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Unified Grain Moisture Algorithm

Recipe Book

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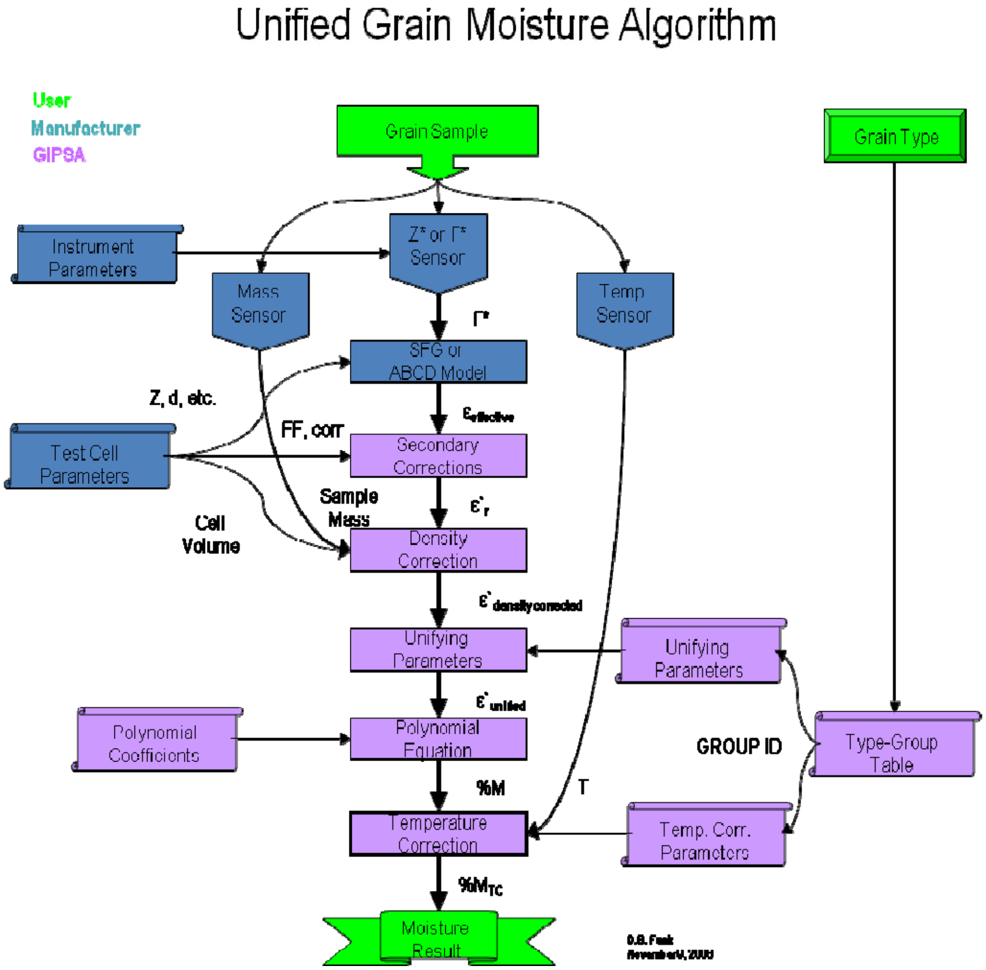
Contents



Unified Grain Moisture Algorithm

Introduction

The purpose of this document is to present a concise description of GIPSA's Unified Grain Moisture Algorithm (UGMA) and associated equations for use by entities who are involved in developing and seeking FGIS certification for UGMA-compatible grain moisture meters. More detailed explanations of the method (for those without considerable familiarity with the UGMA) are available as links on the Equipment page of the GIPSA website (www.gipsa.usda.gov).

UGMA Steps

1. Measure the dielectric constant (ε_{meas}) of the grain at a defined frequency near 149 MHz using a parallel-plate transmission line test cell of dimensions similar to those of the FGIS master cell and a loading method that provides for operator-independent measurements. This measurement requires the determination of complex impedance or complex reflection coefficient for the transmission line test cell and conversion to dielectric constant through an appropriate mathematical model for the specific test cell design.
2. Measure the ***Mass*** of the grain within the defined volume of the test cell (***TestCellVolume***).
3. Apply the Landau-Lifshitz, Looyenga-based density normalization to transform the measured dielectric constant to density-corrected dielectric constant (ε_{den}) with a common density basis (ρ_{target}= 0.67405 g/ml) for all grain types.

$$\boldsymbol{\varepsilon_{den} = \left[\left(\varepsilon_{meas}^{1/3} - 1\right) \cdot \frac{\rho_{target} \cdot TestCellVolume \cdot VR_s}{Mass} + 1\right]^3} \tag{1}$$

(Note: Grain-group-specific volume ratio factors (VR_s) may need to be inserted as multipliers in the target mass calculation (target density times test cell volume) to compensate for slight differences in loading methods among instrument models. The form of such correction factors should be reviewed with FGIS for acceptability. The ***s*** subscripts refer to grain-group-specific parameters.)

4. Apply grain-group-specific unifying parameters: Slope parameter (SP_s), Translation parameter (TP_s), and Offset parameter (OP_s) (Table 2) to the density-corrected dielectric constant as in Eq. 2.

$$\boldsymbol{\varepsilon_{adj} = (\varepsilon_{den} - OP_s) \cdot SP_s + 2.5 + \frac{TP_s}{6}} \tag{2}$$

5. Calculate the initial moisture estimate (***Moisture 1***) from the adjusted dielectric constant using the 5th order polynomial calibration (Eq. 3), where ***KCC*** is the vector of polynomial coefficients.

$$\boldsymbol{Moisture1 = \sum_{i=0}^{5}\left(KCC_i \cdot \varepsilon_{adj}^{i}\right)} \tag{3}$$

6. Using Eq. 4, apply the translation parameter (TP_s, moisture axis shift) to get the predicted moisture (prior to temperature correction) (***Moisture2***).

$$\boldsymbol{Moisture2 = Moisture1 - TP_s} \tag{4}$$

7. Apply the temperature correction function (Eq. 5). (Notes: The temperature correction function (Eq. 7), a function of temperature and moisture, may use from one to three coefficients depending on the nature of the correction required. The form of Eq. (5), used here and below, is meant to state that the ***TempCorr*** is a function involving parameters ***Temperature*** and ***Moisture2***.)

$$\boldsymbol{Moisture3 = Moisture2 - TempCorr(Temperature, Moisture2)} \tag{5}$$

8. Apply the secondary kernel-density correction (as yet, only needed for corn) to obtain the final predicted moisture result.

$$\boldsymbol{MoistureFinal = Moisture3 - SecDensCorr(Moisture3, Mass)} \tag{6}$$

Measured Values: (Note: These are critical measured parameters for demonstrating conformance with the UGMA.)

- ε_{den}: density-corrected dielectric constant at approximately 149 MHz
- Sample temperature
- Sample mass

Unifying Parameters

Three grain-group-dependent parameters are necessary to use the same polynomial calibration (basic calibration curve shape) for all grain groups. Unifying parameters are derived using an optimization algorithm that FGIS will provide upon request as an Excel file.

- OP_s: Offset parameter
- SP_s: Slope parameter
- TP_s: Translation parameter

Calibration Coefficients

The calibration is the relationship between the adjusted dielectric constant and reference moisture content (back-corrected for sample temperature and secondary kernel-density correction and adjusted by the translation parameter). For corn there is no adjustment because the unifying parameters are ***OP***=0, ***SP***=1 and ***TP***=0. ***KCC*** is the vector containing the coefficients of the fifth order polynomial calibration equation. One "dummy point" was inserted in the calibration data (Figure 1) to control the shape of the extreme high moisture end of the polynomial curve.

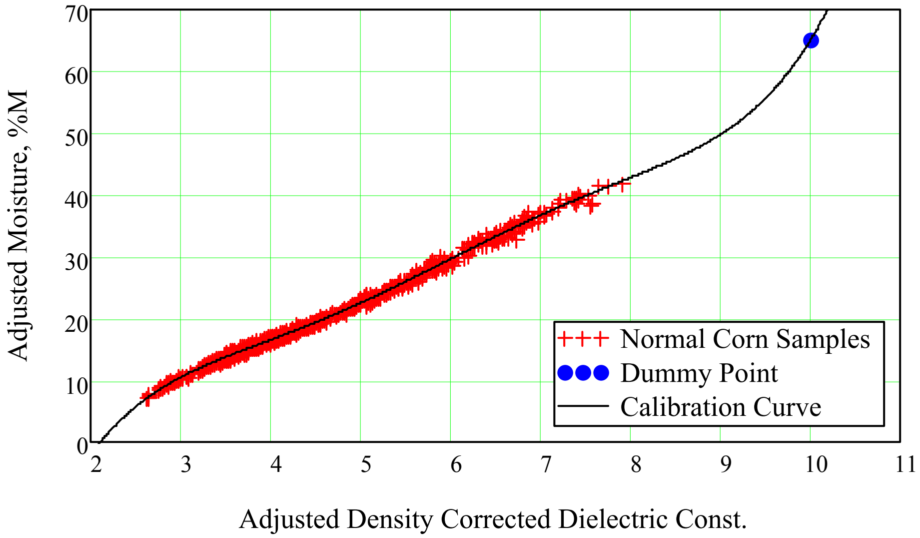


Figure 1. Calibration curve

Temperature Correction

Temperature correction is applied to the predicted moisture to minimize the effect of sample temperature—that is, to cause the final moisture estimate to closely match the estimate that would be given for that sample if measured at room temperature (22°C). FGIS has developed temperature corrections over a wide temperature range (from -18°C to 45°C.) The UGMA exhibits a significant advantage (relative to most other moisture meters) in its ability to accurately predict moisture content for grain (at normal market moisture levels) at temperatures well below 0°C. The form of the correction can be moisture level dependent and may be linear or quadratic with temperature. Accurate temperature correction over wide temperature and moisture ranges usually requires the moisture-dependent/quadratic temperature correction, but less demanding applications may use the simpler corrections with fewer determined coefficients. (That is, the ***KCTQ*** and/or ***KTCS*** values may be zero.)

$$Moisture3 = \frac{Moisture2 - KTC_s \cdot (T - TTC) - KTCQ_s \cdot (T - TTC)^2}{1 + KTCS_s \cdot (T - TTC)} \qquad (7)$$

The target temperature (***TTC***) was chosen as 22°C because that is the nominal laboratory temperature for all the calibration sample tests at FGIS. Making the target temperature equal to the nominal laboratory temperature minimizes the interaction between the temperature coefficients and the unifying parameters and polynomial calibration coefficients.

The listed temperature correction coefficient (***KTC$_s$***) values (see Table 3) were estimated from FGIS tests done in 2007-2012 using a special insulated test cell (GP test cell) and the HP-4291A Impedance Analyzer and FGIS tests performed in 2012 with commercial UGMA moisture meters.

Secondary Kernel/Bulk Density Correction

The secondary bulk density correction is applied to the predicted moisture to reduce the error caused by extremes in corn density related to kernel density. This correction appears to be unnecessary for grain types other than corn. The correction (Eq. 8) was developed by Zoltan Gillay in 2010 and was published at the ISEMA 2011 Conference in Kansas City in June 2011. Additional details are shown below. Note that both the ***TargetDensity*** and the ***SlopeCorrection*** values are moisture-dependent and are found by linear interpolation from the TD Table (Table 5) and SC Table (Table 6), respectively.

$$\boldsymbol{SecDensCorr}(\boldsymbol{Moisture3}, \boldsymbol{Mass}) = \left(\frac{\boldsymbol{Mass}}{\boldsymbol{TestCellVolume}} - \boldsymbol{TargetDensity}\right) \cdot \boldsymbol{SlopeCorrection} \quad (8)$$

Where:

$$\boldsymbol{TargetDensity} = \boldsymbol{LinearInterpolation}(\boldsymbol{TDTable}, \boldsymbol{Moisture3}) \quad (9)$$

$$\boldsymbol{SlopeCorrection} = \boldsymbol{LinearInterpolation}(\boldsymbol{SCTable}, \boldsymbol{Moisture3}) \quad (10)$$

Parameters, Coefficients, and Grain Groups

The parameters may be refined annually as FGIS conducts tests on additional samples. These are current as of November 15, 2012, but some further changes will be made before May 2013.

The full numeric resolution shown in the tables is necessary to agree with FGIS results within 0.01% M.

The first eleven grain groups (soybeans, sorghum, sunflower, corn, oats, hard wheat, soft wheat, durum, barley, long grain rough rice, medium grain rough rice) are the "major" grains. The other grain groups (and their parameters) are still subject to revision as more samples of "minor" grain types are tested. The beans and processed rice groups show some scatter among individual grain types; the grouping of edible bean and processed rice types is expected to be refined based on further data. Grain types marked with an asterisk (*) have been assigned tentatively to groups based on data obtained using the original larger UGMA grain test cell, and they may be reassigned based on new data for the current standard test cell.

Table 1. Grain types within grain groups listed alphabetically by grain type.

Major Groups	Grain Type Names
1. Soybeans	Soybeans
2. Sorghum	Sorghum
3. Sunflower	Sunflower Seed, Oil-type
	Sunflower Seed, Confectionary (minor grain)
4. Corn	Corn
	Popcorn * (minor grain)
5. Oats	Oats
	Oats, Hull-Less * (unlisted grain)
6. Hard Wheat	Wheat, Hard White
	Wheat, Hard Red Winter
	Wheat, Hard Red Spring
7. Soft Wheat	Wheat, Soft Red Winter
	Wheat, Soft White
8. Durum	Durum
9. Barley	Barley, Six-Rowed
	Barley, Two-Rowed
10. Rice, Long Rough	Rice, Long Grain Rough
11. Rice, Medium Rough	Rice, Medium Grain Rough

Minor Groups	Grain Type Names
12. Rice, Short Rough	Rice, Short Grain Rough
13. Rice, Processed	Rice, Long Grain Milled
	Rice, Medium Grain Milled
	Rice, Long Grain Brown
	Rice, Medium Grain Brown
	Rice, Brewers Milled *
	Rice, Long Grain Brown Parboiled *
	Rice, Short Grain Brown *
	Rice, Second Head Milled Parboiled *
	Rice, Long Grain Milled Parboiled *
	Rice, Long/ Medium Second Head Milled *
	Rice, Medium Grain Milled Parboiled *
	Rice, Medium/ Short Second Head Milled *
	Rice, Brewers Milled Parboiled *
	Rice, Short Grain Milled *
	Rice, Short Grain Second Head Milled *
	Rice, Medium Grain Brown Parboiled *
	Rice, Screenings Milled *
	Rice, Short Grain Milled Parboiled *
14. Beans 1	Beans, Blackeye
	Beans, Pinto
	Beans, Cranberry
	Beans, Pink
	Lentils
	Peas, Split *
	Beans, Dark/ Light Red Kidney
15. Beans 2	Beans, Baby Lima
	Beans, Garbanzo
	Beans, Small Red
	Beans, Yelloweye *
	Beans, Small White *
	Beans, Pea
16. Beans 3	Beans, Black
	Beans, Great Northern
	Beans, Large Lima
17. Peas	Peas, Austrian Winter *
	Peas, Smooth Green Dry
	Peas, Wrinkled Dried *
18. Safflower	Safflower
19. Canola	Canola
	Rapeseed *
20. Mustard	Mustard Seed, Yellow
	Mustard Seed, Oriental
	Mustard Seed, Brown
21. Triticale & Rye	Triticale *
	Rye
22. Flaxseed	Flaxseed

Table 2. Unifying parameters for each grain group with target temperature *TTC* = 22°C.

Grain Group	**OP**	**SP**	**TP**
Soybeans**	2.21777	0.8527	0.25808
Sorghum**	2.47963	1.16408	0.8321
Sunflower**	2.90536	0.59158	3.6289
Corn**	2.5	1	0
Oats*	2.43385	1.0978	1.71883
Wheat, Hard*	2.45262	1.17814	0.74465
Wheat, Soft*	2.40942	1.13823	0.59997
Durum*	2.47479	1.1408	0.97078
Barley*	2.04862	0.86187	-2.83951
Rice, Long Rough*	2.50284	1.09896	-0.83441
Rice, Medium Rough*	2.48876	1.14818	-1.22497
Rice, Short Rough	2.44885	1.16697	-1.37851
Processed Rice	2.58622	1.14905	2.72485
Beans 1	2.02546	0.7984	-2.40271
Beans 2	2.14809	0.90013	-1.22725
Beans 3	2.10861	0.94338	-1.49144
Peas	2.02903	0.95915	-2.09272
Safflower	2.79858	0.72184	2.44242
Canola	2.72228	0.79913	3.14315
Mustard	1.97008	0.57332	-2.24529
Triticale & Rye	2.30481	1.08055	0
Flaxseed	2.49214	0.55567	0

**FGIS Official and NTEP-certified calibration

* NTEP-Certified calibration

Table 3. Temperature correction factors for Eq. 7. Moisture limit is the upper limit for sample temperatures below ***0°C***

	KTC	**KTCS**	**KTCQ**	**Temp Limit °C/°F**	**Moist Limit (%M)**
Soybeans**	0.01706	0.006400	-0.000400	-18/0	20
Sorghum**	0.10770	0.000000	-0.000656	-18/0	16
Sunflower**	0.03900	0.004080	0.000000	-18/0	12
Corn**	0.15920	-0.002820	-0.000769	-18/0	19
Oats*	0.09910	0.000000	-0.000348	-18/0	13
Wheat, Hard*	0.09590	0.001530	-0.000581	-18/0	19
Wheat, Soft*	0.09590	0.001530	-0.000581	-18/0	19
Durum*	0.09590	0.001530	-0.000581	-18/0	19
Barley*	0.12050	-0.000600	-0.000700	-18/0	18
Rice, Long Rough*	0.22020	-0.008650	-0.001119	-18/0	18
Rice, Medium Rough*	0.22020	-0.008650	-0.001119	-18/0	18
Rice, Short Rough	0.22020	-0.008650	-0.001119	-18/0	18
Processed Rice	0.10380	0.000000	-0.000628	-18/0	13
Beans 1	0.04440	0.006480	-0.000146	-18/0	15
Beans 2	0.04440	0.006480	-0.000146	-18/0	15
Beans 3	0.04440	0.006480	-0.000146	-18/0	15
Peas	0.10300	0.000000	0.000000	0/32	0
Safflower	0.05840	0.000000	-0.000240	-18/0	8
Canola	0.01480	0.008457	0.000000	-18/0	10
Mustard	-0.04490	0.015310	0.000000	-18/0	9
Triticale & Rye	0.09590	0.001530	-0.000581	-18/0	19
Flaxseed	-0.01520	0.010900	0.000000	-18/0	8

** FGIS Official and NTEP-certified calibration

* NTEP-certified calibration

Table 4. FGIS Official and NTEP-certified UGMA 5th order polynomial coefficients with 22°C target temperature.

Exponent	***KCC***
0	-112.71
1	111.3076
2	-40.37566
3	7.403341
4	-0.649454
5	0.02193348

Table 5. FGIS Official and NTEP-certified secondary density correction target density lookup table (***TDTable***) to determine the ***Target Density*** value by linear interpolation. ***Moisture3*** is the temperature-corrected predicted moisture from Eq. 7. (This correction is applicable only to corn.)

Moisture3	***Target Density*** g/ml
0	0.7168
15	0.7168
17	0.7116
19	0.7018
27	0.6451
30	0.6297
33	0.6253
100	0.6253

Table 6. FGIS Official and NTEP-certified (secondary density correction) ***Slope Correction*** lookup table (***SC Table***) to determine the ***Slope Correction*** value by linear interpolation. ***Moisture3*** is the temperature-corrected predicted moisture from Eq. 7. (This correction is applicable only to corn.)

Moisture3	***Slope Correction*** %M per g/ml
0	10.4
13	10.4
33	-17
100	-17

Performance Statistics

The statistics represent all samples (Table 7) that were available as of February 1, 2012 for the FGIS Master UGMA System.

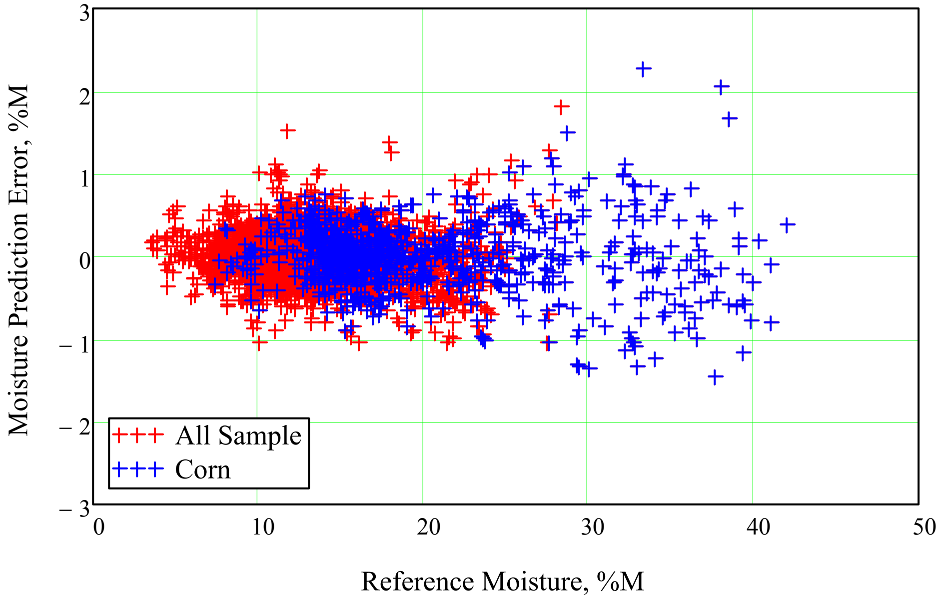


Figure 2. UGMA moisture prediction errors with respect to air oven moisture for all grain samples for 2008-2011 crop years.

Table 7. UGMA calibration statistics by grain groups for 2008-2011 crop years. STD is the standard deviation of predicted moisture error for the calibration samples for the FGIS Master UGMA system. Slope is the slope of the predicted moisture errors. *Note that biases were adjusted to zero (using unifying parameters) for each grain group based on these data.

Grain Group	Samples	Bias*	STD	Slope	Moisture Range
Soybeans	453	0.00	0.19	0.00	8 - 23
Sorghum	164	0.00	0.21	-0.01	10 - 24
Sunflower	313	0.00	0.38	-0.01	5 - 28
Corn	851	0.00	0.40	0.00	7 - 42
Oats	85	0.00	0.26	-0.05	10 - 18
Wheat, Hard	827	0.00	0.18	-0.01	7 - 21
Wheat, Soft	514	0.00	0.18	-0.01	8 - 22
Durum	182	0.00	0.19	0.00	5 - 28
Barley	298	0.00	0.26	-0.02	8 - 18
Rice, Long Rough	322	0.00	0.34	-0.01	9 - 26
Rice, Medium Rough	205	0.00	0.40	-0.01	10 - 28
Rice, Short Rough	25	0.00	0.42	-0.01	11 - 24
Processed Rice	132	0.00	0.22	-0.04	10 - 17
Beans 1	164	0.00	0.26	-0.01	7 - 20
Beans 2	95	0.00	0.23	0.00	7 - 19
Beans 3	103	0.00	0.22	-0.01	10 - 21
Peas	85	0.00	0.20	-0.01	9 - 16
Safflower	36	0.00	0.21	-0.01	3 - 12
Canola	28	0.00	0.18	-0.01	4 - 10
Mustard	16	0.00	0.28	0.00	5 - 19
Triticale & Rye	16	0.00	0.25	-0.08	12 - 15
Flaxseed	18	0.00	0.13	-0.09	7 - 9

Table 8. UGMA calibration statistics for individual grain types for the FGIS Master UGMA System for 2008-2011 crop years. Slope is the slope of the predicted moisture errors. Note that the bias values* are not necessarily zero because the unifying parameters were adjusted to minimize the average error for all grain types within each grain group, not for individual grain types.

Grain Types	**Samples**	**Bias***	**STD**	**Slope**	**Moisture Range**
Barley, Six-Rowed	155	-0.04	0.26	0.00	8 - 18
Barley, Two-Rowed	150	0.04	0.26	-0.03	9 - 18
Beans, Baby Lima	29	-0.07	0.25	0.16	10 - 14
Beans, Black	30	0.16	0.23	-0.02	10 - 18
Beans, Black-Eyed	30	-0.07	0.18	-0.06	9 - 14
Beans, Cranberry	11	-0.20	0.20	0.03	12 - 19
Beans, Dark/ Light Red Kidney	22	0.12	0.24	0.06	10 - 20
Beans, Garbanzo	46	0.00	0.23	-0.06	7 - 17
Beans, Great Northern	13	0.13	0.13	-0.01	12 - 19
Beans, Large Lima	13	0.03	0.21	0.01	10 - 15
Beans, Pea	48	-0.14	0.12	0.00	12 - 21
Beans, Pink	10	-0.23	0.28	-0.01	10 - 19
Beans, Pinto	28	-0.19	0.24	0.03	9 - 18
Beans, Small Red	21	0.10	0.17	-0.01	9 - 19
Canola	28	0.00	0.18	-0.01	4 - 10
Corn	851	0.00	0.40	0.00	7 - 42
Durum	185	0.00	0.19	0.00	5 - 28
Flaxseed	18	0.00	0.13	-0.09	7 - 9
Lentils	63	0.14	0.19	-0.01	7 - 14
Mustard Seed, Oriental	4	0.15	0.34	-0.02	7 - 19
Mustard Seed, Yellow	12	-0.05	0.23	-0.06	5 - 11
Oats	87	0.00	0.26	-0.05	10 - 18
Peas, Smooth Green Dry	86	0.00	0.20	-0.01	9 - 16
Peas, Split	2	-0.08	0.02	----	12 - 13
Rice, Long Grain Brown	25	-0.04	0.19	-0.08	11 - 16
Rice, Long Grain Milled	33	0.06	0.17	-0.03	11 - 14
Rice, Long Grain Rough	325	0.00	0.34	-0.01	9 - 26
Rice, Medium Grain Brown	42	-0.10	0.22	-0.04	10 - 17
Rice, Medium Grain Milled	37	0.09	0.21	0.01	12 - 16
Rice, Medium Grain Rough	205	0.00	0.40	-0.01	10 - 28
Rice, Short Grain Rough	25	0.00	0.42	-0.01	11 - 24
Rye	16	0.00	0.25	-0.08	12 - 15
Safflower	36	0.00	0.21	-0.01	3 - 12
Sorghum	165	0.00	0.21	-0.01	10 - 24
Soybeans	467	0.00	0.19	0.00	8 - 23
Sunflower Seed	285	-0.01	0.37	-0.02	5 - 28
Sunflower Seed, Confectionary	30	0.13	0.40	0.09	8 - 14

Table 8. Continued

Grain Types	**Samples**	**Bias**	**STD**	**Slope**	**Moisture Range**
Wheat, Hard Red Spring	298	-0.07	0.21	0.00	7 - 21
Wheat, Hard Red Winter	408	0.03	0.16	-0.01	7 - 19
Wheat, Hard White	138	0.04	0.16	0.02	8 - 21
Wheat, Soft Red Winter	337	0.01	0.17	-0.01	9 - 22
Wheat, Soft White	181	-0.02	0.20	-0.01	8 - 19

Details of Secondary Density Correction Method

The secondary kernel/bulk density correction dramatically reduces the error for corn caused by unusually low (or high) density. Figure 3 illustrates key aspects of the correction. The plot shows all the corn samples with the several low density samples (blue diamonds) segregated from the “normal samples” (red +).

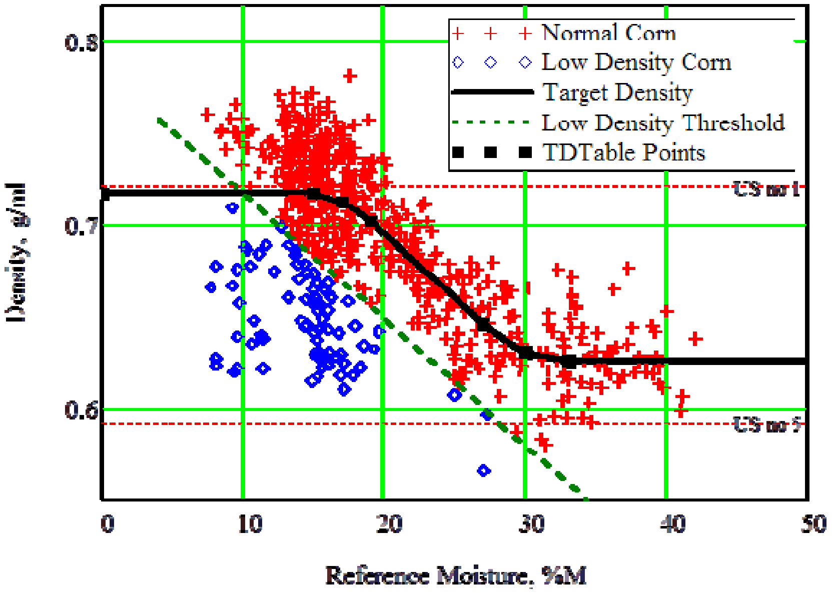


Figure 3. Target density curve (***TDTable***, Table 5)

The separation or threshold function is by Eq. 11 and the dotted line in Figure 3.

$$\boldsymbol{LowDensityThreshold}(\%\boldsymbol{M}) = \left[\left(\frac{\mathbf{45-53}}{\mathbf{30-15}}\right)\cdot(\%\boldsymbol{M}-\mathbf{15})+\mathbf{53}\right]\cdot\boldsymbol{ConversionParameter} \qquad (11)$$

ConversionParameter (0.01287 g/ml per lb/bu) transforms the values from lb/bu to g/ml.

Including the low density samples in the calibration caused significant errors both for the normal and low density samples. For optimizing the calibration for the normal samples, the low density samples were not included in the calibration. The samples for which the density corrections are zero lie on the solid line in Figure 3—the moisture-dependent target density (***TD***) curve. The predicted moisture error (correction to be applied) is proportional to the vertical distance between the sample density (***Mass*/*TestCellVolume***) and the target density (***TD***) curve. Therefore, the correction function (repeated here) is defined as:

$$\boldsymbol{SecDensCorr}(\boldsymbol{Moisture3},\boldsymbol{Mass}) = \left(\frac{\boldsymbol{Mass}}{\boldsymbol{TestCellVolume}}-\boldsymbol{TargetDensity}\right)\cdot\boldsymbol{SlopeCorrection} \qquad (8)$$

The results of the ***SecDensCorr*** function are in units of %M. The calculated density correction is applied by subtracting it from the temperature-corrected predicted moisture as in Eq. 6. The slope correction factor ***SC*** (%M per g/ml density difference from target density at that moisture level) is moisture-dependent. See Figure 4. The slope correction ***SC*** crosses zero at about 21% moisture.

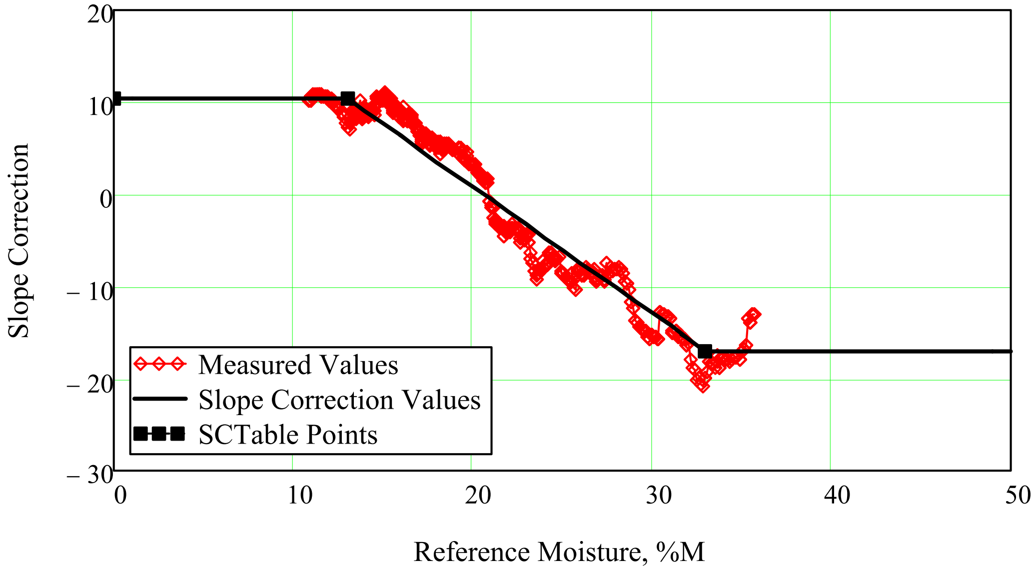


Figure 4. Slope correction values. Visualization of the ***SC Table*** (Table 6).

Table 9 and Figure 5 show that by using the secondary density correction, the errors in predicted moisture for low density corn samples were significantly reduced. Furthermore, the standard deviation of the predicted moisture errors for "normal" samples was improved.

Table 9. Secondary density correction statistics; before (left) and after (right) correction

Samples.	Mean Diff.	STD	Slope
All	-0.03	0.51	0.00
Low Dens.	-0.6	0.46	0.05
Normal	0.05	0.46	-0.01

Samples	Mean Diff.	STD	Slope
Overall	-0.01	0.41	0.00
Low Dens.	-0.09	0.33	0.00
Normal	0.00	0.42	0.00

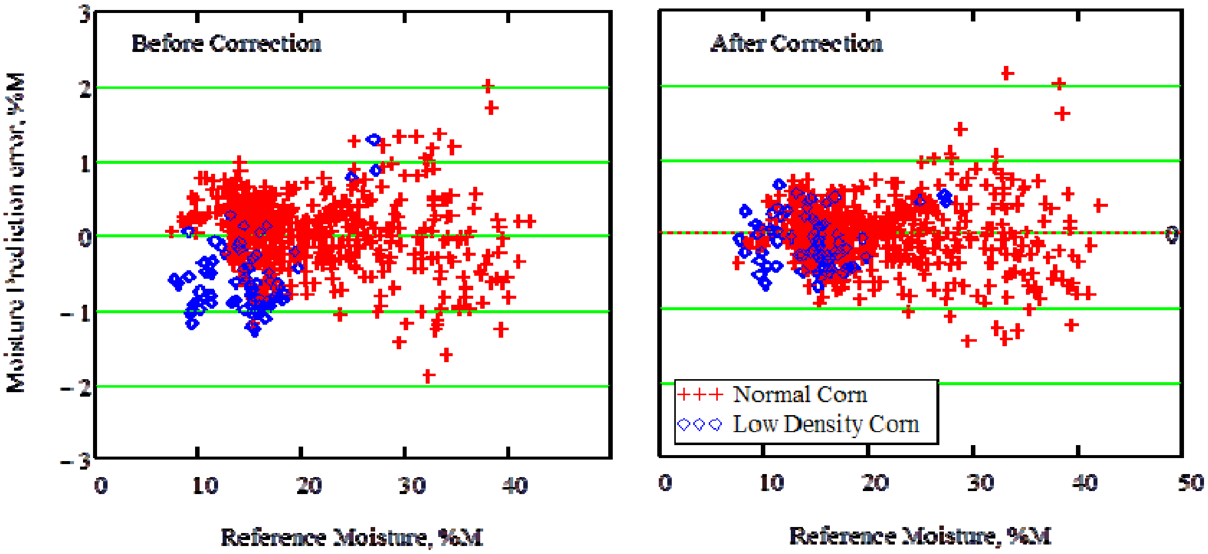


Figure 5. Corn sample predicted moisture errors before and after secondary density correction for 2008-2010 corn.

Sensitivity Analyses

One of the major goals in developing the Unified Grain Moisture Algorithm was to define a measurement technology with sufficient detail that multiple manufacturers could design and produce instruments that could use the same calibrations and produce moisture measurements that are mutually consistent as well as accurate. Developers should not underestimate the extreme care required to design and manufacture instruments that can achieve UGMA-Compatible certification by FGIS. The purpose of this Sensitivity Analyses section is to share FGIS research results regarding the effects of several design parameters on moisture measurement results—and to thereby assist engineers in selecting innovative design strategies that can consistently achieve the necessary performance.

1. **Measurement frequency sensitivity.** Our analysis evaluated two cases of frequency sensitivity: 1) the deliberate choice of a known frequency other than 149.00 MHz, and 2) imprecision or instability in the measurement frequency of specific moisture meters. The exact choice of measurement frequency is not terribly critical; a manufacturer may have reasons to choose a specific frequency to avoid interfering with or being influenced by known problematic signal sources or sensors in the environment. The change in dielectric constant values versus frequency is relatively small, so the same unifying parameters and calibration curve may be used over a limited frequency range. An evaluation with data for over 6000 samples of multiple grain types showed an average moisture error of -0.02% moisture per MHz for measurement frequency changes around 149 MHz. This sensitivity value assumed that the test cell model parameters (but not unifying parameters or calibration coefficients) were optimized for each test frequency. The second case assumes that the measurement frequency varied from the intended value, and that the test cell model parameters were not re-optimized for the specific measurement frequency. In this case, the frequency sensitivity was about ten times larger (+0.2% moisture per MHz of uncompensated measurement frequency error). For further information see: *Analysis of Frequency Sensitivity of the Unified Grain Moisture Algorithm*, ASAE Meeting Paper #053047, Zoltan Gillay and David Funk, 2005.

2. **Temperature measurement sensitivity.** Moisture measurement errors associated with temperature are due to temperature measurement errors and temperature correction function inadequacies. Typical temperature coefficients are about 0.1% moisture per degree Celsius difference from the reference temperature (22 °C). (See ***KTC*** values in Table 3.) If the sample temperature sensor has significant thermal mass or other characteristics that cause measurement error to degrade at temperature extremes, significant moisture errors may result. Temperature measurement accuracy at room temperature must be especially good to avoid contributing significantly to moisture measurement errors during routine in-field performance verification (check testing). The temperature correction function must be sufficiently robust to provide good corrections over the full intended temperature (and moisture) range. Systematic temperature measurement errors for an instrument model (which could be corrected through the selected temperature correction function) cannot be tolerated in official moisture meters, which must use the same set of official moisture calibrations.

3. **Ranges of interest for dielectric constant, density-corrected dielectric constant, and related factors.** The following plots illustrate the ranges of parameters and sensitivities that are relevant for Official grain moisture measurement.

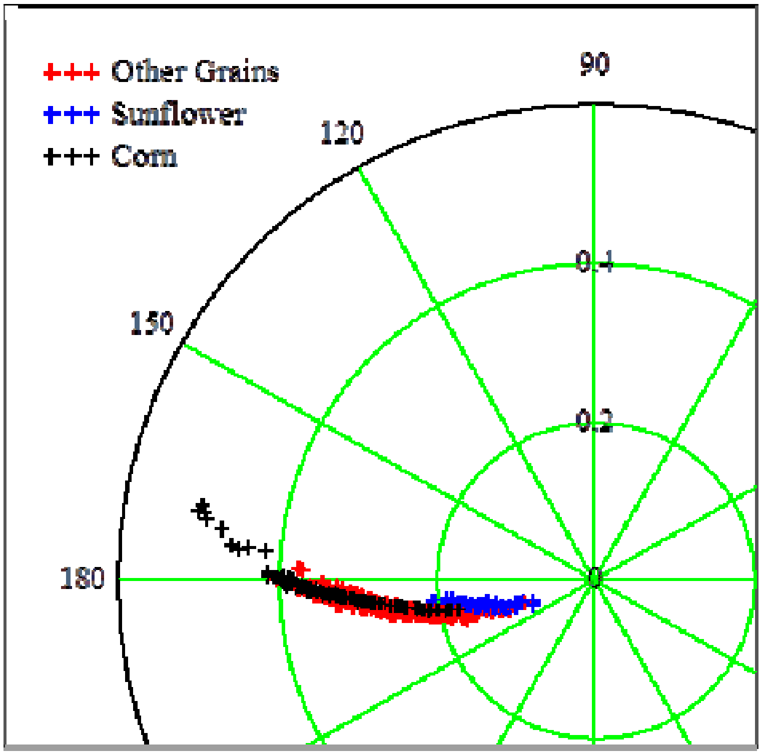


Figure 6. Complex reflection coefficients measured with UGMA Master System for grain samples in 2008, 2009, and 2010 Calibration Studies.

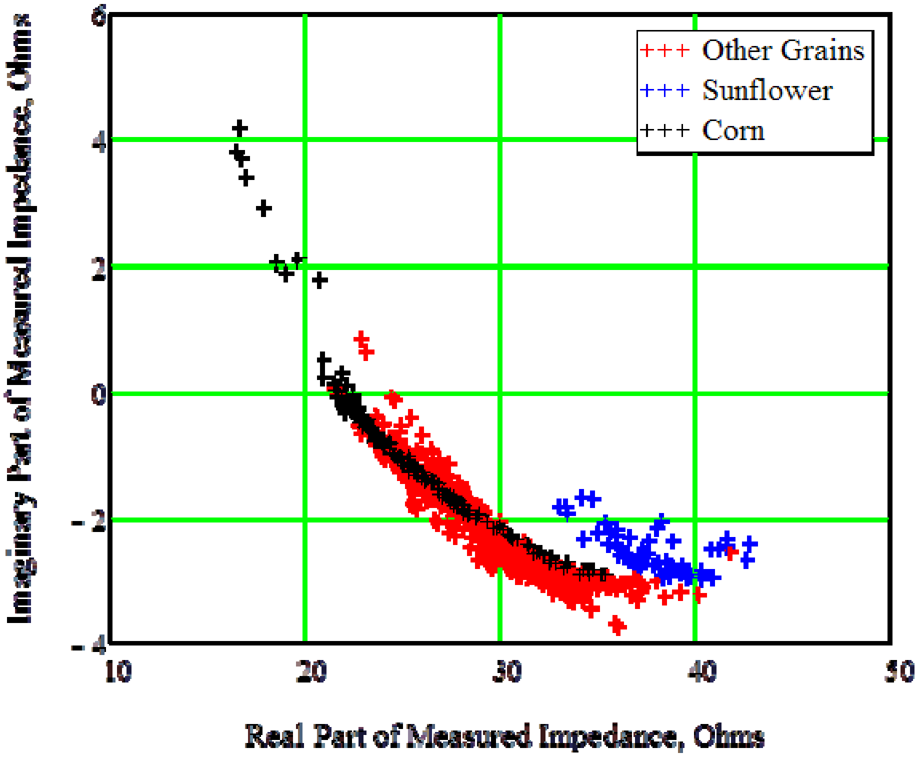


Figure 7. Complex impedance values measured with UGMA Master System for grain samples in 2008, 2009, and 2010 Calibration Studies.

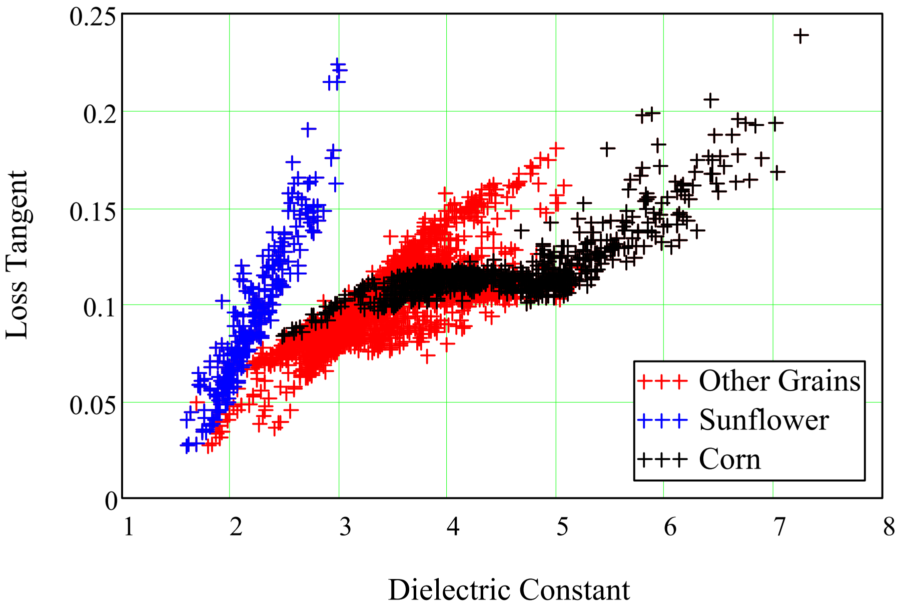


Figure 8. Loss tangent versus dielectric constant values for grains tested in 2008, 2009, and 2010 Calibration Studies.

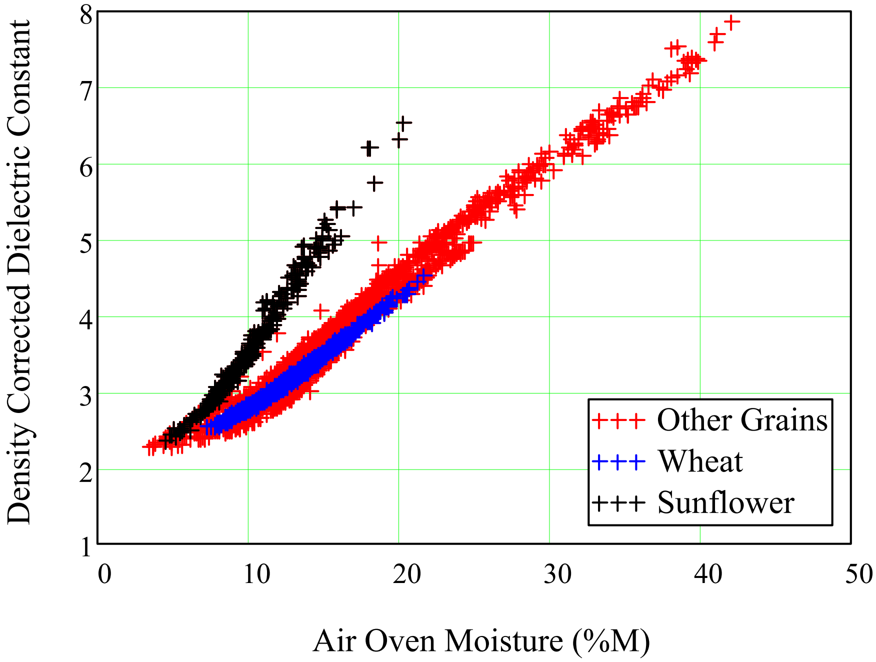


Figure 9. Density-corrected dielectric constant versus moisture values for grains tested in 2008, 2009, and 2010 Calibration Studies.

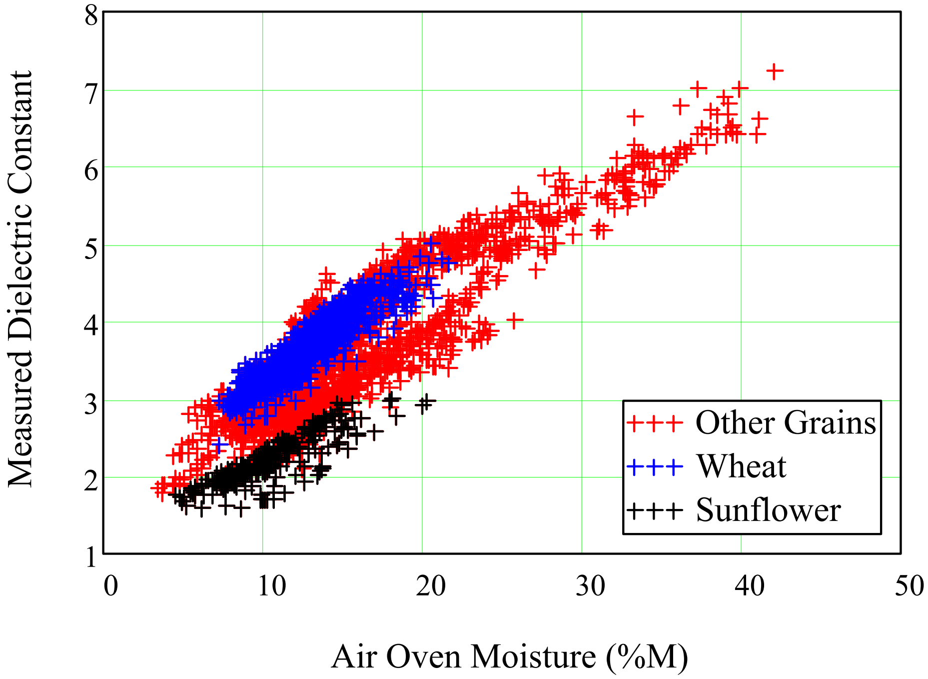


Figure 10. Measured dielectric constant values (prior to density correction) for grains tested in 2008, 2009, and 2010 Calibration Studies.

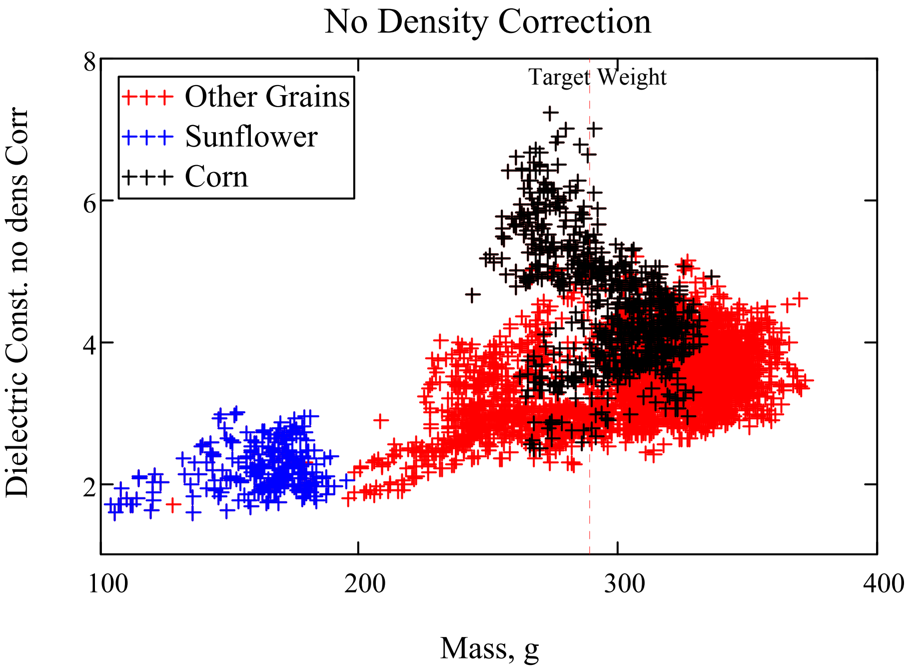


Figure 11. Measured dielectric constant values (without density correction) versus sample mass for grains tested in 2008, 2009, and 2010 Calibration Studies.

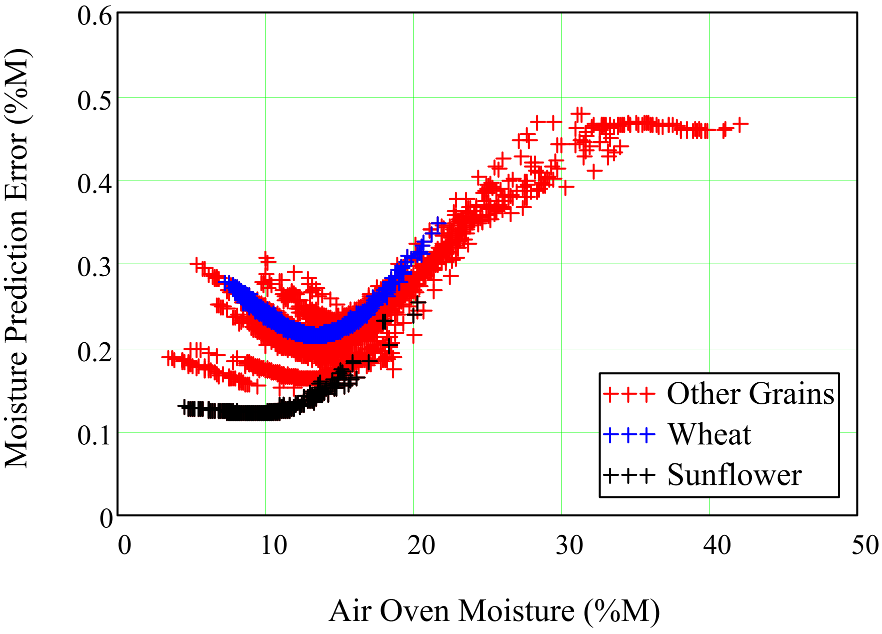


Figure 12. Moisture prediction errors resulting from 1% (of value) errors in density-corrected dielectric constant for grains tested in 2008, 2009, and 2010 Calibration Studies.

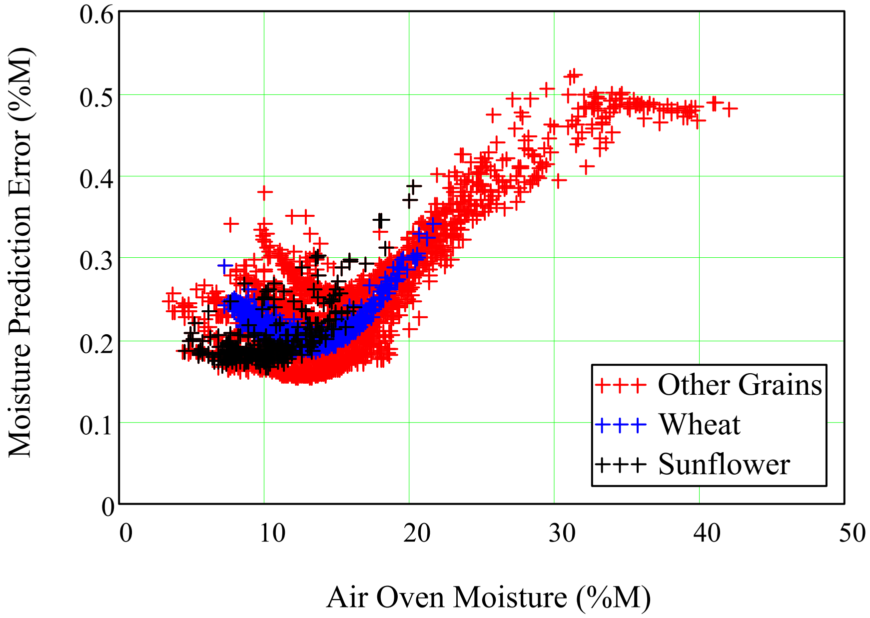


Figure 13. Moisture prediction errors resulting from 1% (of value) errors in measured dielectric constant (prior to density correction) for grains tested in 2008, 2009, and 2010 Calibration Studies.

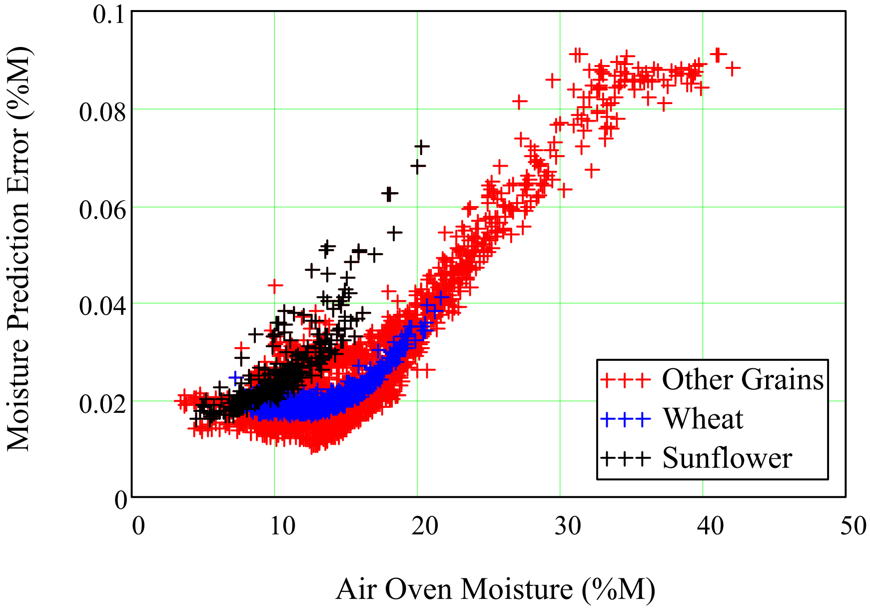


Figure 14. Moisture prediction error resulting from a simulated -0.3 gram mass measurement error for grains tested in 2008, 2009, and 2010 Calibration Studies. (A negative mass measurement error results in a positive moisture prediction error and vice versa.)

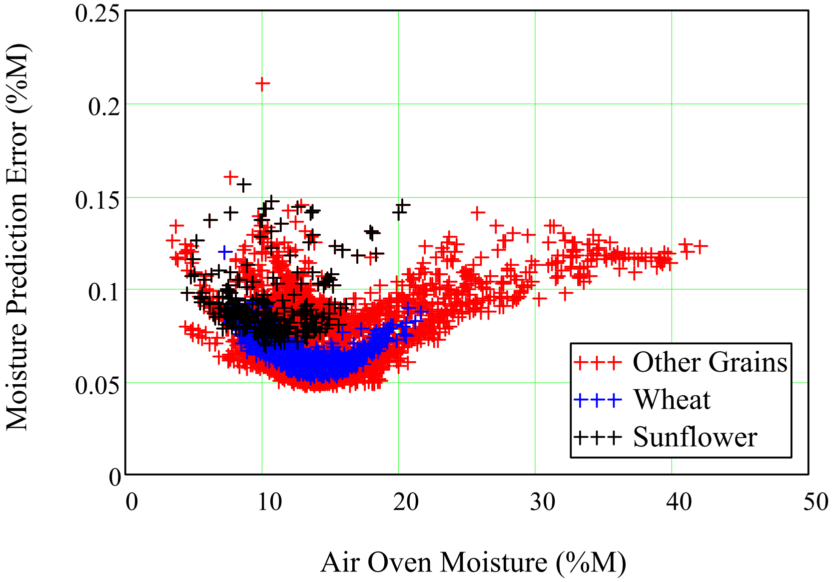


Figure 15. Moisture prediction error caused by a simulated +0.001 error (not relative) in the magnitude of the measured reflection coefficient (at the test cell connector) for grains tested in 2008, 2009, and 2010 Calibration Studies with the FGIS Master UGMA system. (Note: This sensitivity is dependent on instrument design.)

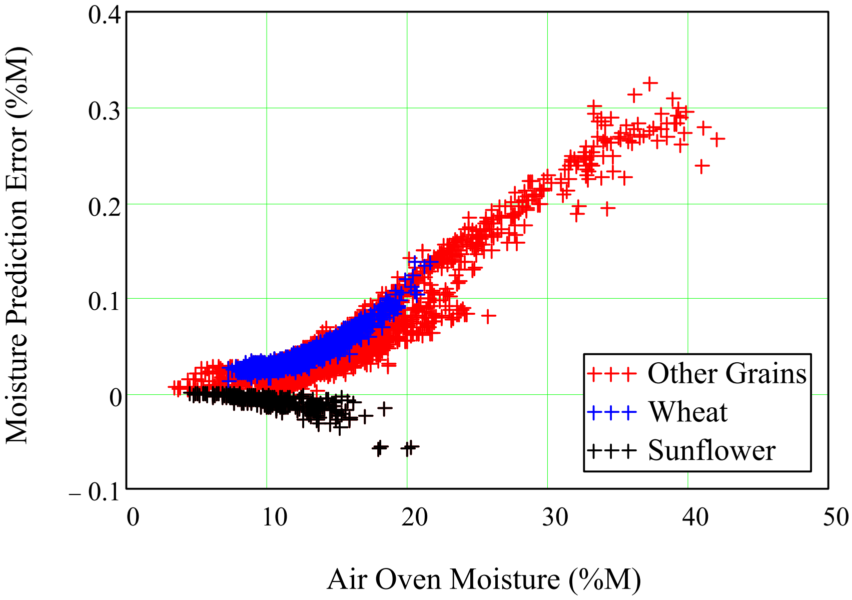


Figure 16. Moisture prediction error caused by a simulated -1 degree error in the phase of the measured reflection coefficient (at the test cell connector) for grains tested in 2008, 2009, and 2010 Calibration Studies with the FGIS Master UGMA system. (Note: This sensitivity is dependent on instrument design.)

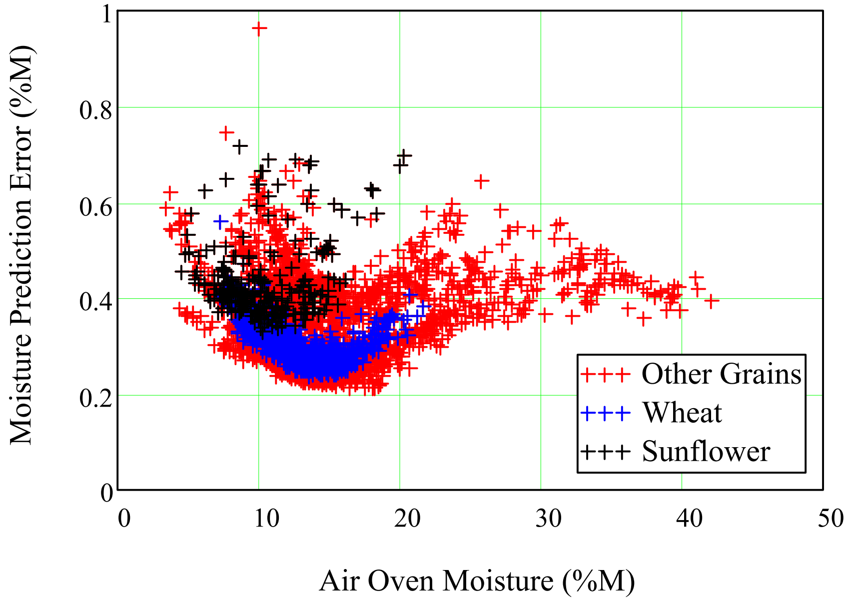


Figure 17. Moisture prediction error caused by a simulated 1% (relative) error in the magnitude of the measured test cell complex impedance (at the test cell connector) for grains tested in 2008, 2009, and 2010 Calibration Studies with the FGIS Master UGMA system. (Note: This sensitivity is dependent on instrument design.)

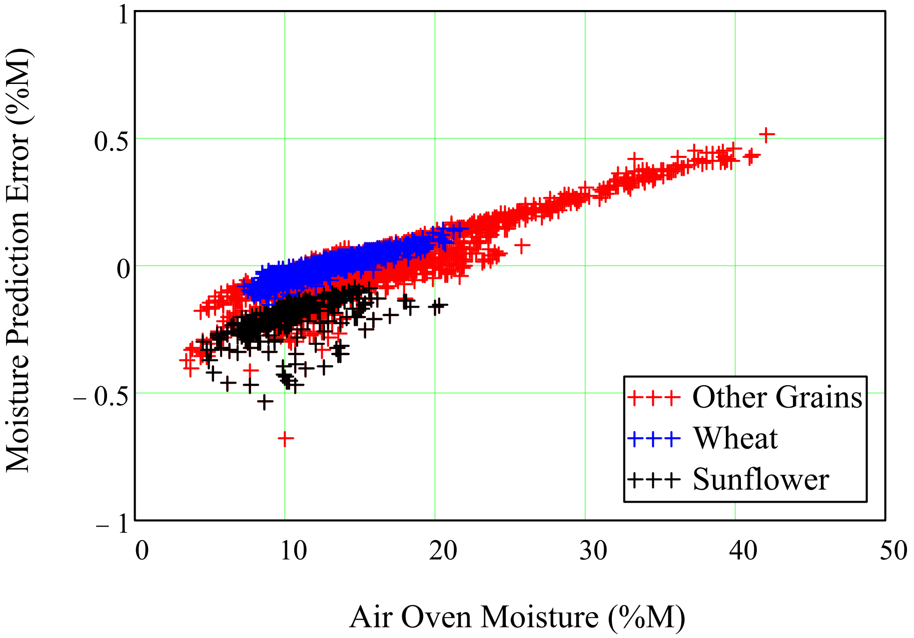
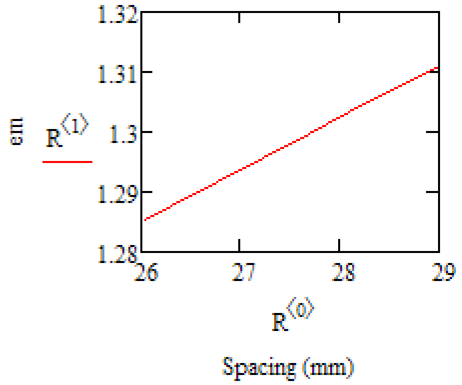


Figure 18. Moisture prediction error caused by a simulated -1 degree error in the measured phase of the test cell impedance (at the test cell connector) for grains tested in 2008, 2009, and 2010 Calibration Studies with the FGIS Master UGMA system. (Note: This sensitivity is dependent on instrument design.)

Spacing predicting em

$$\text{line}\left(R^{\langle 0\rangle}, R^{\langle 1\rangle}\right) = \begin{pmatrix} 1.05770 \\ 8.73573 \times 10^{-3} \end{pmatrix}$$

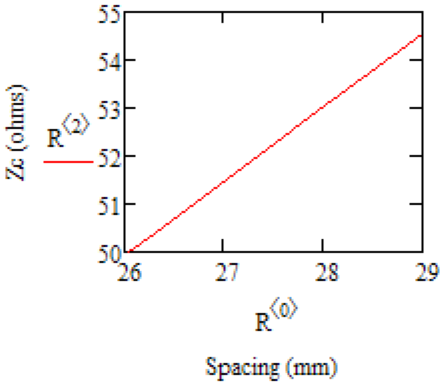
$$\text{corr}\left(R^{\langle 0\rangle}, R^{\langle 1\rangle}\right) = 0.99999$$



Spacing predicting Zc

$$\text{line}\left(R^{\langle 0\rangle}, R^{\langle 2\rangle}\right) = \begin{pmatrix} 9.87548 \\ 1.54056 \end{pmatrix}$$

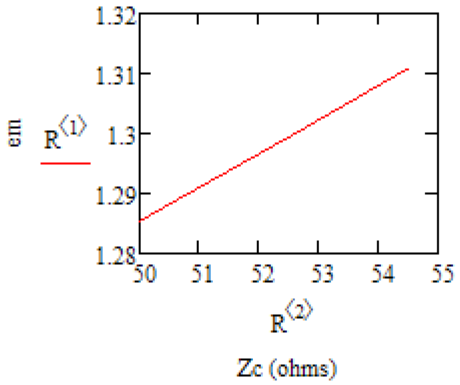
$$\text{corr}\left(R^{\langle 0\rangle}, R^{\langle 2\rangle}\right) = 0.99999$$



Zc predicting em

$$\text{line}\left(R^{\langle 2\rangle}, R^{\langle 1\rangle}\right) = \begin{pmatrix} 1.00170 \\ 5.67044 \times 10^{-3} \end{pmatrix}$$

$$\text{corr}\left(R^{\langle 2\rangle}, R^{\langle 1\rangle}\right) = 0.99999$$



Spacing predicting Zc--air section

$$\text{line}\left(R^{\langle 0\rangle}, R^{\langle 3\rangle}\right) = \begin{pmatrix} 10.726534 \\ 1.494043 \end{pmatrix}$$

$$\text{corr}\left(R^{\langle 0\rangle}, R^{\langle 3\rangle}\right) = 0.99998$$

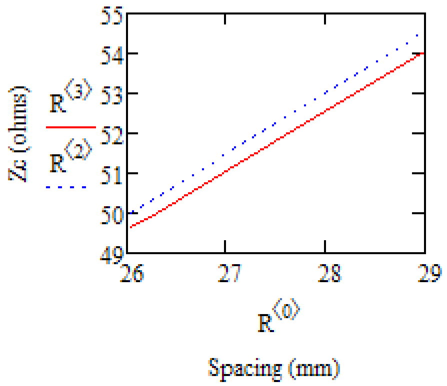


Figure 19. Relationships between test cell plate spacing, characteristic impedance, and filling factor. The relationships are highly linear. These results are from finite element analysis using the dimensions of the FGIS "New Master" (NM) test cell. Note that the "Spacing Predicting Zc—air section" analysis is based on a finite element model that includes the presence of the metallic base plate in the NM test cell, whereas the "Spacing Predicting Zc" analysis excludes the effects of the base plate. For the latter case, the effects of the base plate and the test cell gate are separately included in the test cell model as a constant offset term in the dielectric measurement. In actual instruments, the effects of conductors near the test cell may be significantly more complex and problematic because of the potential for resonances at or near the measurement frequency.

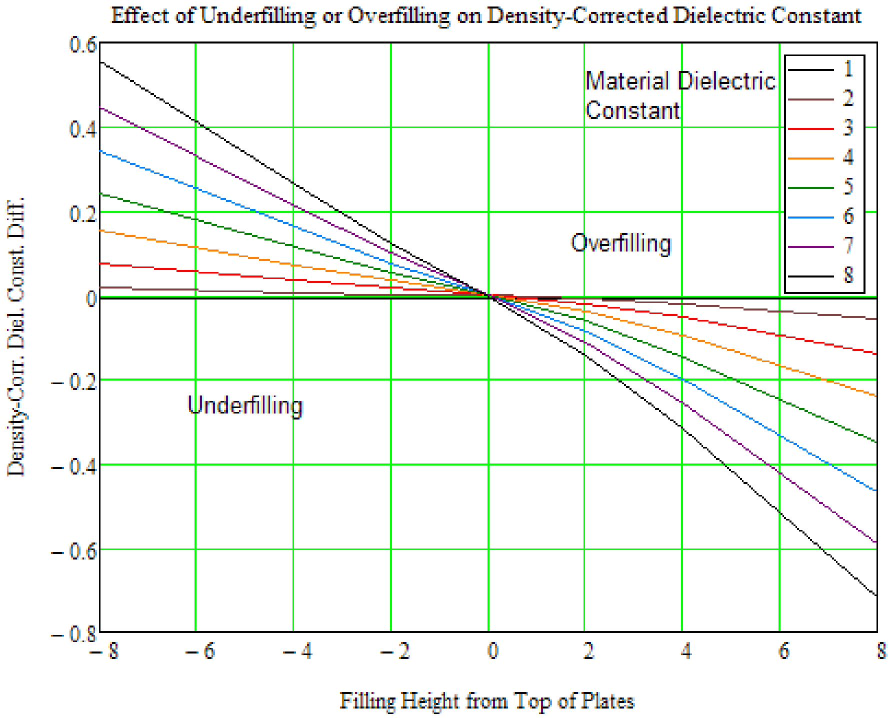


Figure 20. Estimated effects on density-corrected dielectric constant of overfilling and underfilling of the test cell (as a function of filling height in mm). These results are based on finite element analysis of the "New Master" test cell.

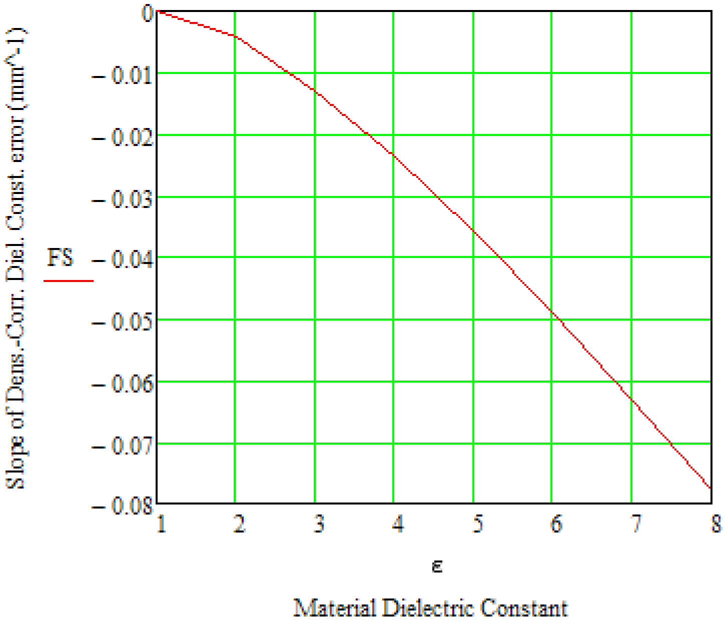


Figure 21. The slope of the density-corrected dielectric constant change with filling height (dielectric constant units per mm) based on finite element analysis of the New Master test cell.

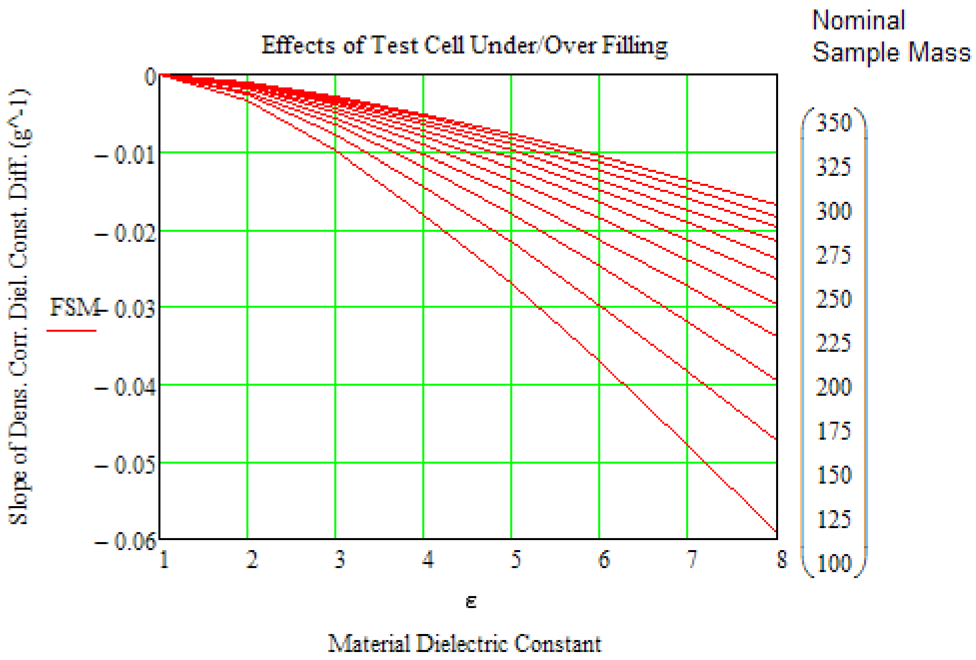


Figure 22. Plot of the slopes of density-corrected dielectric constant per gram of cell overfilling or under-filling. These results, like those of Figs. 19-21, are based on finite element analysis of the New Master test cell and assume "rectangular" sample cross-sections.

For further information, please refer to the USDA-GIPSA website (www.gipsa.usda.gov) or send questions by email to UGMA-QA@usda.gov or by mail or phone to the address below.

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