Basic Questions

• Why do we care about moisture content?
• What is water, really?
• How can we measure moisture content?
• How do moisture meters work?
• What has FGIS achieved by adopting UGMA moisture meters?
• How is FGIS ensuring the continued accuracy of Official moisture results?
• How can moisture meter users optimize their moisture measurement results?
Price Paid for Grain

Price per Unit Wet Mass Delivered

Uncompensated Dry Matter

Extra Cost for Drying

Dry Matter Value

"Market" Moisture

Moisture Content--Wet Basis
Water: 2 hydrogen atoms + 1 oxygen atom
Water Molecule Neutral but Atoms Share Charge Unequally

• Water molecule has same number of protons (positive) and electrons (negative) so it is electrically neutral, but...

• Oxygen atom is more “electronegative” than hydrogen, so it “hogs” the hydrogen atoms electrons that it shares through covalent bonding.

• Oxygen atom has net negative (-) charge.

• Hydrogen atoms have net positive (+) charges.
Water Molecule is Bent

- Oxygen atom’s preferred directions for covalent bonding are tetrahedral.
- Oxygen needs to share two electrons, thus two hydrogen atoms.
- Hydrogen atoms make a 104° angle
Water Molecule is Polarized

• The oxygen side of the water molecule is negatively charged.
• The hydrogen side is positively charged.
• This displacement of charge is called a “Dipole Moment”
Hydrogen Bonding

• No “free” water except in gas.
• Positive hydrogen atoms are electrostatically attracted to and attached to negative oxygen atoms through “hydrogen bonding.”
• Water attaches to other molecules and other water molecules through hydrogen bonds of varying strengths.
• Dielectric characteristics of grain are profoundly affected by hydrogen bonding.
So, how to measure moisture content?

• Reference methods
  – Air oven
  – Other such as Karl Fischer
• NIR
• Dielectric spectroscopy
Air Oven Method

• Mass loss on drying
• Not absolute method—a affected by many factors:
  – Oven temperature
  – Length of time grain/flour is in oven
  – Relative humidity of laboratory air
  – Amount of air circulation in oven
  – Grain/flour particle size
  – Depth of grain/flour in drying vessel
• Possibility of non-aqueous material loss
• Air oven methods specify drying time, temperature, particle size etc. to match more basic methods and amount of dry matter accessible in processing.
NIR and Dielectric Methods
Water Molecule Interacts with Electric Fields

• Static Electric Fields
• Alternating Electric Fields
  – Audio frequencies
  – Radio frequencies
  – Microwave frequencies
  – Light
NIR and Dielectric Moisture Meters Use Very Different Frequencies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Wavelength</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIR</td>
<td>1.94 x 10^{-6} m</td>
<td>1.5 x 10^{14} Hz</td>
</tr>
<tr>
<td>UGMA</td>
<td>2 m</td>
<td>1.5 x 10^{8} Hz</td>
</tr>
<tr>
<td>Model 919</td>
<td>17 m</td>
<td>1.8 x 10^{7} Hz</td>
</tr>
<tr>
<td>GAC 2100</td>
<td>150 m</td>
<td>2.0 x 10^{6} Hz</td>
</tr>
<tr>
<td></td>
<td>60 km</td>
<td>5.0 x 10^{3} Hz</td>
</tr>
</tbody>
</table>
Dielectric Spectroscopy

• Moisture measurements by dielectric spectroscopy also depend upon the interaction of electric fields with the water molecule’s dipole moment—but in reorientation, not vibration.
Basic Units for Electricity

Ohm’s Law

Current = Pressure / Resistance

Current (Coulombs/sec)
Water Analogy

Pressure = depth x density (lb/sq. inch)

Flow = Pressure/Resistance

Resistance (smaller hole, higher resistance)

Flow rate (ft³/min)
Water Analogy for Capacitance

Amount of water in tank \( Q = \text{depth} \times \text{area of surface} \)

The amount of water \( Q \) the pump can force into the tank is directly related to the pressure \( P \) the pump can achieve.

The greater the area \( A \) of the tank, the more water a pump with max pressure \( P \) can force into it.

So: \( Q = A \times P \times (\text{a constant}) \)
The amount of charge $Q$ separated on the facing plates is proportional to the voltage $V$ of the battery and the area $A$ of the facing plates.

**Capacitance** $C = \frac{Q}{V}$

For a capacitor formed by parallel plates of area $A$ in air, separated by distance $d$,

$$C = \varepsilon_0 \times \frac{A}{d}$$

Where $\varepsilon_0$ is the permittivity of free space $= 8.85 \times 10^{-12}$ Farad/meter

The space between the two plates contains an **Electric Field** $E$ (volts/meter).
Relative Dielectric Constant

If the space between the plates is filled by some material other than air, more charge can be stored on the capacitor for the same voltage applied to the capacitor. The ratio of the capacitance with material present to the capacitance with air is the relative dielectric constant $\varepsilon_r$.

$$C = \varepsilon_0 \times \varepsilon_r \times \frac{A}{d}$$

For air, $\varepsilon_r = 1.000$

Since the relative dielectric constant of other non-conducting materials is greater than 1.0, the capacitor with some material other than air as its “dielectric” can store more charge for the same impressed voltage $V$. 
Conductance

If the material between the plates is not a perfect insulator, current may flow from plate to plate.

Conductance of the dielectric ($G$) is defined as $1/\text{resistance}$ of the dielectric.

$$G = \frac{I \text{ (current)}}{V \text{ (voltage)}}$$
With Alternating Voltage Drive

The situation gets much more “complex” in many ways.

Dielectric constant and conductance vary with the frequency of the driving voltage.

Polar water molecules attempt to reorient to align with the time-varying electric field.
Complex Permittivity

\[ \varepsilon^* = \varepsilon_0 \cdot (\varepsilon'_r - j \cdot \varepsilon''_r) \]

\( \varepsilon'_r \): **dielectric constant** = real part of relative complex permittivity (energy stored per cycle)

\( \varepsilon''_r \): **loss factor** = imaginary part of relative complex permittivity (energy dissipated per cycle)
Water Molecules React to Electric Fields by Rotating
Non-polar Atoms & Molecules React to Electric Fields by Slight Shape Shifting
Dielectric Constant

• Dielectric constant is a physically-defined, measurable material property.
• For liquid water at room temperature, $\varepsilon'_r = 78.5$
• For non-polar grain constituents, $\varepsilon'_r = 2$ to $3$
• Therefore, measurements of dielectric constant are closely related to moisture content.
• Dielectric constant ranges from about $2$ for very dry grain to about $8$ for high moisture grain.
• But measurements are related to the mass of water in the test cell—not the percent water by weight, so results must be density-compensated.
Grain Conductivity Effects

• Grain is not a perfect insulator—that is, it conducts electricity to some extent.
• Grain conductivity interferes with the more useful capacitance measurements.
• Conductivity increases rapidly with increasing moisture content.
• Conductivity increases rapidly with increasing temperature.
• Conductivity decreases relative to capacitance at higher measurement frequencies.
• Conductivity interferes less with moisture measurements at higher frequencies.
On to Moisture Meters

- Model 919
- GAC II/2100
- UGMA
null
Model 919 Operating Principle

• Measure temperature manually before moisture test.
• Weigh out specified mass for specific grain type.
• “Calibrate” 919 by nulling meter with test cell empty.
• Pour weighed sample into loading fixture and drop it into test cell.
• Re-null meter and read value from capacitor dial.
• Dial Capacitor + Calibrate Capacitor + Test Cell Capacitor = Constant
• Change in dial capacitor to achieve null (variable oscillator matches reference oscillator) = increase in test cell capacitance due to grain
• Dial position (capacitance added in test cell) used in lookup table to find predicted moisture.
• Externally measured sample temperature used with lookup table to provide temperature compensation.
Model 919 Test Cell

- Achieved moderate density compensation
- Tapered aluminum center electrode
- Doubly tapered acrylic sleeve
Model 919

- Strengths
- Weaknesses
GAC 2100

- Originally designed in 1976-1977 (GAC II version)
- First U.S. fully automated moisture meter.
- Adopted as FGIS Official meter in 1998.
GAC II/2100 Operating Principle

- Grain dropped into parallel-plate test cell and struck off by arm with stretched spring.
- Grain mass measured with simple electronic scale system supporting test cell.
- Grain temperature measured by simple temperature sensor at bottom of test cell.
  - Temperatures measured at two times used to predict final temperature without waiting for stabilization.
- Capacitance (actually admittance) measured at two frequencies: 2 MHz and 5 kHz.
- Measurement at 5 kHz used for rough correction for grain conductivity.
- Mathematically corrected for sample temperature and density.
- Predicted moisture with proprietary equation.
GAC 2100

• Strengths

• Weaknesses
How and why did GIPSA develop the Unified Grain Moisture Algorithm?

- UGMA was the result of extensive GIPSA research and GIPSA-supported research from 1997 to 2011.
- The goal was to develop a superior moisture measurement method and document it so completely that multiple manufacturers could create compatible instruments.
What is GIPSA’s Unified Grain Moisture Algorithm (UGMA)?

• Very accurate dielectric-type moisture method
• Higher measurement frequency (about 149 MHz)
• Based on a defined physical parameter—
  – Dielectric Constant
• Precise grain mass measurement and excellent density correction
• Three “unifying parameters” per grain group
• A single calibration “curve” for all grain types
• Precise, wide-range temperature correction
• Calibrated to GIPSA’s standard Air Oven method
• “Open”—Available to any manufacturer
GIPSA’s Reference System

Agilent E4991A Impedance Analyzer

Master Test Cell
Operation at 149 MHz requires completely different electronics and mathematics.

- The test cell is a significant fraction of the wavelength of the signal (2 meters) so phase differences are extremely important.
- Must describe the test cell mathematically using microwave transmission line techniques.
- Multiple reflections occur within the test cell and yield very complex signals.
- Describing the test cell mathematically permits deducing the grain dielectric constant that would cause the observed reflected wave.
Convert Reflection Coefficient to Dielectric Constant with (Simplified) ABCD Matrix Model

Source 50 Ω  →  Air-filled section  →  Grain-filled section  →  Air-filled section  →  Termination 50 Ω
Fortunately, the user need not understand the horrendous mathematics involved!
Sample densities are all normalized to a single density using special equation.
Eureka! #1: Effectiveness of the Landau-Lifshitz, Looyenga Density Correction

LLL_Exponent = 0  
SEC = 1.396

Density Correction--Corn @ 149 MHz
Eureka! #2: Geometrically-Similar Shapes in VHF Range

\[ r := \text{FRAME} \quad \quad f_{\text{FRAME}} = 1 \times 10^6 \]
Landau-Lifshitz, Looyenga
Density Normalization
Adjust Slope Parameter for Slope of 6.0 %M per unit dielectric constant in 10-20 % Range
Adjust Offset Parameter

[Graph showing the relationship between Adjusted Dielectric Constant and Reference Moisture (%)]
5th-Order Polynomial Equation

Number of Samples = 6189  Overall SEC = 0.34 % Moisture
Calibration Installation

• Via USB memory device

• Download from Internet to USB memory device

No numbers to enter by hand!!!