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Unified Grain Moisture Algorithm

Recipe Book

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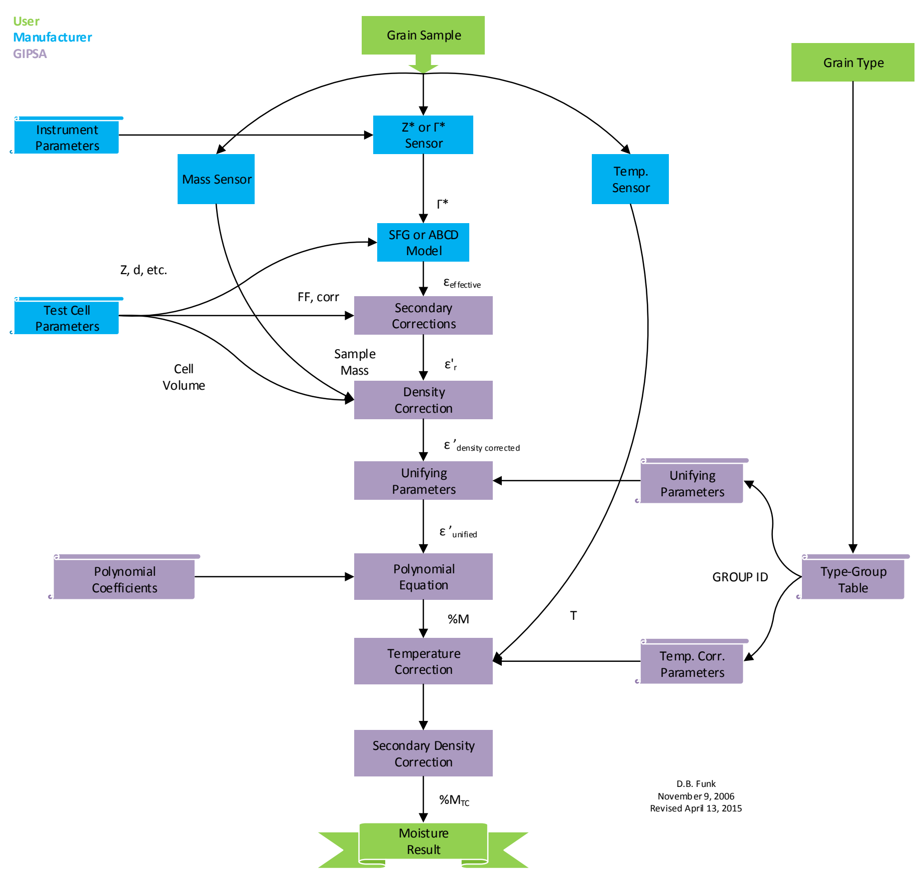

Unified Grain Moisture Algorithm

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 Moisture Equipment page of the GIPSA website (www.gipsa.usda.gov).

UGMA Steps

1. Measure the dielectric constant ($\boldsymbol{\varepsilon_{meas}}$) of the grain at a defined frequency within the range of 148.5 to 150.5 MHz where the selected frequency is controlled within $\pm$ 0.05 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. (Note: Grain-group-specific dielectric offset (EO_S) and dielectric slope (ES_S) factors may need to be applied (as $\boldsymbol{\varepsilon_{meas'}} = \boldsymbol{\varepsilon_{meas}} \cdot ES_S + EO_S$) to compensate for slight differences in loading methods among instrument models. The ***s*** subscripts refer to grain-group-specific parameters that may be different for different instrument models.)
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 ($\boldsymbol{\varepsilon_{den}}$) with a common density basis ($\boldsymbol{\rho_{target}}$= 0.67405 g/ml) for all grain types.

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

(Note: Grain-group-specific volume ratio factors ($\boldsymbol{VR_s}$) 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.)

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

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

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.

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

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 density correction to obtain the final predicted moisture result. This correction, which was primarily intended to overcome the effect of kernel density in corn, has also proven useful for adjusting the calibration line shape by moisture range. Currently, this correction is applied to corn (density), long grain rough rice (line shape), medium grain rough rice (line shape), oats (density) and soybeans (line shape).

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

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 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. At some point in the future, the order of the polynomial curve may be increased to 7 to allow better fit for extremely dry samples; manufacturers should allow for this possibility in their software. Currently the secondary density correction is being employed in a special way to accomplish small line shape changes on certain grains, because changing the polynomial curve would require modification of all calibrations that are based on the existing curve.

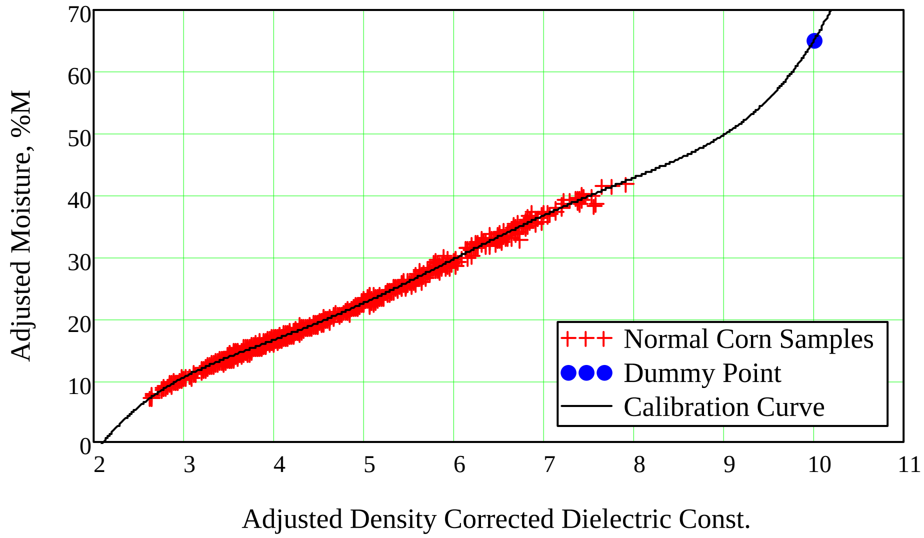

Figure 1. Calibration curve

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 values (see Table 3) were estimated from FGIS tests done in 2007-2013 using a special insulated test cell (GP test cell) and precision impedance analyzers (HP-4291A and Agilent E4991A) and FGIS tests performed in 2013 with commercial UGMA moisture meters.

<u>Secondary (Bulk) Density Correction</u>

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 most 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. This method may also be applied as a line shape correction to the predicted moisture to improve moisture measurement accuracy at moisture extremes for some grain types. When used for line shape correction, the parameters in the secondary density correction equation are adjusted to modify the slope of the calibration curve in selected moisture ranges—without making a secondary density correction.

Note that the value of the *Mass/TestCellVolume* term in Equation 8 is approximately 0.5 and varies only a little around this value. The values of *TargetDensity* and *SlopeCorrection* at different predicted moisture levels are specified in lookup tables (TDTable and SCTable, respectively). By setting *TargetDensity* to a number much larger than 0.5 (such as 100) and the *SlopeCorrection* value to a small number, the slope of the calibration curve can be adjusted as desired without interference from sample mass.

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

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. The listed coefficients are current as of May 1, 2015.

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 have been revised as more samples of "minor" grain types were tested in 2012-2014.

Table 1. Grain types within grain groups

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
5. Oats	Oats
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
	Hulless Oats (minor grain)
	Khorasan (minor grain)
9. Barley	Barley, Six-Rowed
	Barley, Two-Rowed
10. Rice, Long Rough	Rice, Long Grain Rough
11. Rice, Medium Rough	Rice, Medium Grain Rough

Table 1. Continued

Minor Groups	Grain Type Names
12. Rice, Short Rough	Rice, Short Grain Rough
13. Rice, Long & Medium Milled	Rice, Long Grain Milled
	Rice, Medium Grain Milled
14. Rice, Brown	Rice, Long Grain Brown
	Rice, Medium Grain Brown
	Rice, Short Grain Brown
	Rice, Long Grain Brown Parboiled
15. Rice, Short Milled	Rice, Short Grain Milled
	Rice, Second Head Milled
	Rice, Screenings Milled
	Rice, Brewers Milled
16. Rice, Parboiled	Rice, Long Grain Brown Parboiled
	Rice, Second Head Milled Parboiled
	Rice, Long Grain Milled Parboiled
	Rice, Medium Grain Milled Parboiled
	Rice, Brewers Milled Parboiled
17. Beans 1	Beans, Blackeye
	Beans, Pinto
	Beans, Cranberry
	Beans, Pink
	Peas, Split
18. Beans 2	Beans, Baby Lima
	Beans, Garbanzo (Chickpeas)
	Beans, Small Red
	Beans, Yelloweye
19. Beans 3	Beans, Black
	Beans, Great Northern
	Beans, Large Lima
20. Beans 4	Beans, Small White
	Beans, Pea
21. Beans 5	Beans, Kidney
	Lentils
22. Peas	Peas, Mottled
	Peas, Smooth Dry
	Peas, Wrinkled Dried
23. Safflower	Safflower
24. Canola	Canola
	Rapeseed
25. Mustard	Mustard Seed, Yellow
	Mustard Seed, Brown
26. Mustard, Oriental	Mustard Seed, Oriental
27. Triticale & Rye	Triticale
	Rye
28. Flaxseed	Flaxseed
29. Popcorn	Popcorn
30. Buckwheat	Buckwheat
	Buckwheat Groats

Table 2. 2015 Unifying parameters for each grain group with target temperature *TTC* = 22°C. FGIS-approved calibrations.

Grain Group Name	OP	SP	TP
Soybeans*	2.21777	0.85270	0.25808
Sorghum*	2.47963	1.16408	0.83210
Sunflower*	2.90536	0.59158	3.62890
Corn*	2.50000	1.00000	0.00000
Oats*	2.43385	1.09780	1.71883
Wheat, Hard*	2.45262	1.17814	0.74465
Wheat, Soft*	2.40942	1.13823	0.59997
Durum*	2.47479	1.14080	0.97078
Barley*	2.04862	0.86187	-2.83951
Rice, Long Rough*	2.59400	1.17000	-0.83400
Rice, Medium Rough*	2.60900	1.25000	-0.83400
Rice, Short Rough	2.51387	1.26732	0.86818
Rice, Long & Medium Milled	2.49682	0.99284	0.00000
Rice, Brown	2.61542	1.21730	2.24150
Rice, Short Milled	2.56639	1.12468	0.00000
Rice, Parboiled	2.72023	1.28083	3.53399
Beans 1	2.04415	0.82087	-2.14253
Beans 2	2.14871	0.90055	-1.22113
Beans 3	2.15008	0.95575	-1.12211
Beans 4	2.10321	0.95610	-1.20983
Beans 5	2.02755	0.77947	-2.34291
Peas	2.05219	0.99142	-2.30674
Safflower	2.79858	0.72184	2.44242
Canola	2.75613	0.89355	4.42769
Mustard	2.45021	0.82628	1.34283
Mustard, Oriental	1.08520	0.43347	-5.76496
Triticale & Rye	2.07808	0.89967	-2.78647
Flaxseed	2.49214	0.55567	0.00000
Popcorn	2.71612	1.22804	1.92617
Buckwheat	2.32026	1.06465	0.00000

*Also NTEP-certified

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

Grain Group Name	KTC	KTCS	KTCQ	Lower Temp. Limit (°C/°F)	Upper Moist. Limit (%M)
Soybeans*	0.01706	0.00640	-0.000400	-18/0	20
Sorghum*	0.10770	0.00000	-0.000656	-18/0	16
Sunflower*	0.03900	0.00408	0.000000	-18/0	12
Corn*	0.15920	-0.00282	-0.000769	-18/0	19
Oats*	0.09910	0.00000	-0.000348	-18/0	13
Wheat, Hard*	0.09590	0.00153	-0.000581	-18/0	19
Wheat, Soft*	0.09590	0.00153	-0.000581	-18/0	19
Durum*	0.09590	0.00153	-0.000581	-18/0	19
Barley*	0.12050	-0.00060	-0.000700	-18/0	18
Rice, Long Rough*	0.22020	-0.00865	-0.001119	-18/0	18
Rice, Medium Rough*	0.22020	-0.00865	-0.001119	-18/0	18
Rice, Short Rough	0.22020	-0.00865	-0.001119	-18/0	18
Rice, Long & Medium Milled	0.06357	0.00310	-0.000372	-18/0	16
Rice, Brown	0.10380	0.00000	-0.000628	-18/0	16
Rice, Short Milled	0.10380	0.00000	-0.000628	-18/0	16
Rice, Parboiled	0.12898	0.00000	-0.000366	-18/0	13
Beans 1	0.04440	0.00648	-0.000146	-18/0	15
Beans 2	0.05876	0.00494	0.000000	-18/0	15
Beans 3	0.04440	0.00648	-0.000146	-18/0	15
Beans 4	0.04440	0.00648	-0.000146	-18/0	15
Beans 5	0.00603	0.01015	0.000000	-18/0	15
Peas	0.02883	0.00815	0.000000	-18/0	11
Safflower	0.05840	0.00000	-0.000240	-18/0	12
Canola	0.04190	0.002996	0.000000	0/32	0
Mustard	-0.04095	0.01532	0.000000	-18/0	9
Mustard, Oriental	-0.04095	0.01532	0.000000	-18/0	9
Triticale & Rye	0.07258	0.00423	-0.000691	-18/0	16
Flaxseed	-0.01520	0.01090	0.000000	-18/0	10
Popcorn	0.15920	-0.00282	-0.000769	-18/0	19
Buckwheat	0.10928	0.00000	-0.000528	-18/0	13

* Also NTEP-certified

Table 4. FGIS-approved 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 5a*. *TDTable for Corn. FGIS-approved 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.

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 5b. TDTable for Soybeans. FGIS-approved and NTEP-certified secondary line shape correction lookup table (***TDTable***) to determine the ***TargetDensity*** value by linear interpolation. ***Moisture3*** is the temperature-corrected predicted moisture from Eq. 7.

Moisture3	***Target Density*** g/ml
0	100
5	100
7	100
10	100
100	100

Table 5c. TDTable for Long Grain Rough Rice. FGIS-approved and NTEP-certified secondary line shape correction lookup table (***TDTable***) to determine the ***TargetDensity*** value by linear interpolation. ***Moisture3*** is the temperature-corrected predicted moisture from Eq. 7.

Moisture3	***Target Density*** g/ml
0	100
8	100
15	0
21	0
30	100
100	100

Table 5d. TDTable for Medium Grain Rough Rice. FGIS-approved and NTEP-certified secondary line shape correction lookup table (***TDTable***) to determine the ***TargetDensity*** value by linear interpolation. ***Moisture3*** is the temperature-corrected predicted moisture from Eq. 7.

Moisture3	***Target Density*** g/ml
0	100
10	100
15	0
21	0
30	100
100	100

Table 5e. TDTable for Oats. FGIS-approved and NTEP-certified secondary line shape correction lookup table (***TDTable***) to determine the ***TargetDensity*** value by linear interpolation. ***Moisture3*** is the temperature-corrected predicted moisture from Eq. 7.

Moisture3	***Target Density*** g/ml
0	0.525
100	0.525

Table 6a. SCTable for Corn. FGIS-approved 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.

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

Table 6b. SCTable for Soybeans. FGIS-approved and NTEP-certified (secondary line shape 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.

Moisture3	***Slope Correction*** %M per g/ml
0	-0.02
5	-0.02
7	-0.005
10	0
100	0

Table 6c. SCTable for Long Grain Rough Rice. FGIS-approved and NTEP-certified (secondary line shape 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.

Moisture3	***Slope Correction*** %M per g/ml
0	0.013
8	0.013
15	0
21	0
30	-0.035
100	-0.035

Table 6d. SCTable for Medium Grain Rough Rice. FGIS-approved and NTEP-certified (secondary line shape 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.

Moisture3	***Slope Correction*** %M per g/ml
0	0.01
10	0.01
15	0
21	0
30	-0.035
100	-0.035

Table 6e. SCTable for Oats. FGIS-approved and NTEP-certified (secondary line shape 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.

Moisture3	***Slope Correction*** %M per g/ml
0	-4.471
100	-4.471

Performance Statistics

Figure 2 and statistics in Tables 7 and 8 represent samples that were available as of May 1, 2015 for the FGIS Master UGMA System.

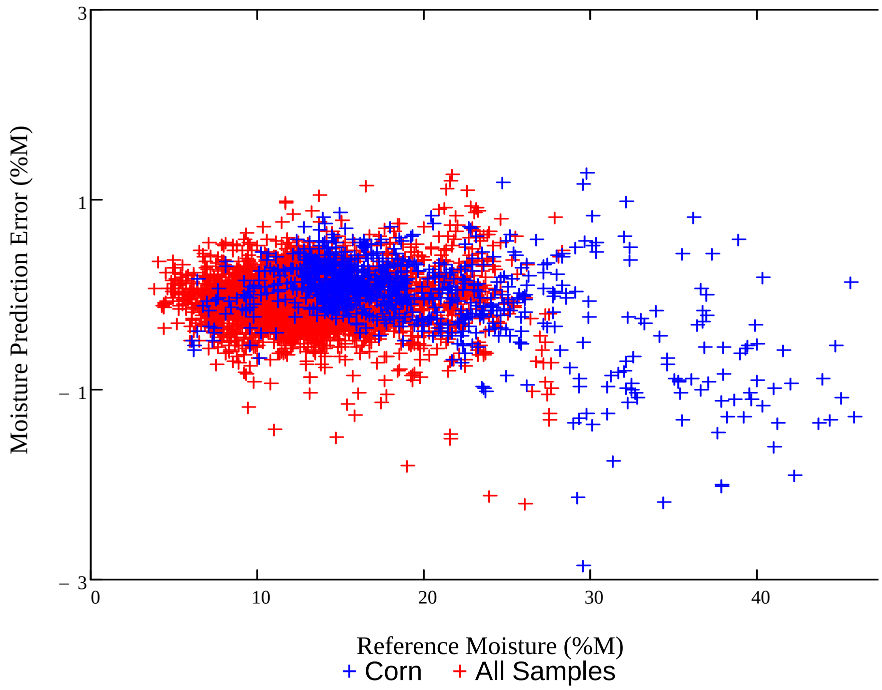

Figure 2. UGMA moisture prediction errors with respect to air oven moisture for all grain samples for 2010-2015crop years.

Table 7. UGMA calibration statistics by grain groups for 2010-2014crop years. STD is the standard deviation of predicted moisture error (with respect to the USDA-GIPSA air oven method) for the calibration samples for the FGIS Master UGMA system. Slope is the slope of the predicted moisture errors.

Grain Group	Samples	Bias	STD	Slope	Moisture Range
Soybeans	492	-0.04	0.17	0.00	4 - 23
Sorghum	172	-0.07	0.26	-0.02	10 - 25
Sunflower	331	-0.12	0.37	-0.02	5 - 28
Corn	826	-0.01	0.44	-0.03	6 - 46
Oats	69	0.00	0.21	0.01	9 - 18
Wheat, Hard	935	-0.04	0.18	0.00	6 - 21
Wheat, Soft	518	-0.05	0.19	0.01	7 - 22
Durum	197	-0.01	0.20	0.00	5 – 28
Barley	329	-0.08	0.22	0.00	8 - 18
Rice, Long Rough	414	-0.01	0.29	0.01	9 - 26
Rice, Medium Rough	287	-0.03	0.33	0.01	10 - 28
Rice, Short Rough	58	-0.07	0.38	-0.03	11 - 28
Rice, Long &Medium Milled+	70	0.00	0.20	-0.05	11 - 16
Rice, Brown+	80	0.00	0.20	-0.01	10 - 22
Rice, Short Milled+	58	0.00	0.13	-0.03	11 - 15
Rice, Parboiled+	52	0.00	0.18	-0.05	10 - 13
Beans 1	89	-0.02	0.20	0.00	9 - 19
Beans 2+	96	0.00	0.23	0.00	7 - 19
Beans 3+	61	0.00	0.20	-0.01	10 - 19
Beans 4+	51	0.00	0.11	0.00	9 - 21
Beans 5+	85	0.00	0.20	0.00	7 - 20
Peas	109	-0.02	0.24	0.01	7 – 17
Safflower+	36	0.00	0.21	-0.01	3 - 12
Canola	46	-0.03	0.20	0.00	4 - 18
Mustard	22	-0.03	0.19	-0.01	5 – 11
Mustard, Oriental+	17	0.00	0.20	0.00	5 - 19
Triticale & Rye+	26	0.00	0.22	-0.02	8 – 16
Flaxseed+	22	-0.05	0.15	-0.04	7 - 14
Popcorn	48	0.00	0.18	0.00	10 - 31
Buckwheat+	27	0.00	0.23	0.00	10 - 21

***Data range for the grain type is too limited to calculate a meaningful slope value.

+Statistics for minor grain groups for 2008 – 2013 crop years.

Table 8. UGMA calibration statistics for individual grain types for the FGIS Master UGMA System for 2010-2014 crop years. Slope is the slope of the predicted moisture errors.

Grain Types	Samples	Bias	STD	Slope	Moisture Range
Barley, Hull-Less	23	0.02	0.22	***	–8 - 12
Barley, Six-Rowed	146	-0.14	0.22	0.02	8 – 19
Barley, Two-Rowed	160	-0.03	0.21	0.01	8 – 17
Beans, Baby Lima+	29	-0.07	0.25	0.16	10 - 14
Beans, Black+	30	0.02	0.23	-0.02	10 - 18
Beans, Black-Eyed+	30	0.10	0.19	-0.07	9 - 14
Beans, Cranberry+	15	-0.03	0.17	0.03	12 - 19
Beans, Dark/ Light Red Kidney+	22	-0.04	0.22	0.04	10 - 20
Beans, Garbanzo+	46	0.00	0.23	-0.06	7 - 17
Beans, Great Northern+	16	0.02	0.12	-0.01	11 - 19
Beans, Large Lima+	15	-0.06	0.21	0.01	10 - 15
Beans, Pea+	48	0.00	0.11	-0.01	12 - 21
Beans, Pink+	17	-0.04	0.26	0.00	10 - 19
Beans, Pinto+	27	-0.03	0.23	0.02	9 - 18
Beans, Small Red+	21	0.10	0.17	-0.01	9 - 19
Beans, Small White+	3	-0.01	0.08	0.08	9 - 11
Buckwheat	19	0.01	0.27	-0.01	10 - 21
Buckwheat Groats+	8	0.00	0.05	***	12 - 13
Canola	29	-0.08	0.19	0.01	4 - 18
Corn	826	-0.01	0.44	-0.03	6 - 46
Popcorn	48	0.00	0.18	0.00	9 - 31
Durum	190	-0.01	0.21	0.00	5 - 29
Flaxseed+	22	-0.05	0.15	-0.04	7 - 14
Lentils+	63	0.02	0.20	-0.03	7 - 14
Mustard Seed, Brown+	3	0.17	0.16	***	5 - 7
Mustard Seed, Oriental+	17	0.00	0.20	0.00	5 - 19
Mustard Seed, Yellow	21	-0.04	0.20	-0.01	5 - 11
Oats	69	0.00	0.21	0.01	9 - 18
Oats, Hulless+	7	-0.15	0.09	0.04	8 - 13
Peas, Mottled Dry	23	0.11	0.19	-0.13	7 - 11
Peas, Smooth Dry	72	-0.07	0.26	0.04	–8 - 17
Peas, Split	39	-0.04	0.07	0.01	–8 - 15
Peas, Wrinkled Dry+	14	-0.04	0.10	0.14	7 - 9
Rapeseed+	17	0.07	0.21	0.01	4 - 13
Rice, Brewers Milled+	15	-0.10	0.05	-0.01	11 - 13
Rice, Long Grain Brown+	28	0.01	0.18	-0.02	11 - 19
Rice, Long Grain Brown Parboiled+	15	0.02	0.26	***	11 - 13
Rice, Long Grain Milled+	33	0.00	0.17	-0.06	11 - 14

***Data range for the grain type is too limited to calculate a meaningful slope value.

+Statistics for minor grains are for 2008 – 2013 crop years.

Table 8. Continued

Grain Types	Samples	Bias	STD	Slope	Moisture Range
Rice, Long Grain Milled Parboiled+	13	-0.03	0.14	-0.07	10 - 12
Rice, Long Grain Rough	414	-0.01	0.29	0.01	9 - 26
Rice, Long/ Medium Second Head Milled+	15	0.11	0.05	0.09	12 - 13
Rice, Medium Grain Brown+	47	0.01	0.22	0.02	10 - 19
Rice, Medium Grain Milled+	37	0.00	0.22	-0.06	12 - 16
Rice, Medium Grain Milled Parboiled+	10	-0.07	0.06	***	12 - 13
Rice, Medium Grain Rough	287	-0.03	0.33	0.01	10 - 28
Rice, Second Head Milled Parboiled+	14	0.05	0.13	***	10 - 11
Rice, Short Grain Brown+	5	-0.16	0.06	-0.01	13 - 22
Rice, Short Grain Milled+	12	0.05	0.10	0.03	12 - 14
Rice, Short Grain Rough	58	-0.07	0.38	-0.03	11 - 28
Rice, Short Grain Second Head Milled+	16	-0.04	0.17	-0.11	12 - 15
Rye+	24	-0.02	0.21	0.00	11 - 15
Safflower+	36	0.00	0.21	-0.01	3 - 12
Sorghum	172	-0.07	0.26	-0.02	10 - 25
Soybeans	492	-0.04	0.17	0.00	4 - 23
Sunflower Seed	310	-0.14	0.36	-0.02	5 - 28
Sunflower Seed, Confectionary	21	0.09	0.42	0.07	8 - 14
Triticale+	9	0.04	0.20	-0.04	9 - 11
Wheat, Hard Red Spring	340	-0.09	0.20	-0.01	6 - 22
Wheat, Hard Red Winter	405	0.00	0.15	0.00	7 - 19
Wheat, Hard White	190	-0.05	0.18	0.04	6 - 21
Wheat, Soft Red Winter	352	-0.01	0.19	0.00	9 - 22
Wheat, Soft White	166	-0.14	0.17	-0.01	7 - 19

***Data range for the grain type is too limited to calculate a meaningful slope value.
+Statistics for minor grains are for 2008 – 2013 crop years.

Details of Secondary Density Correction Method

The secondary density correction dramatically reduces the error for corn caused by unusually low (or high) density samples. 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 +). A similar approach may be applied to other grains where the moisture error correlates to the density, such as with oats; it is anticipated that most grains will not need a density correction.

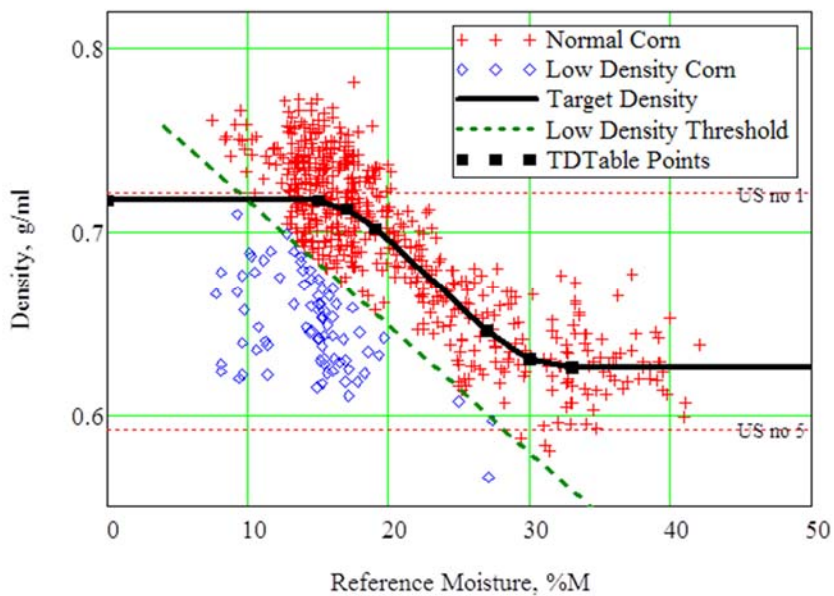

Figure 3. Target density curve (***TDTable***, Table 5)

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

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

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:

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

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.

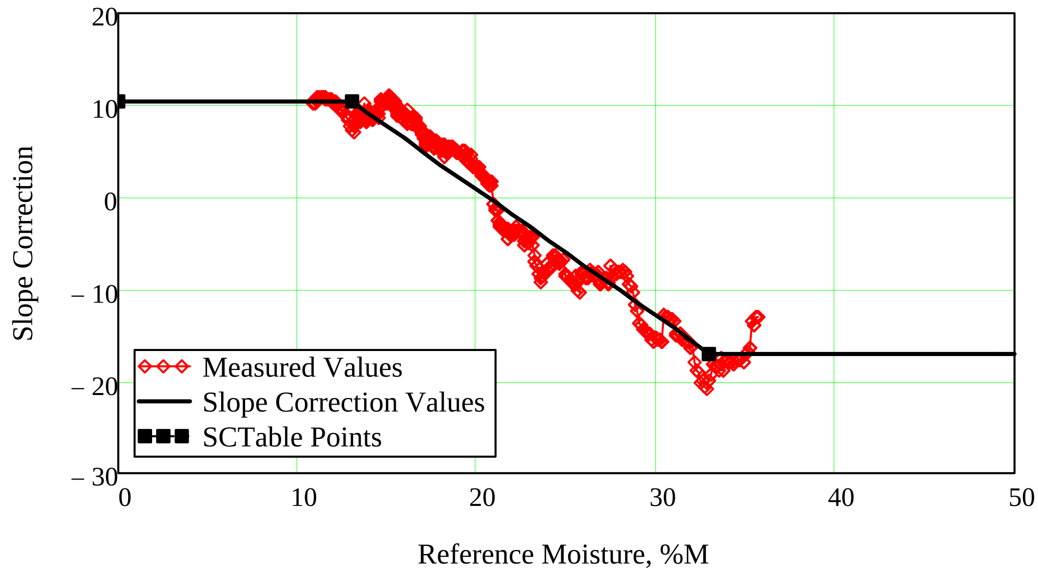

Figure 4. Slope correction values. Visualization of the ***SC Table*** (Table 6).

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.	-0.60	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

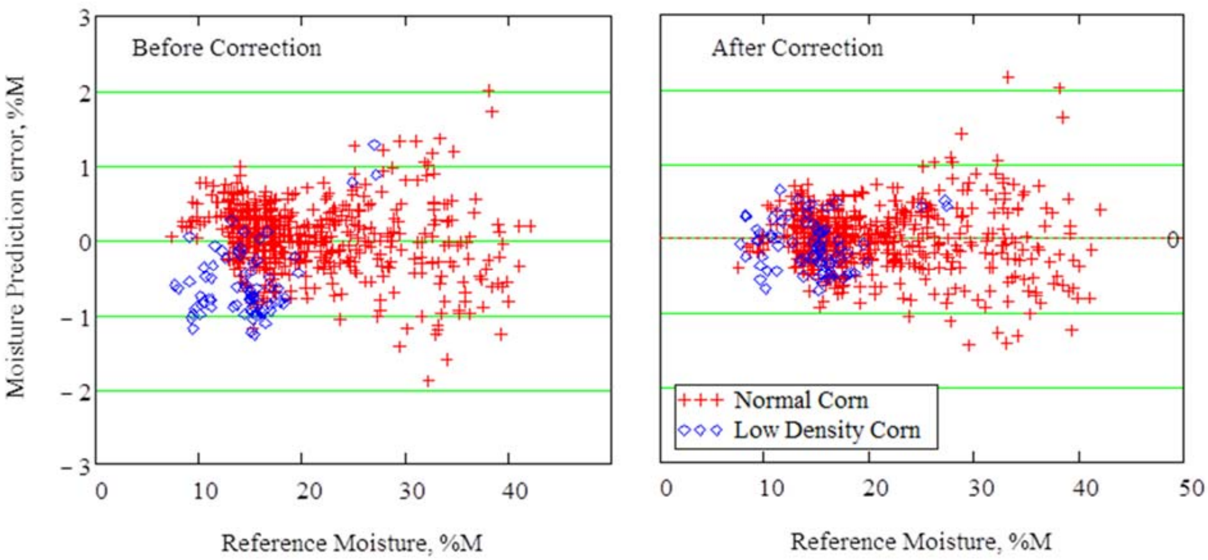

Figure 5. Corn sample predicted moisture errors before and after secondary density correction for 2008-2010 corn.

Details of Secondary Line Shape Correction Method

The secondary line shape correction dramatically reduces the error for soybeans, long grain rough rice and medium grain rough rice caused by unusually dry samples and/or wet samples for the grain group. This correction addresses subtle differences in a grain group's line shape that may not be completely accounted for with the unifying parameters and without changing the UGMA from a fifth order polynomial to a seventh order polynomial. It should be noted that changing to a seventh order polynomial would require the unifying parameters for all grain groups be changed. Figure 6 illustrates key aspects of the correction. The long grain rough rice plot shows the samples below 15% moisture have a different slope compared to the samples above 15%. It also shows that the samples above approximately 20% moisture have a different slope compared to the samples below 20%.

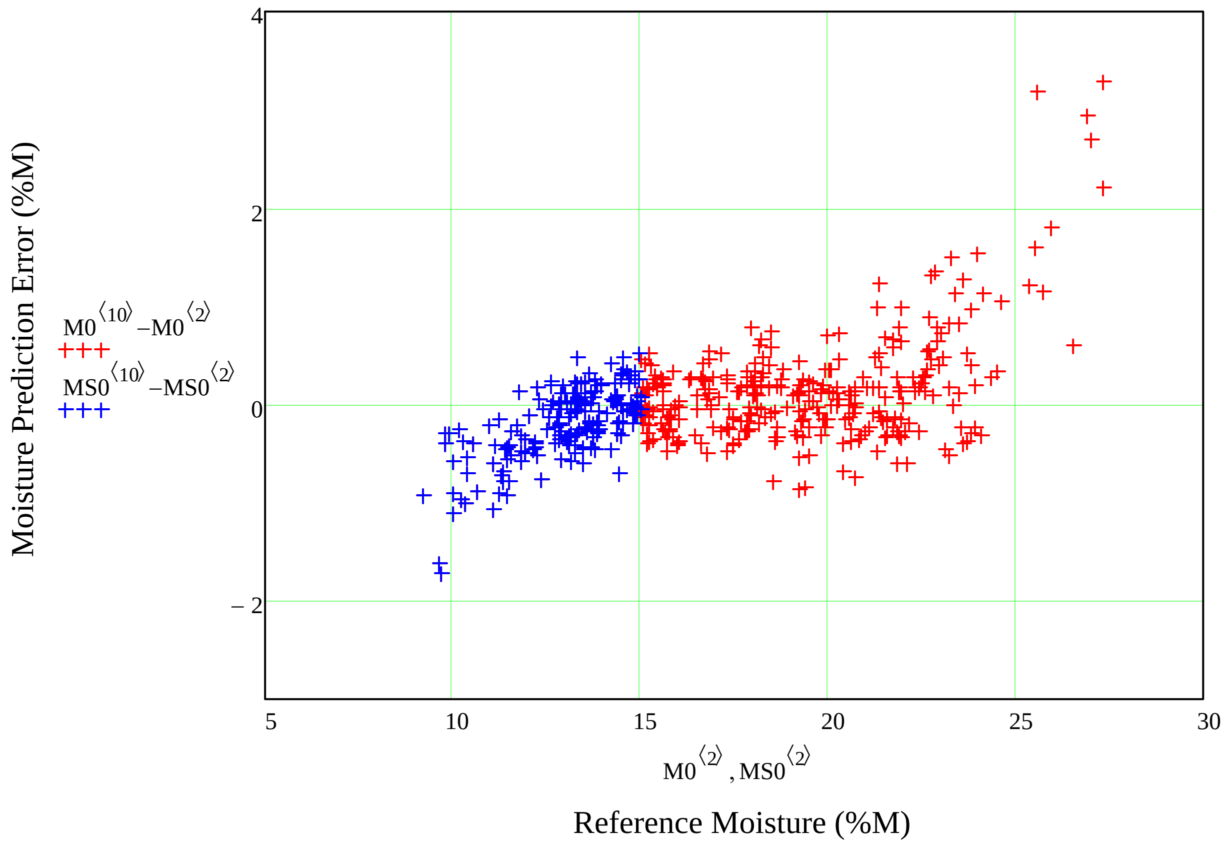

Figure 6. Long grain rough rice sample predicted moisture errors before secondary line shape correction for 2009 – 2013 crop.

Figure 7 illustrates the improvement in the moisture prediction error by applying the line shape corrections listed in Tables 5c and 6c. THR1 is the upper moisture limit for the slope correction applied to samples with a moisture below 15% (blue +) and THR2 is the lower moisture limit for the slope correction applied to samples with a moisture above 21% (green +).

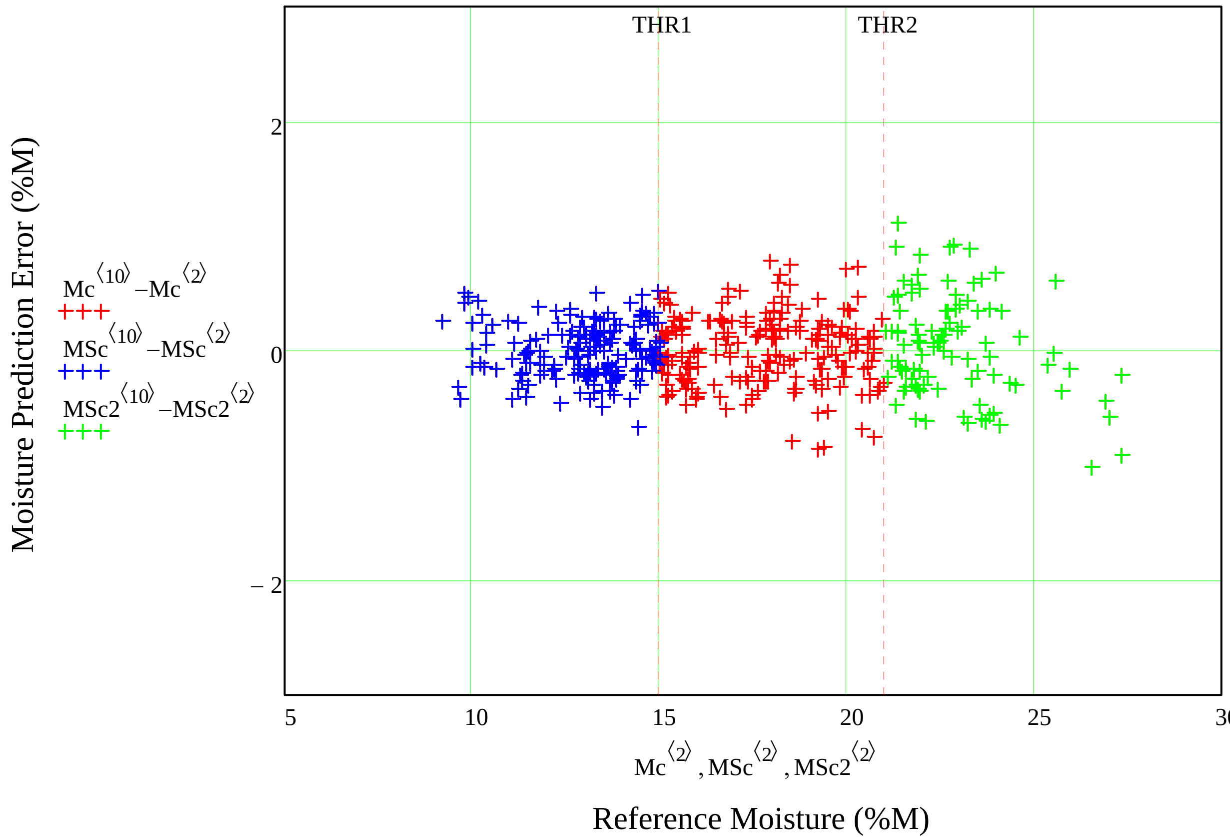

Figure 7. Long grain rough rice sample predicted moisture errors after applying line shape correction for 2009 – 2013 crop.

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). 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 measurements.

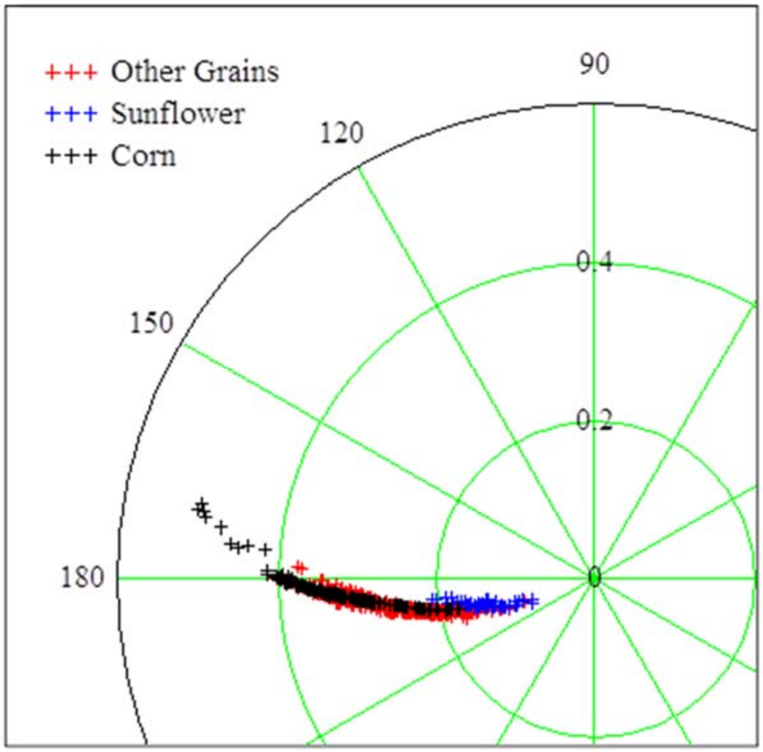

Figure 6. Complex reflection coefficients measured with UGMA Master System for grain samples in 2008, 2009, and 2010 Calibration Studies.

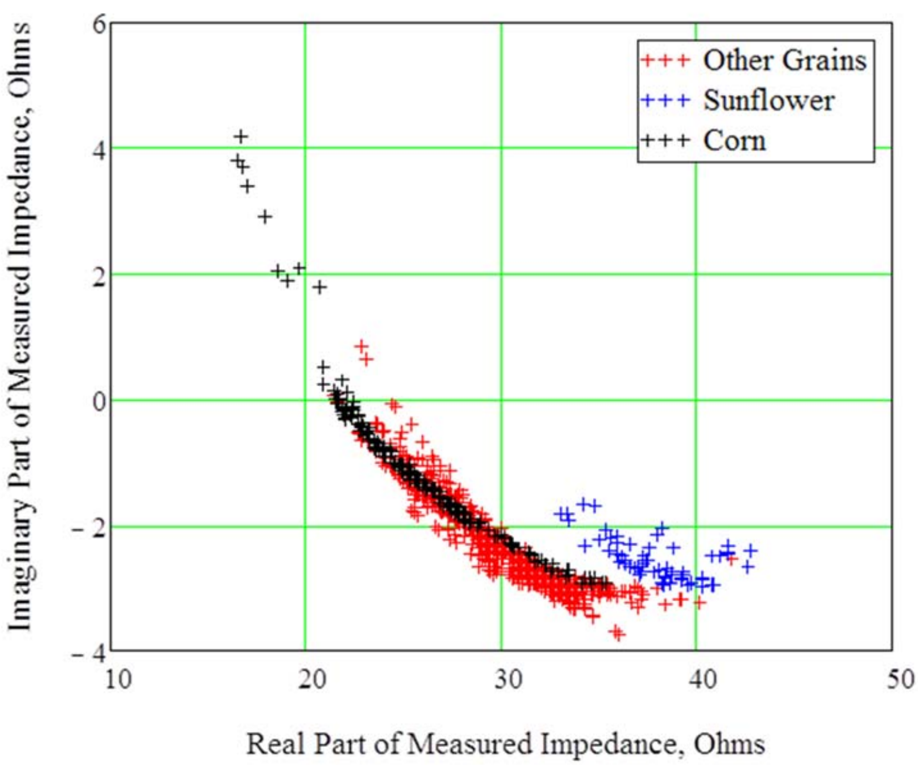

Figure 7. Complex impedance values measured with UGMA Master System for grain samples in 2008, 2009, and 2010 Calibration Studies.

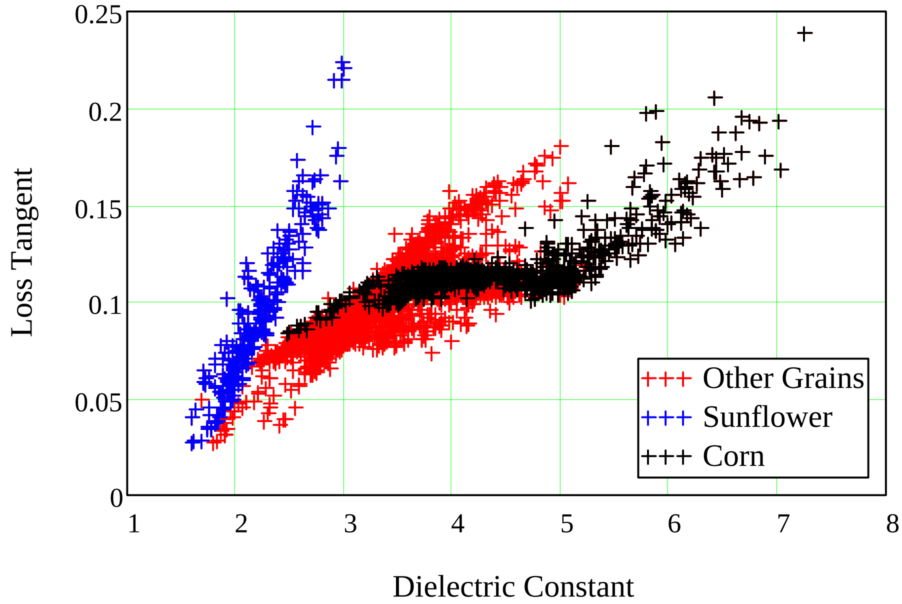

Figure 8. Loss tangent versus dielectric constant values for grains tested in 2008, 2009, and 2010 Calibration Studies.

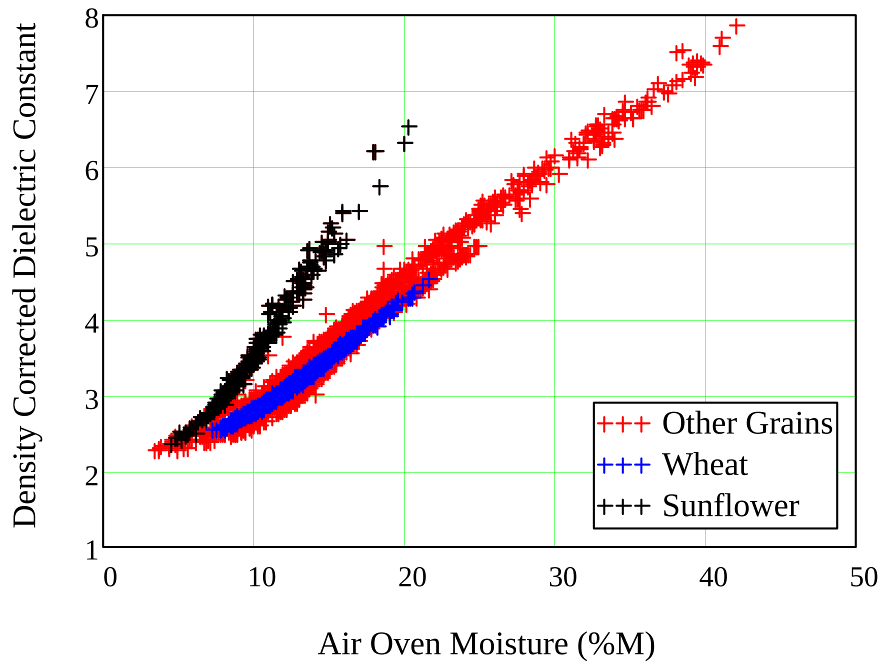

Figure 9. Density-corrected dielectric constant (ε_{den}) versus moisture values for grains tested in 2008, 2009, and 2010 Calibration Studies.

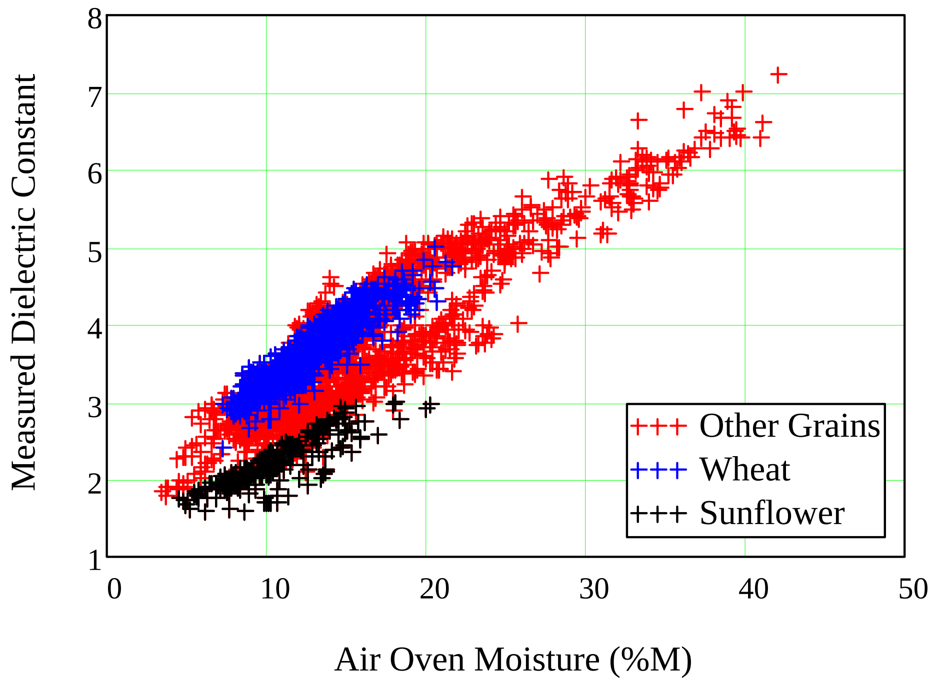

Figure 10. Measured (ε_{meas}) dielectric constant values (prior to density correction) for grains tested in 2008, 2009, and 2010 Calibration Studies.

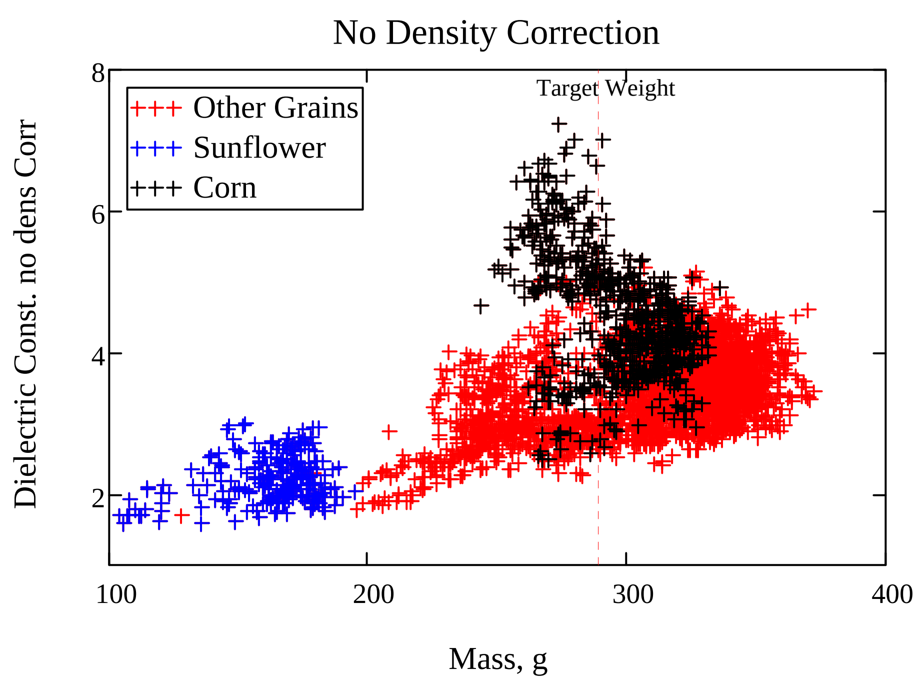

Figure 11. Measured (ε_{meas}) dielectric constant values (without density correction) versus sample mass for grains tested in 2008, 2009, and 2010 Calibration Studies.

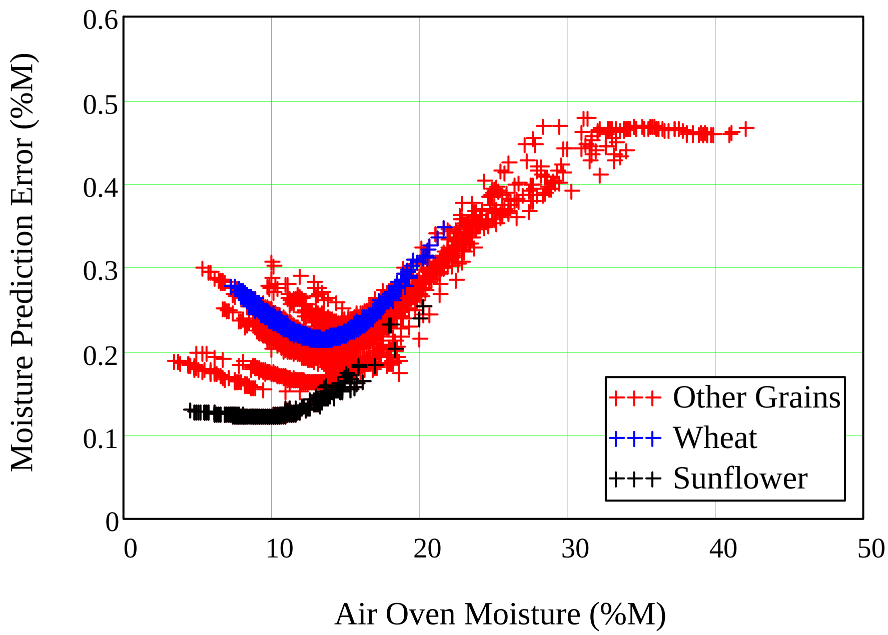

Figure 12. Moisture prediction errors resulting from 1% (of value) errors in density-corrected dielectric constant for grains tested in 2008, 2009, and 2010 Calibration Studies. Simulation equation: $\varepsilon_{den} = \varepsilon_{den} \cdot 1.01$

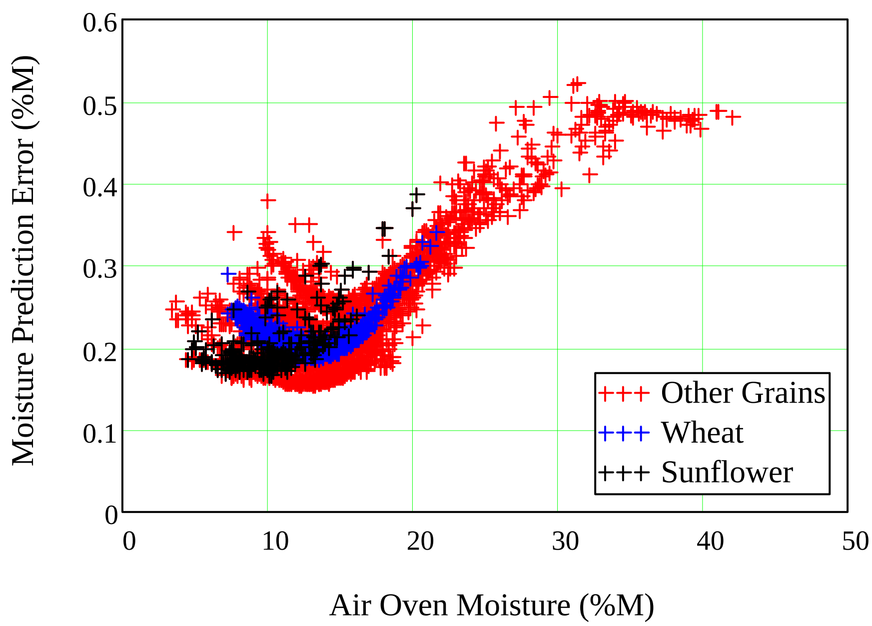

Figure 13. Moisture prediction errors resulting from 1% (of value) errors in measured dielectric constant (prior to density correction) for grains tested in 2008, 2009, and 2010 Calibration Studies. Simulation equation: $\varepsilon_{meas} = \varepsilon_{meas} \cdot 1.01$

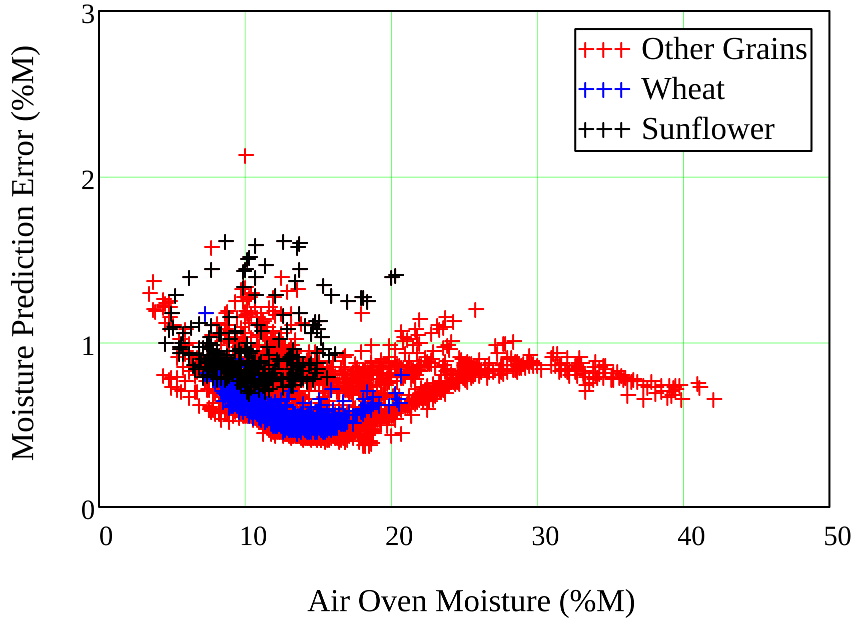

Figure 14. Moisture prediction errors resulting from a change 0f +0.1 in measured dielectric constant (prior to density correction) for grains tested in 2008, 2009, and 2010 Calibration Studies. Simulation equation: $\varepsilon_{meas} = \varepsilon_{meas} + 0.10$

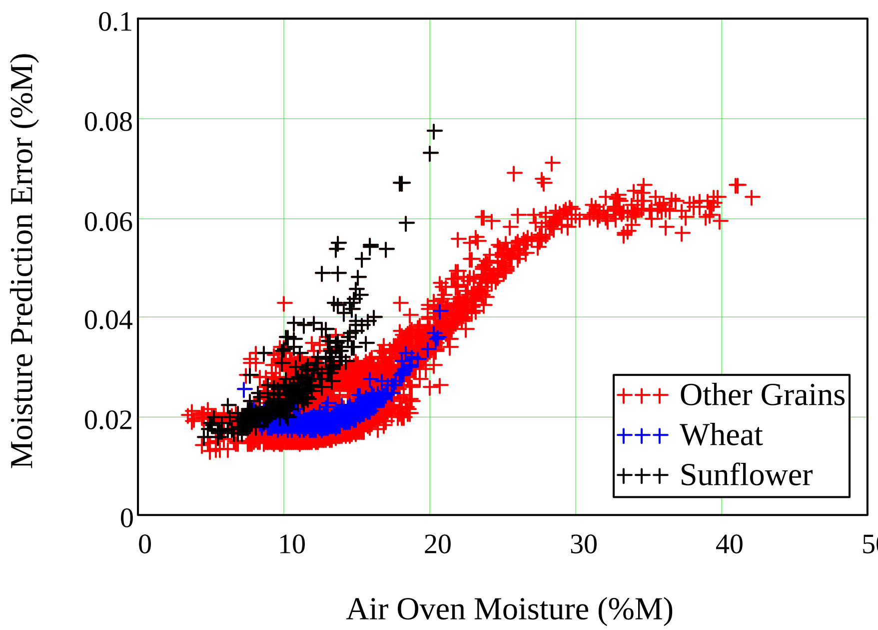

Figure 15. Moisture prediction error resulting from a simulated -0.3 gram mass measurement error for grains tested in 2008, 2009, and 2010 Calibration Studies. (A negative mass measurement error results in a positive moisture prediction error and vice versa.)

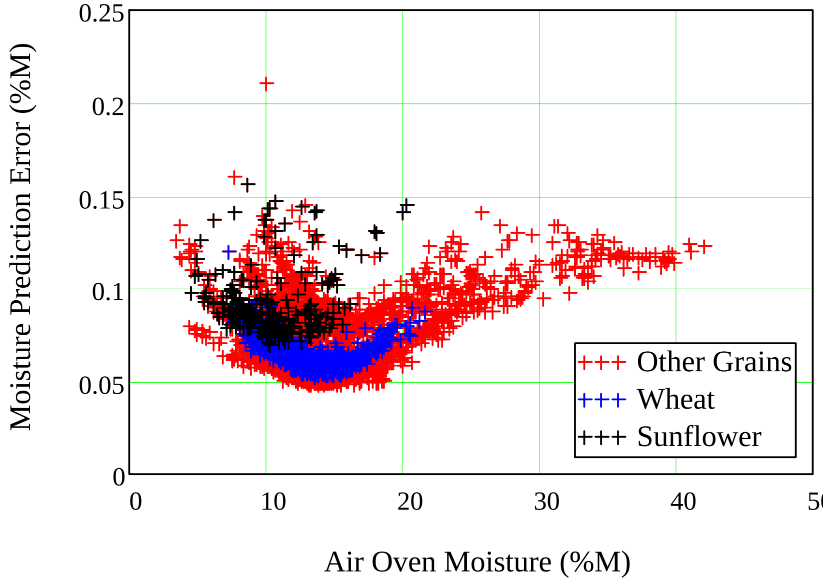

Figure 16. Moisture prediction error caused by a simulated +0.001 error (not relative) in the magnitude of the measured reflection coefficient (at the test cell connector) for grains tested in 2008, 2009, and 2010 Calibration Studies with the FGIS Master UGMA system. (Note: This sensitivity is dependent on instrument design.) Simulation equation:
$\Gamma = (|\Gamma| + 0.001) \cdot e^{i \cdot arg(\Gamma)}$

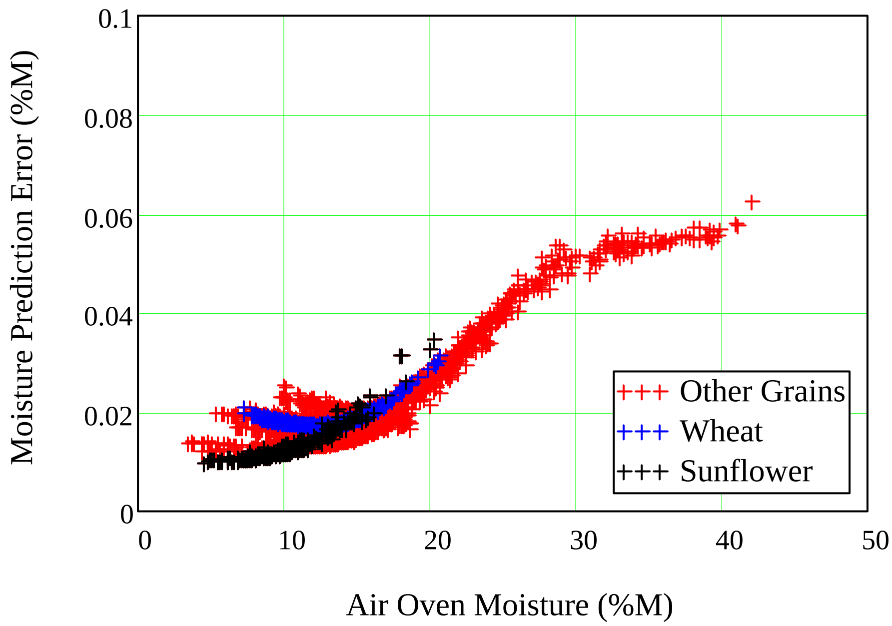

Figure 17. Moisture prediction error caused by a simulated +0.1% relative change in the magnitude of the measured reflection coefficient (at the test cell connector) for grains tested in 2008, 2009, and 2010 Calibration Studies with the FGIS Master UGMA system. (Note: This sensitivity is dependent on instrument design.) Simulation Equation: $\Gamma = |\Gamma| \cdot 1.001 \cdot e^{i \cdot arg(\Gamma)}$

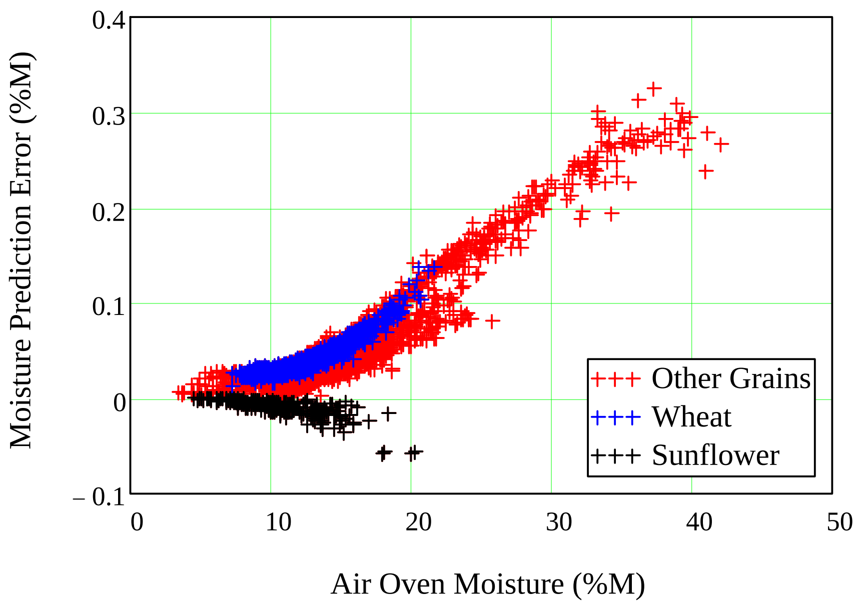

Figure 18. Moisture prediction error caused by a simulated -1 degree error in the phase of the measured reflection coefficient (at the test cell connector) for grains tested in 2008, 2009, and 2010 Calibration Studies with the FGIS Master UGMA system. (Note: This sensitivity is dependent on instrument design.) Simulation Equation: $\Gamma = |\Gamma| \cdot e^{i\cdot(\arg(\Gamma)-1°)}$

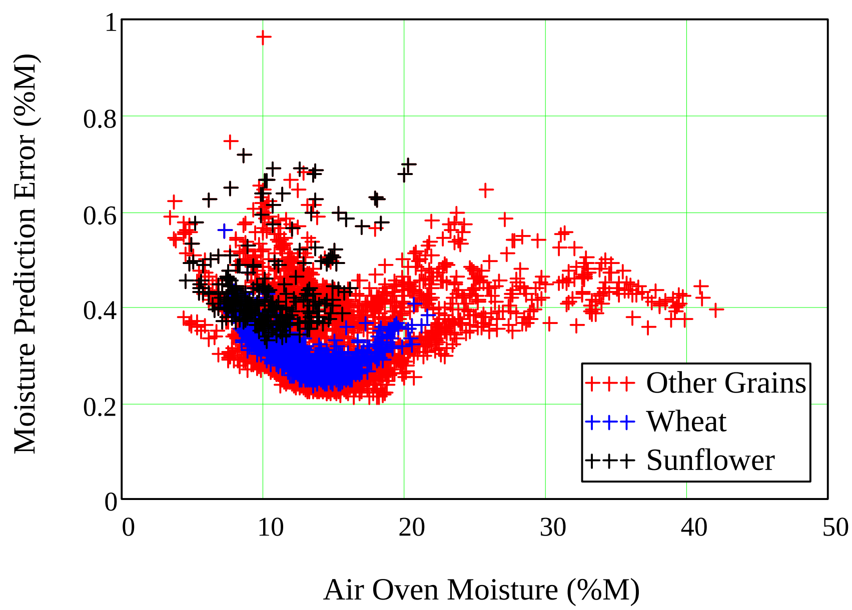

Figure 19. Moisture prediction error caused by a simulated -1% (relative) error in the magnitude of the measured test cell complex impedance (at the test cell connector) for grains tested in 2008, 2009, and 2010 Calibration Studies with the FGIS Master UGMA system. (Note: This sensitivity is dependent on instrument design.) Simulation equation: $Z = |Z| \cdot 0.99 \cdot e^{i\cdot arg(Z)}$

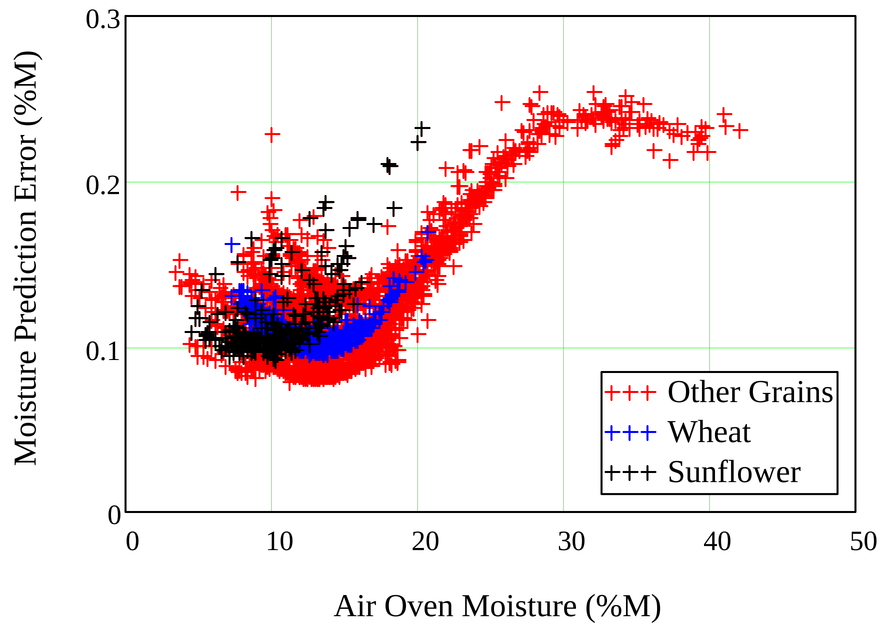

Figure 20. Moisture prediction error caused by a simulated -0.1 ohm error in the magnitude of the measured test cell complex impedance (at the test cell connector) for grains tested in 2008, 2009, and 2010 Calibration Studies with the FGIS Master UGMA system. (Note: This sensitivity is dependent on instrument design.) Simulation equation: $Z = (|Z| - 0.1) \cdot e^{i \cdot arg(Z)}$

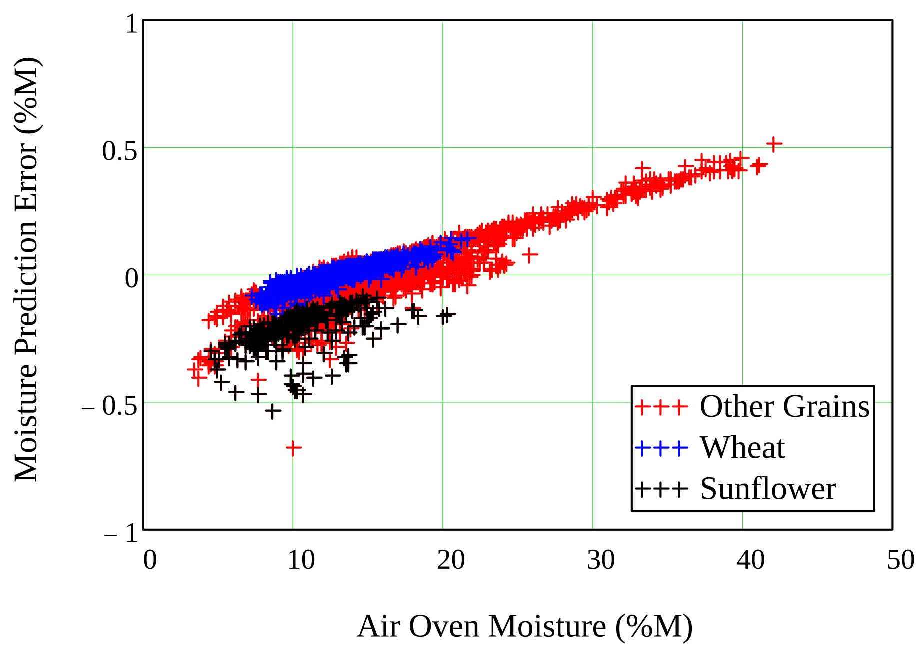

Figure 21. Moisture prediction error caused by a simulated -1 degree error in the measured phase of the test cell impedance (at the test cell connector) for grains tested in 2008, 2009, and 2010 Calibration Studies with the FGIS Master UGMA system. (Note: This sensitivity is dependent on instrument design.) Simulation equation: $Z = |Z| \cdot e^{i \cdot (arg(Z) - 1°)}$

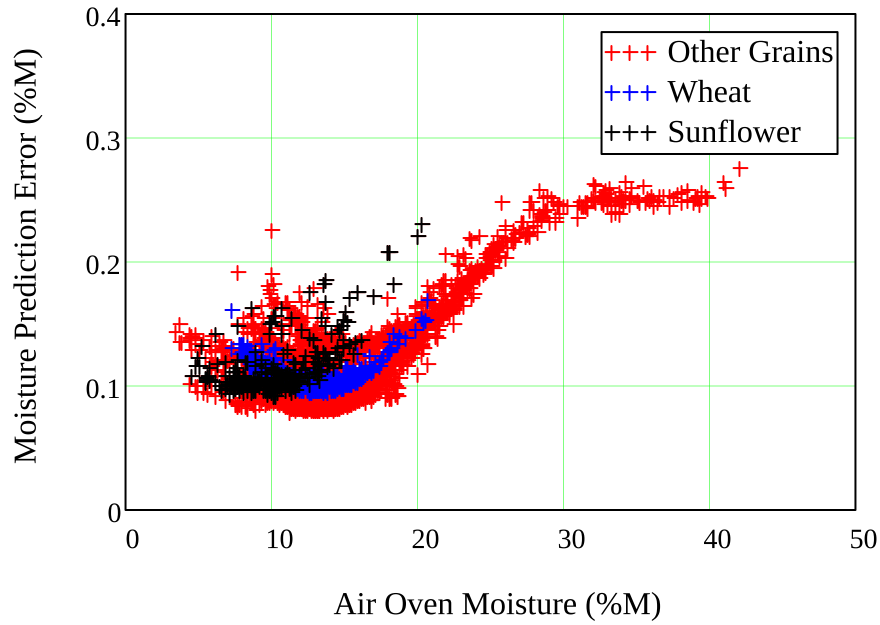

Figure 22. Moisture prediction error caused by a simulated 0.1ohm resistance inserted in the connection between the source-end connector and the center test cell center electrode for grains tested in 2008, 2009, and 2010 Calibration Studies with the FGIS Master UGMA system. (Note: This sensitivity is dependent on instrument design.)

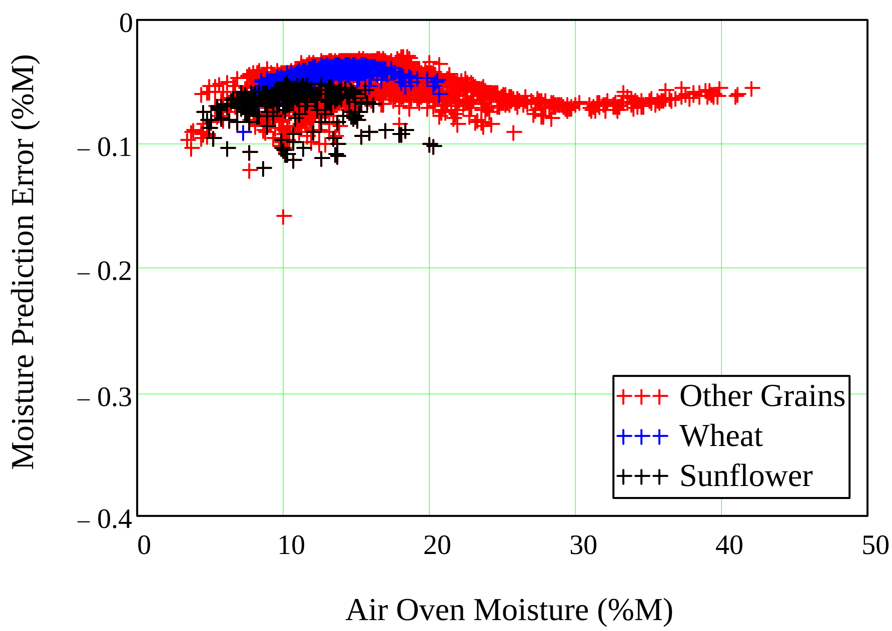

Figure 23. Moisture prediction error caused by a simulated 0.1ohm resistance inserted in the connection between the connector to the 50-ohm load and the center test cell center electrode for grains tested in 2008, 2009, and 2010 Calibration Studies with the FGIS Master UGMA system. The polarity of the change is opposite to that shown in Fig. 22. (Note: This sensitivity is dependent on instrument design.)

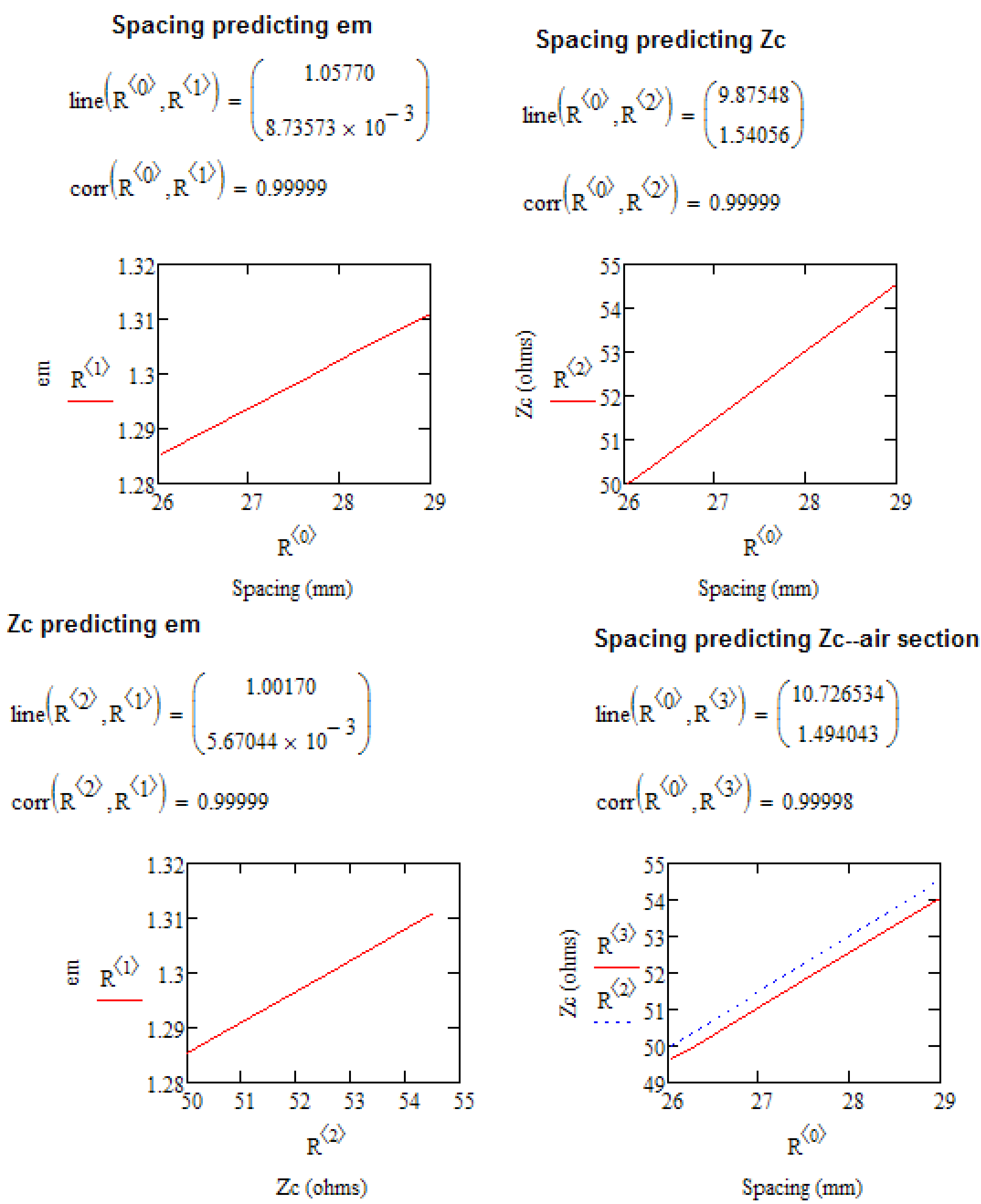

Figure 24. Relationships between test cell plate spacing, characteristic impedance, and filling factor. The relationships are highly linear. These results are from finite element analysis using the dimensions of the FGIS “New Master” (NM) test cell. Note that the “Spacing Predicting Zc—air section” analysis 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.

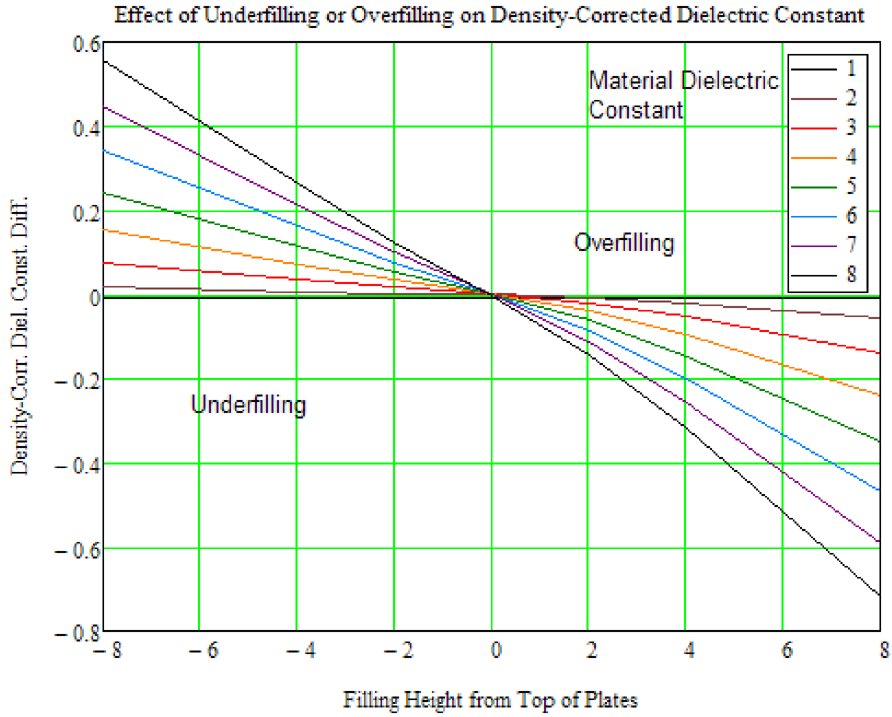

Figure 25. Estimated effects on density-corrected dielectric constant of overfilling and under-filling of the test cell (as a function of filling height in mm). These results are based on finite element analysis of the "New Master" test cell.

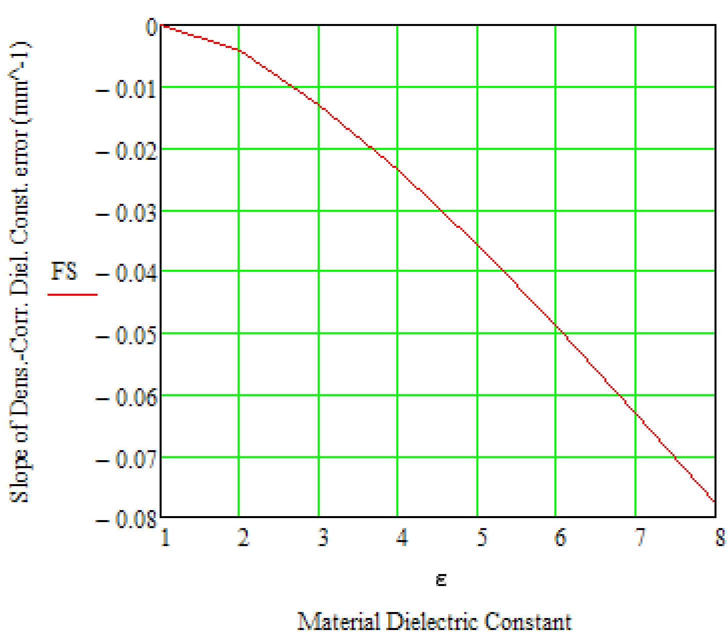

Figure 26. The slope of the density-corrected dielectric constant change with filling height (dielectric constant units per mm) based on finite element analysis of the New Master test cell. These are the slopes about the center point of Figure 25 (at the top of the plates). Over-filling causes the measured dielectric constant to be lower; thus the sign of the slope is negative.

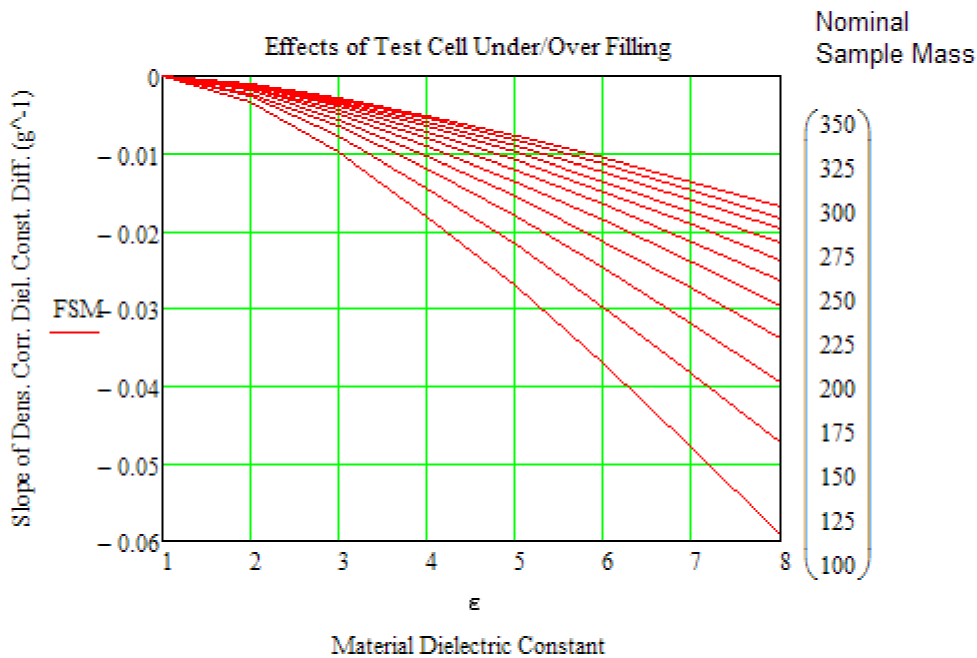

Figure 27. Plot of the slopes of density-corrected dielectric constant per gram of cell over-filling (or under-filling) for different nominal full-sample masses. These results, like those of Figs. 24-26, are based on finite element analysis of the New Master test cell and assume "rectangular" sample cross-sections. These are the slopes about the "full" point corresponding to the center point of Figure 25. Over-filling causes the measured dielectric constant to be lower; thus the sign of the slope is negative.

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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