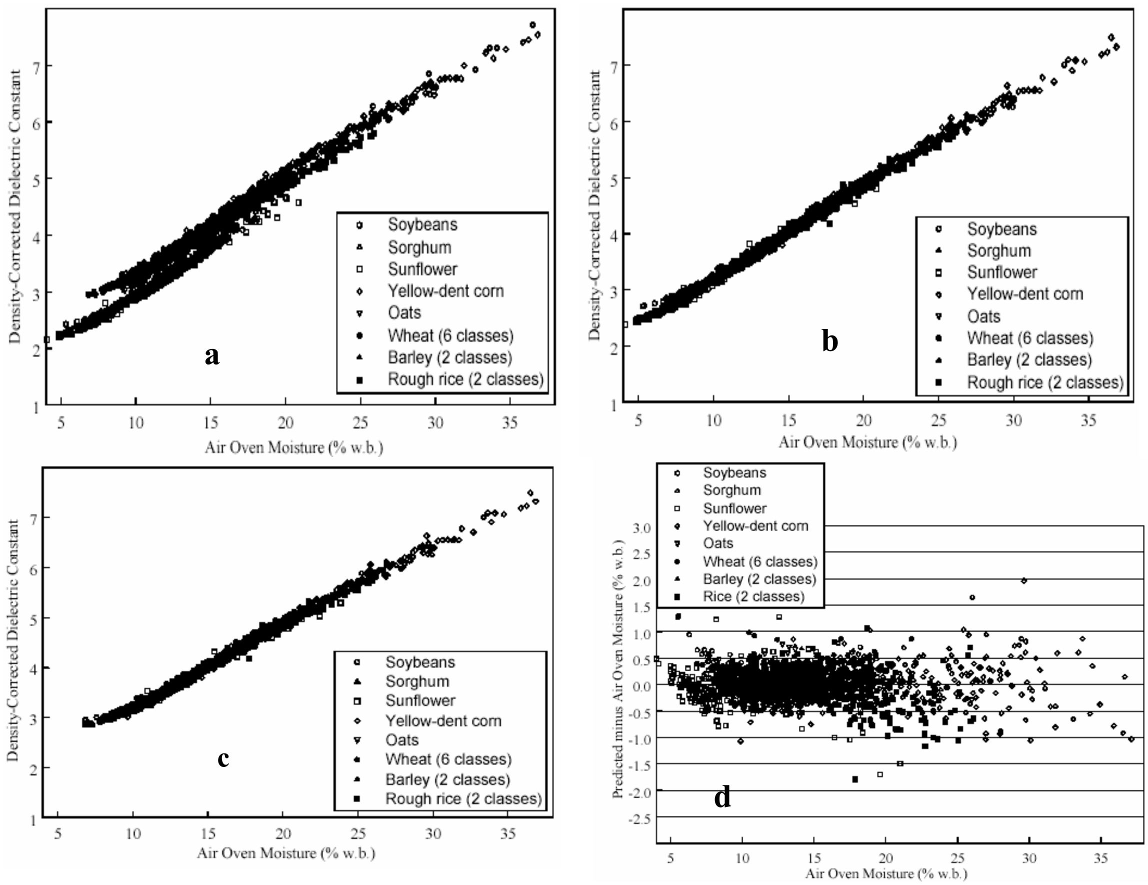


**Figure 2. Details of the first generation of Unified Moisture Algorithm. a) Plot of density corrected dielectric constant (each grain group density-corrected to give slope of 6.000) at 149 MHz using the Landau-Lifshitz, Looyenga mixture equation versus temperature corrected reference moisture for 2331 samples representing over 15 types of U.S. cereal grains, oilseeds and pulses for the 1998-2000 crop years. b) Same as in previous plot except each grain group is offset to minimize the average predicted moisture errors. c) Same as previous plot except the data are translated along the common slope line to align the curve shapes in the low moisture region with 4th order polynomial calibration curve d) Performance of the Unified Moisture Algorithm (predicted minus reference moisture)**

A 4$^{th}$-order polynomial equation was fitted to $M_{adj}$ and $\varepsilon_{adj}$ to create a "unified" calibration equation. (Equation 8) Note that the temperature correction and the translation unifying parameter are subtracted in Equation 8 to get the final predicted moisture value.

$$M_{tc} = \sum_{r=0}^{4} \left(\varepsilon_{adj}\right)^{r} \cdot CC_{r} - Ktc \cdot \left(T - 25\right) - TP \qquad (8)$$

$CC_r$ is the $r$ order polynomial regression coefficient

Figure 2d shows the predicted moisture measurement error for this calibration model. The overall standard deviation of differences for the calibration was 0.29 % moisture.

*Optimizing the First Generation Unifying Parameters*

This project started in 2002 at BKAE University. Data from GIPSA representing over 2000 more grain samples, more crop years (2001 and 2002), lower moisture samples, and many new grain types were added to the unified calibration. These included confectionary sunflower, popcorn, short grain rough rice, many types of processed rice, peas, mustard, many types of edible beans, and triticale. The Mathcad program used for the calibration process was rewritten and more fully automated by Zoltán Gillay, BKAE University. The aim of the optimization was to improve moisture accuracy and to reduce the number of variables in the calibration (put together as many grain types as possible without sacrificing moisture measurement accuracy).

At the beginning of the optimization there were 15 grain separate grain groups (soybean, sorghum, sunflower seed, corn, oats, wheat, barley, rice, durum wheat, confectionary sunflower, peas, mustard, edible beans, processed rice, and triticale). Analyzing the behavior of the grain types in the calibration suggested reducing the number of groups to 13. Confectionary sunflower was grouped with oil-type sunflower seed and durum wheat was grouped with rice based on similar unifying parameters.

A fifth-order order polynomial calibration curve yielded a substantially better fit to the data than the previous fourth-order equation—especially at very low and very high moisture levels. The best achievable overall standard deviation of differences was 0.339 percent moisture as compared to 0.29 with the original (much more limited) data set.

*Second Generation Unifying Parameters*

For this study 4887 grain samples representing almost 50 types of U.S. cereal grains, pulses and processed rices for the 1998-2002 crop years were tested. Figure 3a is a plot of dielectric constant versus reference moisture for those samples.

An attempt to predict the "first generation" unifying parameters from grain chemical and physical parameters was not very successful. Therefore, an alternate approach was developed for defining the unifying parameters. Instead of selecting a separate target weight for density-correcting the samples in each grain group, as in Figure 2a, a single target weight (approximately the average for all samples tested) was used for density-correcting all grain samples of all groups. (Equation 2) The resulting density-corrected dielectric constant values are plotted versus adjusted reference moisture values in Figure 3b. This figure suggested that a simple slope correction might "unify" the data effectively.

For each grain group, the slope (% moisture per unit density-corrected dielectric constant) was calculated for the portion of the samples with reference moisture values between 10 and 20 % moisture. The samples below 10 % moisture and above 20 % moisture were excluded because the “standard” curve shape is quite non-linear in those regions. The slope unifying parameter *SP* was defined as the correction factor needed to adjust the slope of each grain group to 6.000 in the 10 to 20 % moisture range. The data for the different grain groups appeared to rotate about a point (M = 5, $\varepsilon_{dc}$ = 2.5) so an offset unifying parameter *OP* of approximately 2.5 was hypothesized. Figure 3c shows the data with the slope unifying parameter applied. The offset unifying parameter was iteratively adjusted for each grain group, resulting in Figure 3d. As before, a translation unifying parameter *TP* was needed to align the curve shapes for the different grain groups in the low moisture region. After applying the three unifying parameters to each grain group the data appeared as in Figure 3e. A fifth-order polynomial was fit to the data as shown in Figure 3f. The best overall calibration error with this method and these data was 0.3066 percent moisture (standard deviation of differences with respect to reference moisture values).

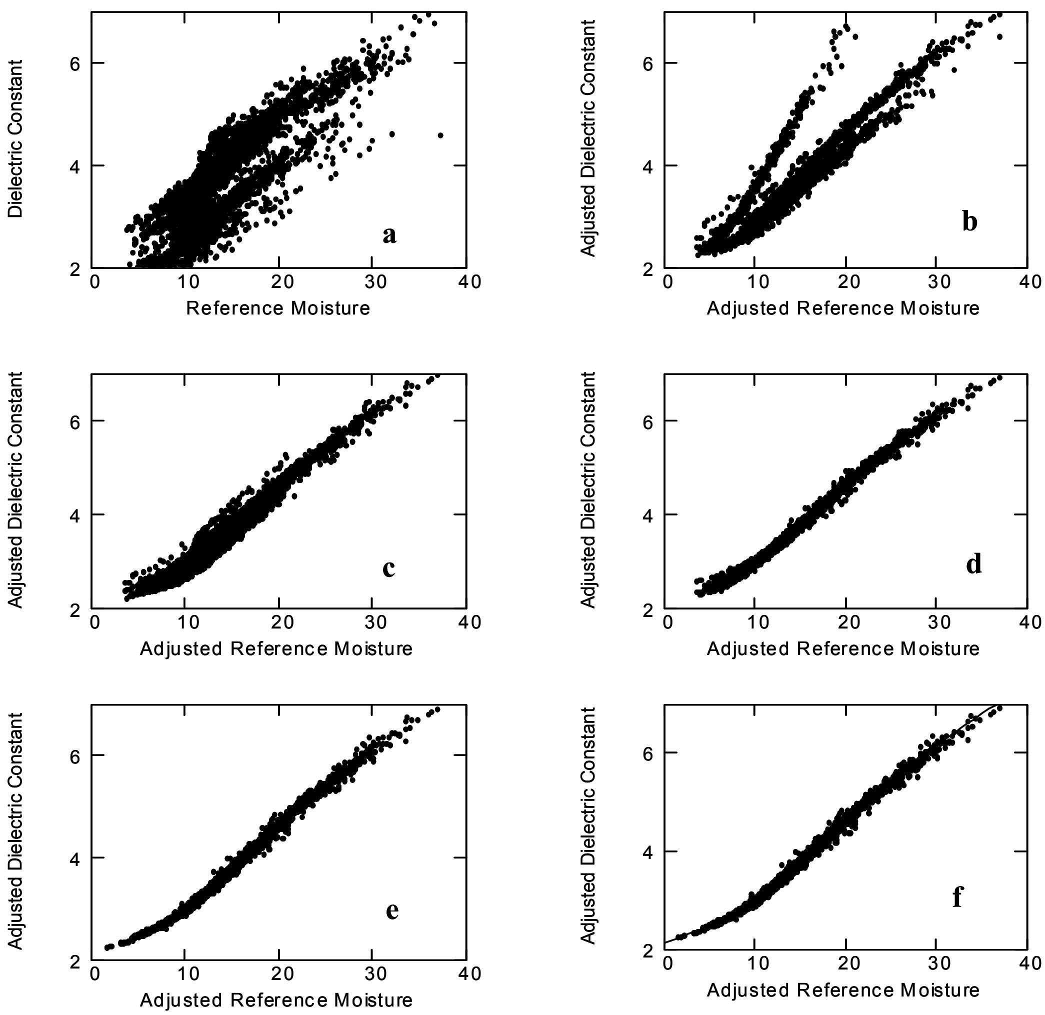


**Figure 3. Details of the second generation Unified Moisture Algorithm. a) Plot of dielectric constant versus reference moisture for 4,887 samples representing about 50 types of U.S. cereal grains, oilseeds, pulses, and processed rices for the1998-2002 crop years. b) Same as previous plot except all dielectric constant values are density-corrected to a common density using Equation 2 and the reference moisture values are temperature corrected (in reverse). c) Same as previous plot except each grain group is adjusted for a common slope (percent moisture per unit dielectric constant) in the 10-20 % moisture range. d) Same as in previous plot except each grain group is offset to minimize the average predicted moisture errors. e) Same as previous plot except the data are translated along the common slope line to align the curve shapes in the low moisture region. f) Same as previous plot except with the best-fit 5$^{th}$ order polynomial calibration curve superimposed on the adjusted dielectric constant versus moisture data plot.**

Equations 9-12 are used for the second generation unifying parameters. The variables are defined above.

$$\varepsilon_{adj} = \left(\varepsilon_{dc} - OP\right) \cdot SP + 2.5 + \frac{TP}{6} \tag{9}$$

$$M_{adj} = M_{ref} + Ktc \cdot \left(T - 25\right) + TP \tag{10}$$

$$M_{pred} = \left( \sum_{r=0}^{5} \left(\varepsilon_{adj}\right)^{r} \cdot CC_r \right) - TP \tag{11}$$

$$M_{tc} = M_{pred} - Ktc \cdot \left(T - 25\right) \tag{12}$$

This approach to the unifying parameters yielded some advantages over the first generation approach. As discussed below, the new unifying parameters were fairly highly correlated to grain chemical and physical parameters. This offered the possibility of creating usable calibrations for new grain types with minimal effort. Calculating the slope unifying parameter directly from linear regression of the data was much less tedious than the iterative process required for finding the optimum target weight for each grain group.

To test the stability of the optimization process, the unifying parameters (with the same target density) were obtained at fifteen other frequencies (19 to 251 MHz). The *SP* values were calculated and the *OP* values were adjusted iteratively to achieve the minimum moisture error at each frequency. Figures 4 and 5 present the *SP* and *OP* values as a function of frequency for three grain types. (*TP* values varied little and are not shown.) The optimum unified parameter values are nearly constant over a wide range of frequencies around 150 MHz.

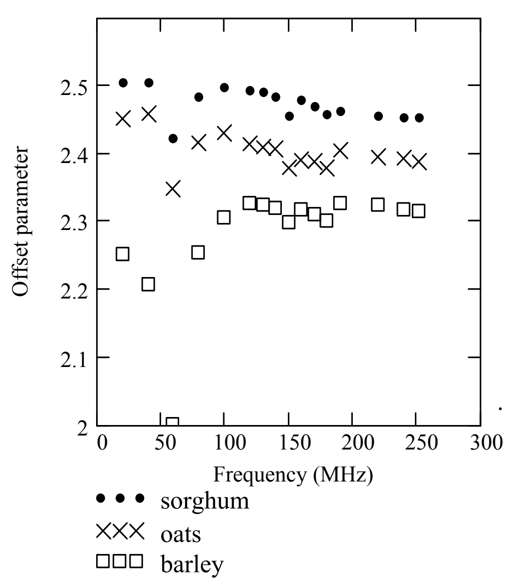


**Figure 4. Offset parameters versus frequency**

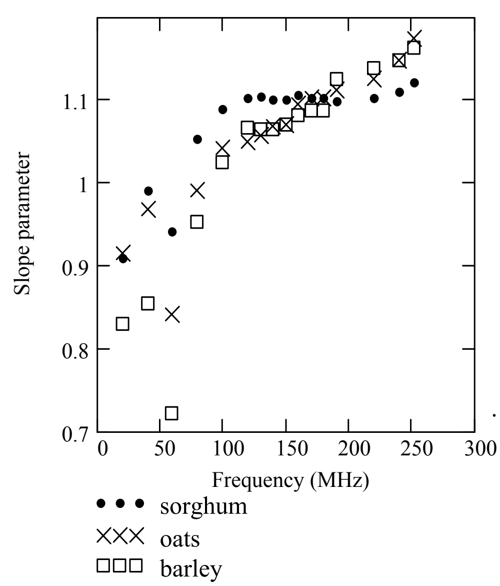


**Figure 5. Slope parameters versus frequency**

*Third Generation Unifying Parameters*

In this stage of the research, several additional grain types were added to the unified calibration. The second generation unifying parameters provided good moisture measurement performance, but further simplification of the process was needed to be able to add more grain types and groups efficiently. The second generation method required iteratively optimizing the offset parameter OP and the translation parameter TP for each grain type and the fifth-order polynomial equation for all grain types together each time a new grain type was added.

The key insight in moving to the third generation approach was that the curve shape should be fixed and additional grain types should simply be adjusted to match the existing standard curve shape (Equation 13). To do this, it was necessary to compare the measured adjusted dielectric constant (Equation 9) to the predicted adjusted dielectric constant calculated from the adjusted reference moisture value (Equation 10). This was accomplished by cubic spline interpolation. For any value of adjusted reference moisture, interpolation gives the associated adjusted dielectric constant value. The unifying parameters are adjusted to minimize the differences between the measured adjusted dielectric constant values (Equation 9) and the values predicted from cubic spline interpolation.

$$M_{pred} = -122.22 + 124.49 \cdot \varepsilon_{adj} - 47.724 \cdot \left(\varepsilon_{adj}\right)^2 + 9.3685 \cdot \left(\varepsilon_{adj}\right)^3 - 0.90096 \cdot \left(\varepsilon_{adj}\right)^4 + 0.034250 \cdot \left(\varepsilon_{adj}\right)^5 \quad (13)$$

Figure 6 illustrates the process (with synthetic data used for clarity). To begin the process, density-correct the dielectric constant data (using Equation 2 and the standard target weight). Select a tentative temperature correction coefficient *Ktc* based on the known Ktc values for other grain types with similar chemical composition. Select initial unifying parameter values based on those of similar grain types (though the initial unifying parameter values are not important). Calculate the adjusted dielectric constant values (Equation 9) and the adjusted reference moisture values (Equation 10) based on the initial parameters and the measured data. Calculate the predicted adjusted dielectric constant values by cubic spline interpolation. Plot the differences between the measured and predicted adjusted dielectric constant values. Figure 6a shows typical values at this stage. The data will likely be offset vertically from the zero (target) line and show two regions with distinctly different slopes.

Adjust the slope unifying parameter *SP* to cause the slope of the high-moisture part of the curve (above about 12 % moisture) to be parallel to the zero line as shown in Figure 6b. Then adjust the translation unifying parameter *TP* to cause the low-moisture part of the curve (below about 12 % moisture) to be parallel with the zero line as shown in Figure 6c. Finally, adjust the offset unifying parameter so that the average difference is zero as in Figure 6d. That completes the process of optimizing the unifying parameters for that grain type.

Besides the relative simplicity, sensitivity, and accuracy of this process, it has the advantage of not affecting the moisture measurements for any other grain type because the standard curve (Equation 13) is not recomputed in the process. After adjusting the unifying parameters for each grain group with this method, the overall calibration error (standard deviation of differences) was 0.308 percent moisture. The calibration performance statistics and unifying parameters for each grain group are listed in Table 2.

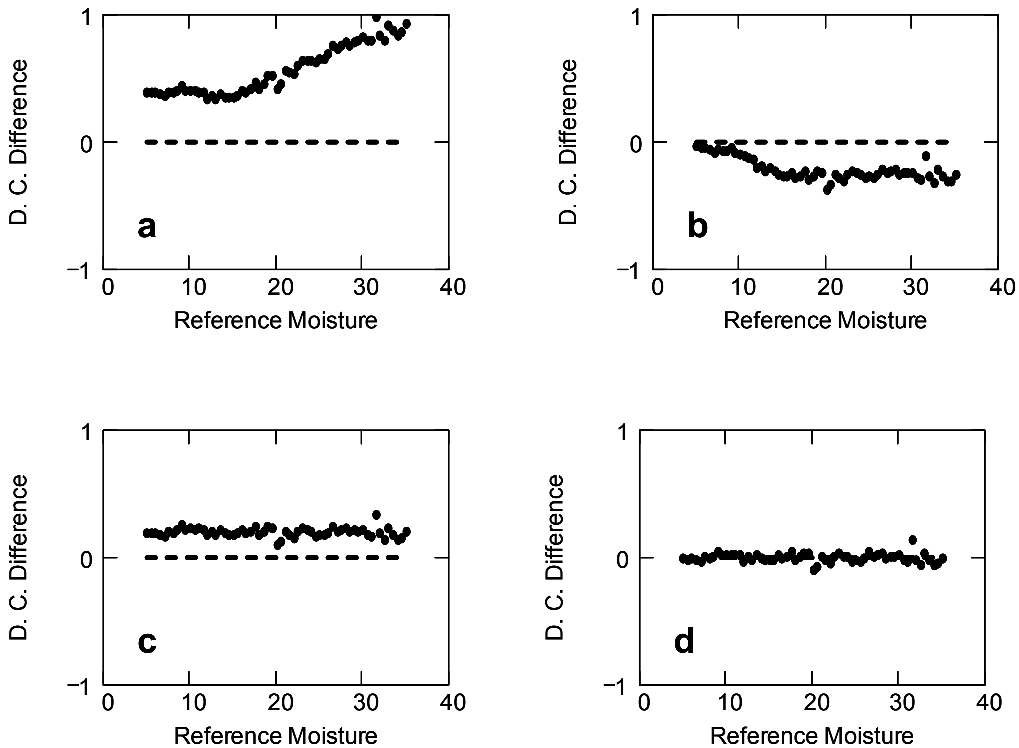


**Figure 6. Details of the third generation Unified Moisture Algorithm illustrated with synthetic data. a) Initial differences between the measured adjusted dielectric constant and predicted adjusted dielectric constant. b) Same as previous plot except the slope parameter is adjusted to minimize slope error above 12 % moisture. c) Same as previous plot except the translation parameter is adjusted to minimize the slope error in the moisture range below 12%. d) Same as previous plot except the offset parameter is adjusted to achieve zero mean error between the measured and predicted adjusted dielectric constant values.**

*Determining Unifying Parameters from Chemical and Physical Properties of Grains*

After optimizing the unifying parameters (slope, offset and translation parameters) for numerous grain types, the authors attempted to establish relationships between the unifying parameters and the grain groups' physical and chemical properties. The purpose of this research was to simplify and reduce the cost and time to fit new grain types or grain groups into the calibration process.

Physical and chemical properties of several grain types were determined from the literature. (Nelson, 2001, 2002) (IGP, 1988) Grain types used for this study included soybeans, sorghum, sunflower seed, corn, oats, wheat, rice, durum wheat, confectionary sunflower, and edible beans. The chemical properties that were considered in the analysis were protein (%), oil (%), ash (%), and carbohydrates (%); and the physical properties were bulk density (g/cm$^3$), seed weight (g), seed volume (mm$^3$), kernel density (g/cm$^3$) and kernel major, minor, and middle axis dimensions (mm). Multiple linear regression functions written in Mathcad were used to find correlations between the third generation of unifying parameters and the grain physical and chemical properties.

Slope parameters were found to correlate most highly with carbohydrate content and the kernel major axis dimension. The multiple correlation coefficient ($R^2$) using those two variables was 0.979. The offset parameters correlated most highly with carbohydrate and protein contents. The $R^2$ value was 0.963. The translation parameters adjustment values were found to correlate with oil, protein content, and the length of the intermediate axis of the kernel. The $R^2$ value was lower, 0.909, for predicting the translation parameters.

The slope, offset, and translation parameters were re-predicted from grain physical and chemical properties using the equations derived from multiple linear regression. Figure 5 presents the predicted parameters versus the optimized unifying parameters. More complete data on grain physical and chemical properties are needed to refine the predictive equations, but the present results are encouraging. The slope parameter is predicted best, and that parameter is the most important for creating new calibrations. If the slope parameter can be predicted well from grain physical and chemical parameters and the main moisture range of interest is above 10 % (so that the translation parameter is not very important) then a reasonably good calibration can be created with just a few samples needed to adjust the offset parameter.

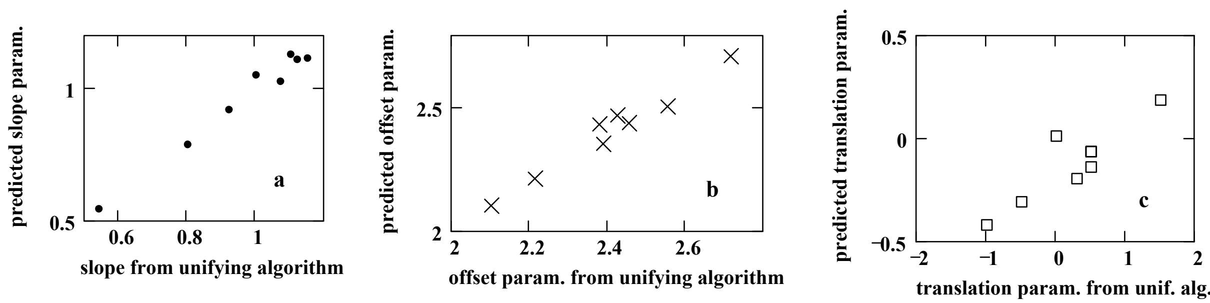


**Figure 7. Plots of the unifying parameters that were predicted from grain chemical and physical properties versus the parameters that were determined by applying the unifying algorithm to the grain dielectric and reference moisture data. a) Slope unifying parameter. b) Offset unifying parameter. c) Translation unifying parameter.**

**Table 2. Calibration statistics and estimated unifying parameters for the combined grain groups.**

| Group Name | Number of Samples | Types in Group | Error St. Dev. (% M) | Slope | Slope Unif. Para. | Trans. Unif. Para. | Offset Unif. Para. | Temp. Coefficient (%M / ºC) |
|---|---|---|---|---|---|---|---|---|
| Soybeans | 642 | 1 | 0.169 | 0.996 | 0.80 | -1.0 | 2.100 | 0.072 |
| Sorghum | 193 | 1 | 0.214 | 1.022 | 1.10 | 0.5 | 2.456 | 0.108 |
| Sunflower | 472 | 2 | 0.342 | 0.995 | 0.54 | 1.5 | 2.715 | 0.054 |
| Corn | 926 | 3 | 0.365 | 1.000 | 1.00 | 0.0 | 2.553 | 0.108 |
| Oats | 125 | 1 | 0.264 | 0.988 | 1.07 | 0.5 | 2.378 | 0.086 |
| Wheat | 1027 | 5 | 0.212 | 0.999 | 1.15 | 0.3 | 2.388 | 0.094 |
| Barley | 308 | 2 | 0.296 | 0.954 | 1.07 | -1.0 | 2.288 | 0.104 |
| Rice & Durum | 746 | 4 | 0.427 | 1.009 | 1.12 | 0.5 | 2.424 | 0.077 |
| Peas | 81 | 3 | 0.249 | 0.995 | 1.10 | -1.5 | 2.146 | 0.054 |
| Mustard | 33 | 2 | 0.297 | 0.936 | 0.88 | 0.5 | 2.399 | 0.108 |
| Edible Beans 1 | 141 | 9 | 0.403 | 0.962 | 0.92 | -0.5 | 2.213 | 0.108 |
| Triticale | 12 | 1 | 0.171 | 0.942 | 1.22 | 0.5 | 2.368 | 0.108 |
| Processed Rice | 260 | 11 | 0.273 | 0.969 | 1.20 | 0.5 | 2.622 | 0.077 |
| LG Proc. Rice | 56 | 2 | 0.228 | 0.986 | 1.30 | 0.5 | 2.830 | 0.077 |
| Edible Beans 2 | 30 | 2 | 0.416 | 0.949 | 0.92 | -0.5 | 2.480 | 0.108 |
| Canola | 16 | 1 | 0.249 | 1.091 | 0.60 | -2.0 | 2.420 | 0.054 |
| Safflower | 12 | 1 | 0.450 | 0.860 | 0.60 | 0.0 | 3.010 | 0.054 |
| Flaxseed | 28 | 1 | 0.123 | 0.966 | 0.60 | -0.2 | 2.460 | 0.054 |
| High-Oil Corn | 33 | 1 | 0.177 | 0.993 | 1.01 | 0.5 | 2.827 | 0.108 |
| **Summary** | **5141** | **53** | **0.308** | | | | | |

## CONCLUSIONS

The Unified Moisture Algorithm developed by USDA-GIPSA offers excellent accuracy and greatly reduced cost and time to develop and maintain grain moisture meter calibrations. The third generation unifying parameter process presented here provides a much simpler, more precise, and less iterative way of determining the unifying parameters for the Unified Moisture Algorithm than what was previously described in the literature. The possibility of producing accurate calibrations quickly and with minimal cost makes the UMA an attractive alternative for meeting the needs of domestic and international trade in emerging types of specialty crops. Further research is needed to better define the relationships between unifying parameters and grain physical and chemical values.

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## REFERENCES

1. Burden, W. J. 1988.Working Instructions for Air Oven Methods, in WI No: AO1-10 USDA-GIPSA-TSD, Kansas City, Missouri
2. Funk, D. 2001. An investigation of the nature of the radio-frequency dielectric response in cereal grains and oilseeds with engineering implications for grain moisture meters, Ph.D. diss. Kansas City, Missouri: University of Missouri-Kansas City
3. Gillay, Z. Funk, D.B. 2003. Sensitivity Analysis for VHF Dielectric Grain Moisture Measurements, ASAE Paper No. 033136, St. Joseph, Mich.: ASAE.
4. *Grain Manufacturing Processes Handbook 1988.* International Grains Program, Manhattan, Kansas
5. Paliwal, J.Visen, N. S. and Jayas, D.S. 1998. Determination of Physical Properties of Different Grain Types Using Machine Vision, ASAE Paper No. 98-3060, St. Joseph, Mich.: ASAE.
6. Lawrence K. C., Funk D. B., and Windham W. R., 1999. "Parallel-Plate Moisture Sensor for Yellow-Dent Field Corn," *Trans. ASAE.* **42** (5), 1353-1357

7. Mathsoft. 2000. Mathcad Users Guide with Reference Manual, Ver. 2001. Cambridge, Mass.: Mathsoft, Inc.

8. Mészáros, P. Funk, D. B. 2003. Moisture Limits for Measurement of Moisture in Cereal Grains and Oilseeds Below Zero Degrees Celsius by the Dielectric Method, ASAE Paper No. 033020, St. Joseph, Mich.: ASAE.

9. Nelson, S. O. 1992. Correlating Dielectric Properties of Solids and Particulate Samples Through Mixture Relationships,. *Trans. ASAE.* **35** (2), 625-629

10. Nelson, S. O. 2002. Dimensional and Density Data For Seeds of Cereal Grain and Other Crops, *Trans. ASAE.* Vol. **45**(1):165-170

11. Nelson, S. O. 1977. Use of Electrical Properties for Grain-Moisture Measurement, *Journal of Microwave Power* **12** (1), 67-72.

12. Nelson, S. O. 1980.Moisture-Dependent Kernel- and Bulk-Density Relationships for Wheat and Corn, *Trans. ASAE Vol.* ***23***, No. 1, pp. 139-143.

13. Nelson, S. O. 2001. Dimensional and Density Data for Kernels and Seeds of Grain and Other Crops, ASAE Paper No. 01-6137, St. Joseph, Mich.: ASAE.

14. USDA-GIPSA. 1999. *Moisture Handbook*, Washington, D.C. Available at: http://www.usda.gov/gipsa/reference-library/handbooks/moisture/moisture.htm, Accessed 14. May 2004.