LOW-COST GRAIN BIN MOISTURE SENSOR USING MULTIPLE CAPACITIVE ELEMENTS

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SUPERVISORY AND EXAMINING COMMITTEE

Kevin Martin Knutson, candidate for the degree of Master of Applied Science in Electronic Systems Engineering **,** has presented a thesis titled, ***Low-Cost Grain Bin Moisture Sensor Using Multiple Capacitive Elements,*** in an oral examination held on June 9, 2014. The following committee members have found the thesis acceptable in form and content, and that the candidate demonstrated satisfactory knowledge of the subject material.

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ABSTRACT

The ability to know the condition of grain stored on the farm is very important. Grains grown in the prairie provinces of Canada are valuable commodities and the farm has become a primary storage location for more and more grain as farming operations have been getting larger and larger. With increased storage, the risk of spoilage is ever present. Both spoilage and the cost of drying grain reduce profit. These factors have created a need for better on farm management of stored grain, and therefore a need for a reasonable cost sensor to continuously monitor the moisture inside the bins. Historically, moderately expensive capacitance based instruments have been used to measure grain moisture samples to an accuracy of ±0.1% w.b. However, these moisture meters only work outside of the bin and therefore samples must be gathered every time a measurement is desired. Recently, some humidity and temperature based monitoring systems have been developed but they suffer from being plugged by dust.

Timely information about the temperature and moisture content can prevent a disaster. To solve this problem an inexpensive capacitive sensor to measure grain moisture, temperature, and the level of grain stored inside a bin on the farm, was designed, constructed, and tested with a limited number of wheat samples in a six inch by five foot plastic pipe. Grain with different moisture levels from 9.7% wet basis (w.b) to 16% w.b. was used. The sensor accuracy was

found to measure grain moisture content to ±0.5% w.b. for the majority of cases, and ±1.5% w.b. for all tested cases.

A number of improvements to the current sensor are important. For one, the geometry should be improved by increasing the size of the anode and cathode plates. In addition, the electronics should be placed to limit parasitic and stray capacitances. Finally, only the high end frequency of 7 MHz was used in this implementation. Lower frequencies in the 500 kHz to 1 MHz range will likely improve the sensitivity and accuracy. These improvements could improve accuracy to ±0.2% w.b.

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DEDICATION

I would like to dedicate this thesis to my parents, my father Carmen and my late mother Vicki, who have supported me throughout my studies.

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LIST OF ABBREVIATIONS AND SYMBOLS

AC	Alternating Current
A/D	Analog to Digital
bu.	Bushel
DC	Direct Current
ε_r	Relative Permittivity
ε_0	Permittivity of Free Space
F	Farad
GHz	Gigahertz
g	Grams
Hz	Hertz
kHz	Kilohertz
L	Litre
MHz	Megahertz
pF	Picofarad
PCB	Printed Circuit Board
R^2	Coefficient of Determination
t	Tonne
V	Volts
w.b.	Wet Basis

1. INTRODUCTION

Massive amounts of grain are being stored on prairie farms. Larger farms mean larger storage facilities, specifically steel bins. As the size of the bin increases the value of the product stored in that bin also increases. A larger bin increases the chances for grain spoilage and if a bin of grain is lost due to spoilage, the associated costs are much higher now than they have been in the past.

1.1. Farming in Saskatchewan

Saskatchewan is a leader in crop production and agriculture, both nationally and globally. Saskatchewan has 40% of Canada's farmland totalling more than 60 million acres and each year, approximately 33 million acres is used for crop production. In 2013, Saskatchewan produced:

- 99% of Canada's chickpeas,
- 96% of Canada's lentils,
- 87% of Canada's durum wheat,
- 82% of Canada's flaxseed,
- 76% of Canada's mustard,
- 64% of Canada's dry peas, and
- 50% of Canada's canola [1].

Saskatchewan is also a world leader in exports and in 2012 Saskatchewan was responsible for:

- 49% of the world's lentil exports,
- 37% of the world's pea exports,
- 24% of the world's flaxseed exports,
- 37% of the world's durum exports,
- 22% of the world's canola seed exports,
- 26% of the world's mustard exports, and
- 22% of the world's canola oil exports [1].

In 2012, Saskatchewan was also the leading Canadian exporter of 13 of the following agri-food products:

- Non-durum wheat - $2.03 billion,
- Canola Seed - $2.7 billion,
- Lentils - $673 million,
- Canola Oil - $1.7 million,
- Peas - $626 million,
- Durum - $1.2 billion,
- Canola Meal - $600 million,
- Flaxseed - $213 million,
- Oats - $234 million,
- Barley - $254 million,
- Canary Seed - $78 million,

- Mustard Seed - $61 million, and
- Chickpeas - $33 million [1].

The total value of exports in 2012 was $8.7 billion.

1.2. Grain Storage

When analyzing grain storage capacities, conversion between the two common measurements for grain in Canada is required. These measurements are bushels (bu.) and tonnes (t). Bushels are the original unit of measure and are still used by the majority of producers. The tonne, or metric ton, is also used and is the standard measurement used especially, once the quantity of grain increases. Tonnes are used at grain terminals, by railway companies, and at shipping ports.

A bushel is a measure of volume, whereas a tonne is a measure of mass (or weight). An Imperial bushel is defined as 36.369 L [2]. For use with grain the bushel has been redefined as a weight but this weight varies for different types of grain. This thesis examines only wheat and for wheat, a bushel is defined as 60 pounds [3]. Using the 60 pound bushel of wheat, one tonne is equal to 36.7440 bushels [4].

1.2.1. Grain Elevator History

The Encyclopedia of Saskatchewan [5], records that the first grain elevator on the prairies was built in 1881 at Gretna, Manitoba, and by 1930 there were close to 6000 primary elevators on the prairies. The average size of an elevator in

1930 was 30 000 bu. or about 800 t. In the early years, many elevators were required because farmers hauled their grain by horse and cart. As time passed the size of the elevators increased and the number of elevators decreased. In 1950, Saskatchewan had 3035 elevators with a total capacity of 283 million bu. (7.7 million t). By 1970, 2750 elevators with a capacity of 225 million bu. (6.1 million t) existed [5]. The Canadian Grain Commission [6] has a searchable list of elevators back to 1962. During that period, the year with the most capacity in Saskatchewan was 1970. In 1970, there were 2732 elevators with a capacity of 5.9 million t (217 million bu.). The average capacity per elevator was about 2200 t (80 000 bu.). The number of elevators declines to 161 in 2009 but increases slightly to 174 in 2013. The current primary elevator capacity in Saskatchewan is 3.4 million t (124 million bu.) and the average capacity per elevator is 19 300 t (711 000 bu.). This trend of fewer but larger elevators has been occurring since the 1930s. To summarize, Saskatchewan had the most elevator storage capacity in 1950 with 7.7 million t, and currently, the province has less than half of that capacity with 3.4 million t at 174 elevators.

Historically, farmers stored less grain on the farm because of the decrease in number and overall capacity of the elevator system, and the increased size and decreased number of farms. In the past, farmers would often take a significant amount of their grain to the elevator directly from the combine. Today, as farms have increased in size and production, larger amounts of grain are stored on the farm. The changes in economic conditions of grain and pulse crops stored on the farm have created a need for monitoring the condition of these commodities.

1.3. Grain Storage Problems

The source of grain spoilage is high moisture content. The effect of high moisture content is heating of the grain. “Stored grain is or can be at risk from damage that results from heating. The heating results from grain respiration, as well as respiration from microorganisms, insects, and mites during storage. The resulting heat from respiration can lead to the development of hot spots within the grain.” [7] Grain can be damaged or spoiled in a variety of ways. If the moisture content is too high, grain will heat and spoil. Also, insects will be more plentiful in grain that has higher moisture content. The most common insects that are a problem for grain storage include the granary weevil, meal moth, red flour beetle, confused flour beetle, rusty grain beetle, saw-toothed grain beetle, and mites [8].

Heating of grain can cause loss in ability to germinate, loss in weight, reduced quality, and in extreme cases burning. “Continuous production of heat may lead to temperatures high enough to kill microorganisms, thus leaving heating due to oxidation (burning without flame). At temperatures of 50°C (122 °F) oxidation increases temperature so rapidly that if left uncontrolled, spontaneous combustion could occur within a short period. While this is the extreme effect of heating, it can also result in loss of ability to germinate as well as poor grain quality.” [7]

1.4. Grain Moisture

There are three grades of moisture content for wheat: dry, tough, and damp. Wheat is considered dry at or below a moisture content of 14.6% w.b. Wheat between 14.6% w.b. and 17.0% w.b. is considered tough, and wheat over 17.0% w.b. is considered damp. Tough wheat needs to be dried to less than 14.6% w.b. for long-term storage. Damp wheat will deteriorate very quickly and can only be stored with extreme caution [8]. Under optimal conditions, wheat is harvested dry and moved to storage. However, the ability to dry grain has some advantages including less dependency on weather and the ability to straight cut instead of swathing to let the crop dry in the field which saves time and fuel. The downside to harvesting grain wet or damp is that it must be dried which increases costs.

1.4.1. Cooling Grain

Figure 1.1 shows the length of time that grain can be stored at a given moisture content and temperature. “Temperature measurement is not only used to detect active deterioration but also to indicate, along with moisture content and infestation information, potential for deterioration (or safe storage time). Each spoilage process has temperature ranges in which the rates of deterioration are rapid, slow, or prevented.” [9] As the temperature of the grain is lowered the amount of time for safe storage is increased. Also, as the moisture of the grain is lowered, the longer it can be stored safely. Reducing the temperature of tough or damp wheat will extend the amount of time that the grain can be stored safely.

Therefore, cooling high moisture grain is essential. Aeration has been used to maintain uniform temperatures and to delay or prevent the formation of high moisture areas and hot spots in a bin [8].

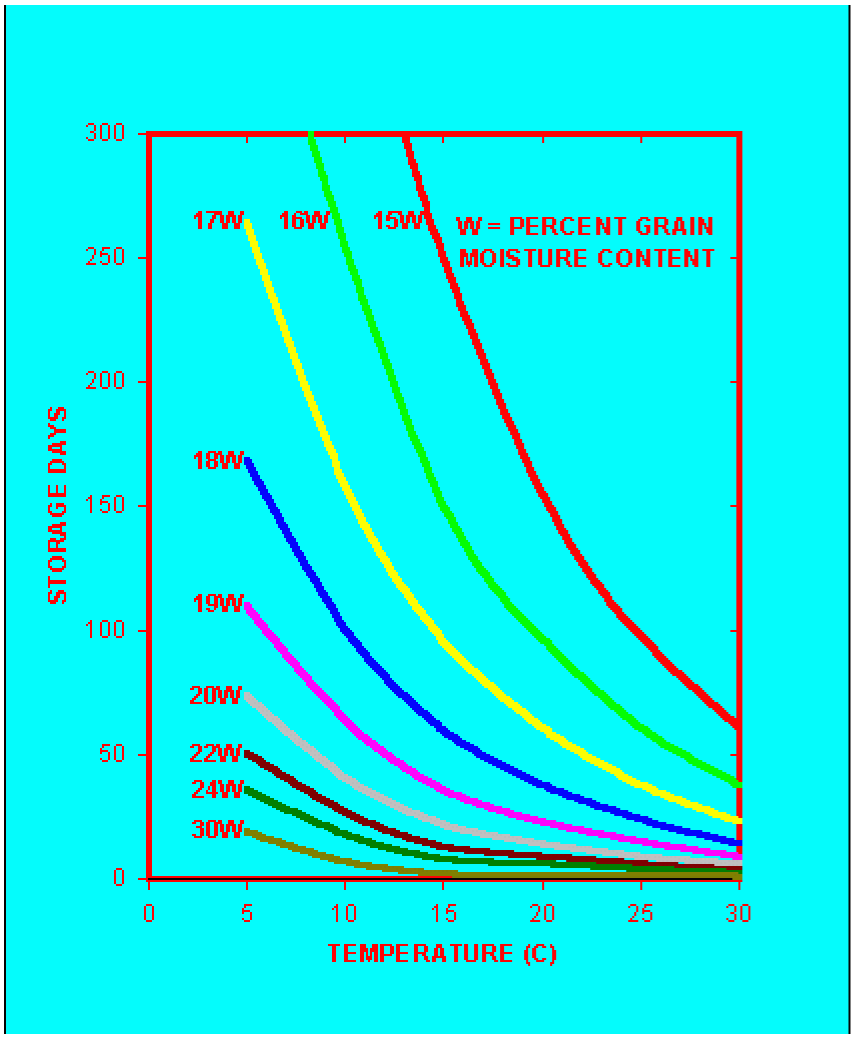

Figure 1.1: The effect of temperature (C) and grain moisture content (percent water, wet basis) on the safe storage time of cereals. [8] (original in colour)

1.4.2. Drying Grain

Moisture will move from grain to the surrounding air until the equilibrium moisture content is reached. The two factors that affect equilibrium moisture content of grain are relative humidity and temperature. As relative humidity decreases and temperature increases, the equilibrium moisture content of grain will decrease. To reduce the equilibrium moisture content of wheat warm dry air can be introduced. The length of time required for grain to dry to below 14.6% w.b. is determined by the airflow. Wheat will have its equilibrium moisture content drop below 14.6% w.b. when it is exposed to air temperatures above 12 °C and relative humidity levels less than 70% [8]. Two methods to dry wheat are natural air drying and heated air drying.

Natural air drying can be used to dry wet grain that has been harvested tough. Modern grain bins are often installed with the provision for fans. These fans are used to force air through the grain which allows it to dry. Air is forced in from the bottom and exhausted at the top. As the grain is being dried, a drying zone moves up through the bin [10]. The advantage over field drying is the protection from wet weather that is offered by the roof of the bin. The challenge of natural air drying is to dry the grain before spoilage takes place. Regular temperature and grain sampling is important to identify potential problems [8].

The advantages of natural-air grain drying include:

- an increase in the amount of combining time,
- an earlier start to harvest,
- more stubble fields are ready for winter wheat seeding,
- more can be accomplished by each combine, which reduces equipment costs,
- straight cut harvesting is more attractive, and
- more control over grain moisture content [8].

The disadvantages of natural-air grain drying include:

- increased grain handling and labour costs, and
- a dependency on air temperatures and relative humidity [8].

Heated air drying can be implemented to give additional control and drying capability. High relative humidity and cool temperatures will limit the drying of grain using natural air. The transfer of water from the grain to the air will be slow at temperatures below 10 °C because the air will not carry much water. For each 10 °C increase in air temperature the relative humidity will be reduced by half. If the outside temperature is 15 °C and the relative humidity is 80%, increasing the temperature of the air to 25 °C will reduce the relative humidity to 40%. A further increase of temperature to 35 °C will reduce the relative humidity to 20%. A small increase in air temperature can produce a large increase in effectiveness, especially when the outside relative humidity is high. Over drying will mean unnecessary drying costs and revenue losses due to lower grain weight [8]. Therefore, monitoring both the temperature and the moisture of the grain while it is being dried is valuable for tracking the progress of the drying zone and avoiding over drying.

1.5. Monitoring Grain Moisture

Currently, farmers have the ability to test the moisture in the combine as they are harvesting and they also take a sample from each truck load delivered to storage. Most farming operations either have a Labtronics 919 moisture meter or will take a sample to their local grain terminal and have their grain tested so they know the moisture content of the grain that they are going to sell directly or store on the farm. However, once the grain is put into the bin for storage there are a few options for monitoring, but many bins have no monitoring at all. Until just recently if a bin had any monitoring at all, it would be a temperature probe. Grain that increases in temperature is an indicator of a problem and may need to be dealt with. “Grain moisture content and temperature are the two most critical factors for maintaining grain quality during storage.” [9] Therefore, both the temperature and moisture of the grain should be monitored.

1.6. Monitoring Options

For many years farmers have used the temperature of the grain to indicate whether or not they have a storage problem. If the temperature of the grain is increasing, there is a problem. However, temperature is only part of the story and by the time the grain has heated up it might be too late. “Temperature monitoring cannot detect all of the mold and insect infestations even though temperature cables are located at the infestation locations.” [9] Therefore, being able to measure the moisture of the grain and track any changes is valuable for effective grain storage.

Two methods are available to monitor the moisture content of stored grain. The first method is to take a sample and measure the moisture with a Labtronics 919 moisture meter. The second is to install monitoring equipment into the grain bin to allow either periodic or continuous monitoring.

During the development of this grain moisture sensor OPI-integris Advance Grain Management has developed a commercial moisture sensor. OPI-integris has supplied monitoring equipment to producers for over 25 years. For much of that time temperature monitoring equipment has been manufactured for the market. The recently developed moisture cable is accurate to ±1.5% w.b. The OPI-integris moisture sensor uses relative humidity sensors to sense the relative humidity of the air around the grain and then calculates grain moisture content from that measurement [11]–[13].

1.6.1. Monitoring System Costs

A new Labtronics 919 moisture meter can be purchased for $1250. The OPI-integris moisture cables can be purchased as a 24 foot, six sensor model for

$790, or as a 40 foot, ten sensor model for $1250. The handheld device used to read the moisture cables can be purchased for $990. OPI-integris also has computer-based logging and control systems available. A computer-based monitoring system for most farms will be in the $10,000 to $15,000 range. This will vary depending on the number of bins that are monitored and whether or not fan and vent controls are included.

2. Background

2.1. Moisture Measurement

Two different methods used to express grain moisture content are wet basis and dry basis. “Grain moisture content is expressed as a percentage of moisture based on wet weight (wet basis) or dry matter (dry basis). Wet basis moisture content is generally used. Dry basis is used primarily in research.” [14] Equation 2.1 [14] is used to calculate grain moisture based on wet weight (wet basis) and Equation 2.2 [14] is used to calculate grain moisture based on dry matter (dry basis).

$$Mw\ (wet\ basis) = \frac{w-d}{w} * (100) \tag{2.1}$$

$$Md\ (dry\ basis) = \frac{w-d}{d} * (100) \tag{2.2}$$

where w is wet weight

d is dry weight

M is moisture content on a percent basis

Moisture content of grain can be determined using either a direct method, the oven method, or by an indirect method. Moisture meters measure electrical properties of the grain and are therefore indirect methods. Indirect methods are calibrated to the oven method. Most moisture content measurements are performed using an indirect method [14].

2.2. Capacitance

Capacitance is the ability to store charge in an electric field. The simplest geometry for a capacitor is a parallel plate capacitor as shown in Figure 2.1. The material between the plates is called the dielectric and different materials will each have a different relative permittivity or dielectric constant. On one side of the dielectric is the anode plate and on the other side is the cathode plate.

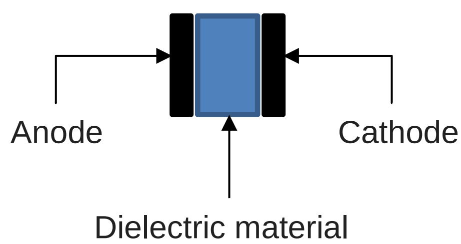

Figure 2.1: Parallel plate capacitor (original in colour)

Equation 2.3 is the equation for calculating the capacitance of a parallel plate capacitor in a vacuum. Equation 2.4 is the equation for a parallel plate capacitor for all other dielectric materials.

$$C = \frac{\varepsilon_0 A}{s} \tag{2.3}$$

$$C = \frac{\varepsilon_r \varepsilon_0 A}{s} \tag{2.4}$$

where C is the capacitance

ε_0 is the permittivity of free space, which is equal to $8.85\text{x}10^{-12}$ F/m

A is the area between the plates

s is separation between the plates

ε_r is the relative permittivity or dielectric constant of the material between the plates.

The relative permittivity or dielectric constant, ε_r, is a constant that changes depending on what dielectric material is between the plates. Materials with a higher relative permittivity have the ability to store more charge in the same geometric shape than a material with a lower relative permittivity. For example, water has a relative permittivity of 80 and air has a relative permittivity of 1. Therefore, in the same area, water will store 80 times the energy than would be stored if air was the dielectric material.

Capacitance sensing devices have been used extensively. The simplest capacitor is two metal plates separated by a non-conducting material, for example: a vacuum, air, ceramic, or plastic. The capacitor value can be intentionally varied by moving the two plates apart (a longer distance reduces capacitance) or by changing the dielectric material between the plates, or both.

Additionally, the capacitor can be varied by some environmental or physical condition. Therefore, the physical world can be controlled or detected using a capacitor together with the appropriate external devices. Typically, this is done by either measuring the capacitor value or measuring the effect of the change in capacitance in an electrical circuit.

One interesting application is a capacitance switch. This is a non-mechanical switch that is completely sealed and requires no moving parts. Two small metal plates placed near each other, have a very small capacitance, on the order of a few picofarads. Typically, there is air around this capacitor which has a relative permittivity of 1. Water, on the other hand, has a relative permittivity of 80. Consider what happens when a water-filled finger (the switch) is brought near the two metal plates. The dielectric value of the capacitor changes to a much higher value and an electronic circuit recognizes that the “switch” has been touched when the capacitor value increases by a large amount.

On the other hand, a microphone can use a capacitor that is mechanically moved (or vibrated) due to sound, and as a result, detects sound. Therefore, a microphone can be created from a capacitor. This type of microphone is called a condenser microphone or capacitor microphone. The capacitor is made with a solid back plate and a front plate that is very light and will move when sound waves hit it, therefore, acting as a diaphragm, as shown in Figure 2.2. When the plates are closer together a charge current occurs due to the increase in capacitance and when the plates separate the capacitance decreases and the capacitor discharges [15].

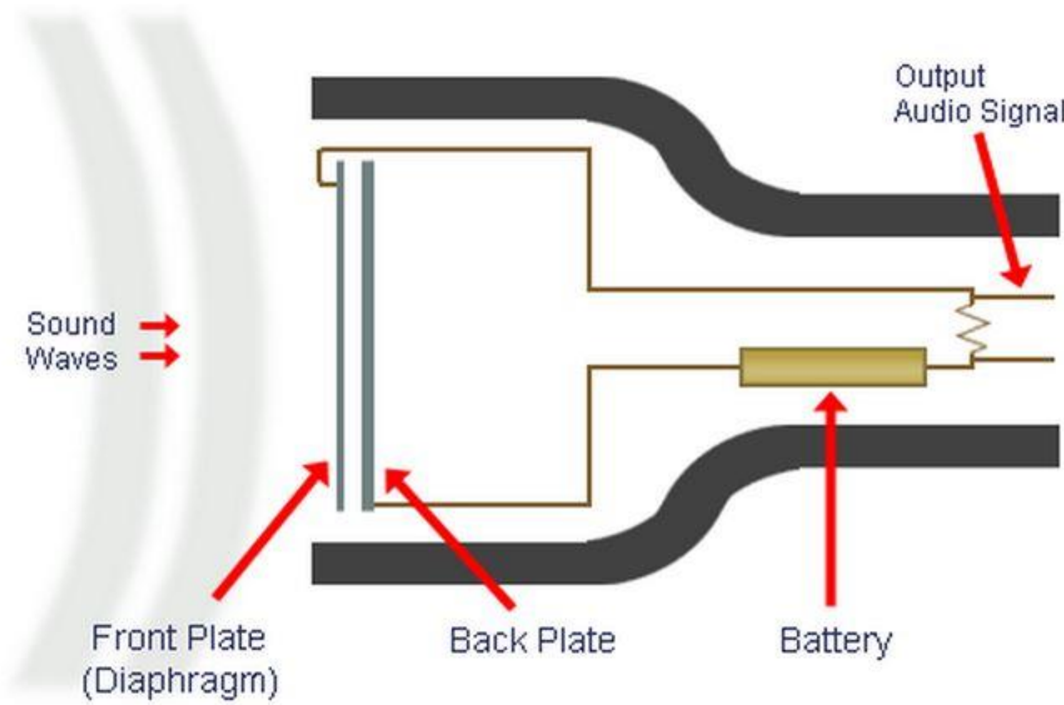

Figure 2.2: Cross-section of a typical condenser microphone [15]

In the past, our research group has used the capacitance effect to measure the height of oil/water interfaces in a tank used to collect oil from oil wells, measure oil field pipe line flow rate using dual capacitors and correlation, and several other types of systems [16], [17].

2.3. Measuring Moisture in the Grain Bin

As mentioned in Chapter 1, and as shown in Figure 1.1 the ability to measure grain moisture content is very important. Dry grain has a relative permittivity between 2 and 3 [18] while wet grain contains more water which significantly increases the dielectric value. The goal of this project was to measure the grain moisture content directly in the grain bin, to eliminate the need to take a sample and test it externally. Capacitance effects can be very difficult to measure because external factors can greatly affect the system. Similar to how a finger can activate a switch, any external items near the measuring system can affect it. This is due to the fringing effect of the electric field that will extend for several inches. Anything entering the electric field that alters it, will affect the measurements. Using metal housing or other conductive shielding will contain the electric field and thereby eliminate these external effects. Grain bins are large and typically metal so they are fairly isolated from external effects. Therefore, in principle, if two metal plates are placed inside the grain bin the capacitance of the surrounding substance, whether it is grain, air, or a combination of both, can be measured. If the plates are kept at a fixed distance, the dielectric value can be calculated, and from that the moisture content can be determined. In addition, if an array of metal plates is positioned in the bin, the moisture content as a function of position in the bin can be measured. Placing temperature sensors in the bin adds additional information which can be used to determine what is happening to the grain. Finally, the transition of grain and air can be determined because of the difference of dielectric value.

In practice, the system is difficult to construct because the plates must be a reasonable size since the capacitance value being measured is quite small. Additionally, running wires out of the bin would be susceptible to huge parasitic capacitance effects and other external changes, and is therefore not possible. The capacitance must be measured at the plates inside the grain to reduce these effects.

The benefit of using capacitance and metal plates that are about one inch by six inches long is that they can be created using inexpensive printed circuit boards with the measuring electronics on the same board. The metal strips are placed side by side causing the electric field to surround the board. The fringing effect takes in roughly a two inch diameter cylinder of the grain, making the measurements much more representative of the grain moisture content and less susceptible to being influenced by a local wet or dry spot. This measurement should be correct over a large temperature range as well, since the dielectric changes are due to the volume of water. Temperature and frequency will affect the measurements but these effects can be calibrated out to some extent and should not vary dramatically as they would with other types of sensing technologies. For example, humidity sensors measure the moisture in the air and are potentially affected by freezing temperatures and other local effects in the grain. A final consideration is to build a system that is sensitive to a small change of grain moisture. Can the sensor detect a change of 1%? For example, can the sensor detect a change from 12% to 13%?

2.3.1. Theoretical Example

To determine if it is a reasonable expectation to detect a 1% change in moisture content, consider the following thought experiment. Assume that grain bins consist of tiny little squares of water, air, or dry grain; where water has a dielectric constant of 80, grain 3, and air 1. Using Equation 2.4, consider two metal strips that are 1 cm by 11.3 cm and are separated by 1 cm. In this example, $A = 0.00113\ m^2$, $d = 0.01$ m and the capacitance for air would be 1 pF. When water is the dielectric material the capacitance is 80 pF, and when grain is the dielectric material the capacitance is 3 pF. These capacitance values are small and difficult to measure accurately at 1 MHz, but it is possible. However, the original question was to find the change in capacitance for a 1% volume change in water content of grain. While not strictly accurate, assume that stored grain is about 30% air, 12% water, and 58% grain for the first case. In the second case adding water of 1% will displace some of the air leaving 29% air, 13% water and 58% grain. After mixing up the container the result will be random squares of water, air, and grain.

The experiment is equivalent to having a series of capacitors where the equivalent capacitance can be calculated by Equation 2.5. However, Equation 2.5 is used for multiple capacitors in series. In this specific example the amount of each capacitor needs to be weighted because the air, water, and grain are all parts of the whole. Therefore, to calculate the values of the two capacitors Equation 2.6 is used. The above percentage contents of stored grain can also be represented as an equivalent material thickness. The first case has dielectric material of air 0.30 cm thick, water 0.12 cm thick, and grain 0.58 cm thick. The second case has air 0.29 cm thick, water 0.13 cm thick, and grain 0.58 cm thick. Using Equation 2.6 the results are 2.021 pF for the first case, and 2.062 pF for the second case. This amounts to a 2% increase in capacitance for a 1% increase in water volume which is a very small, but a measureable amount of change. To detect this amount of change a very sensitive circuit is required and the instrument must also be calibrated well.

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \cdots \qquad (2.5)$$

where C is the total capacitance

C_1, C_2, and C_3 are the individual capacitors in series

$$\frac{1}{C} = \frac{p_1}{C_1} + \frac{p_2}{C_2} + \frac{p_3}{C_3} + \cdots \qquad (2.6)$$

where p_1, p_2, and p_3 are the individual percentages of each substance

$p_1 + p_2 + p_3 = 1$

2.4. Frequency Range and Grain Moisture

To measure the moisture content of grain by a capacitive method an input frequency must be chosen. An ideal frequency for measuring the moisture content of grain is a frequency that has a linear relationship between relative permittivity (dielectric constant) and moisture content. Nelson [19] performed tests from 250 Hz to 12.1 GHz and the results of these tests are shown below in Figure 2.3 through Figure 2.11.

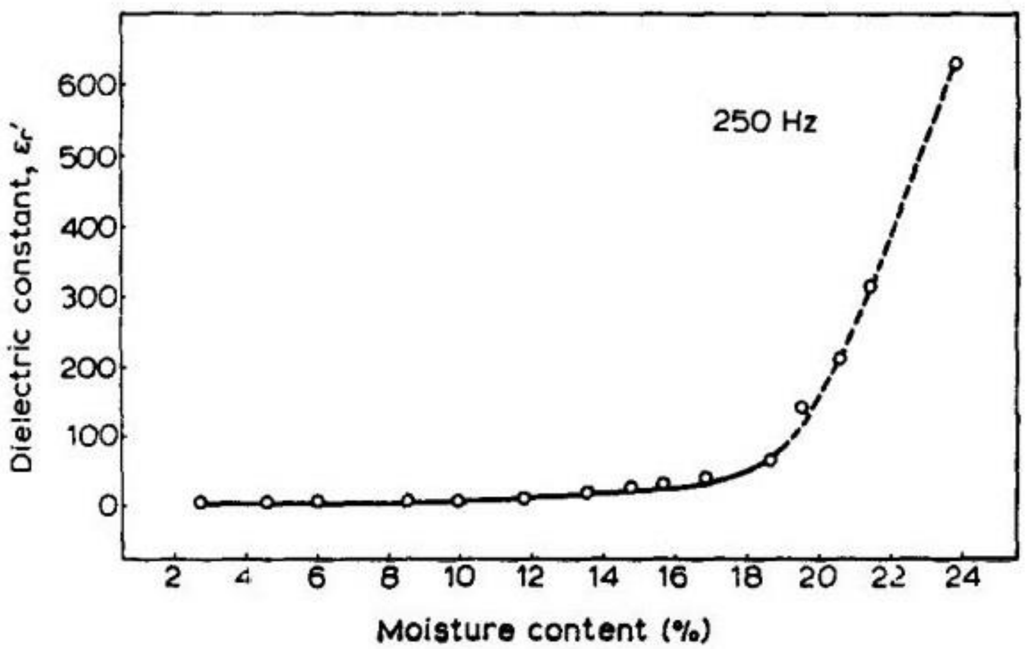

Figure 2.3: Moisture dependence of the dielectric constant of hard red winter wheat at 24 °C and 250 Hz [19]

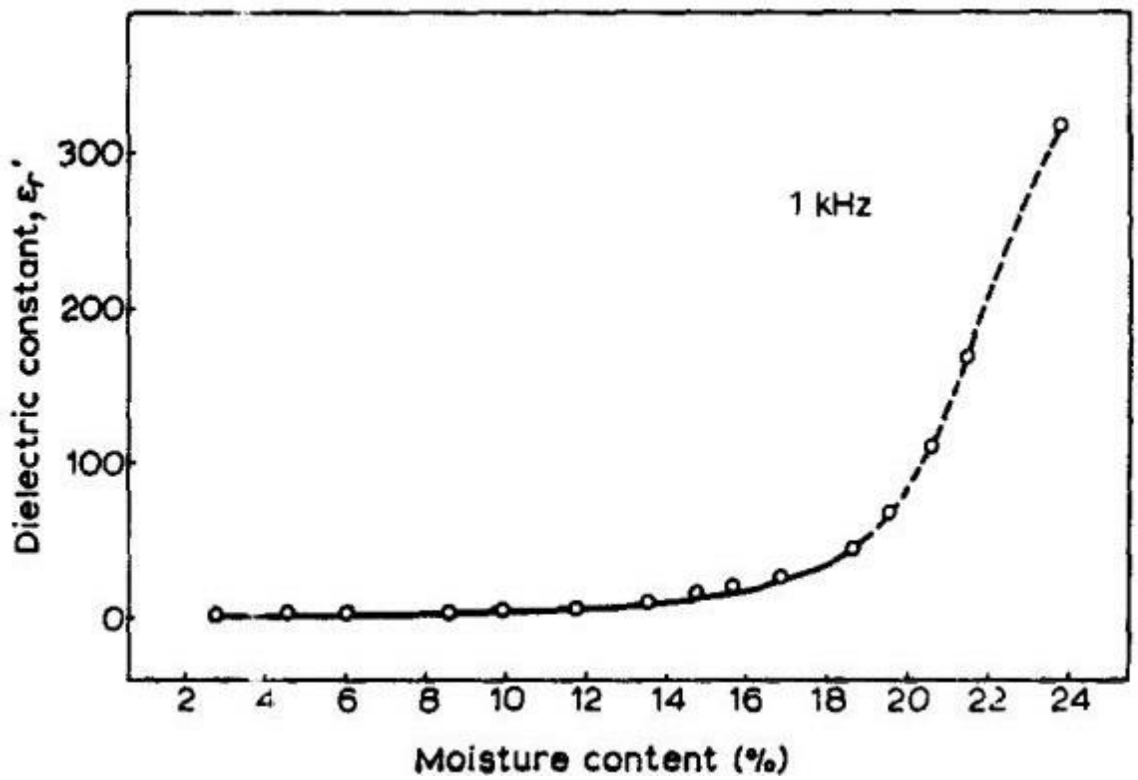

Figure 2.4: Moisture dependence of the dielectric constant of hard red winter wheat at 24 °C and 1 kHz [19]

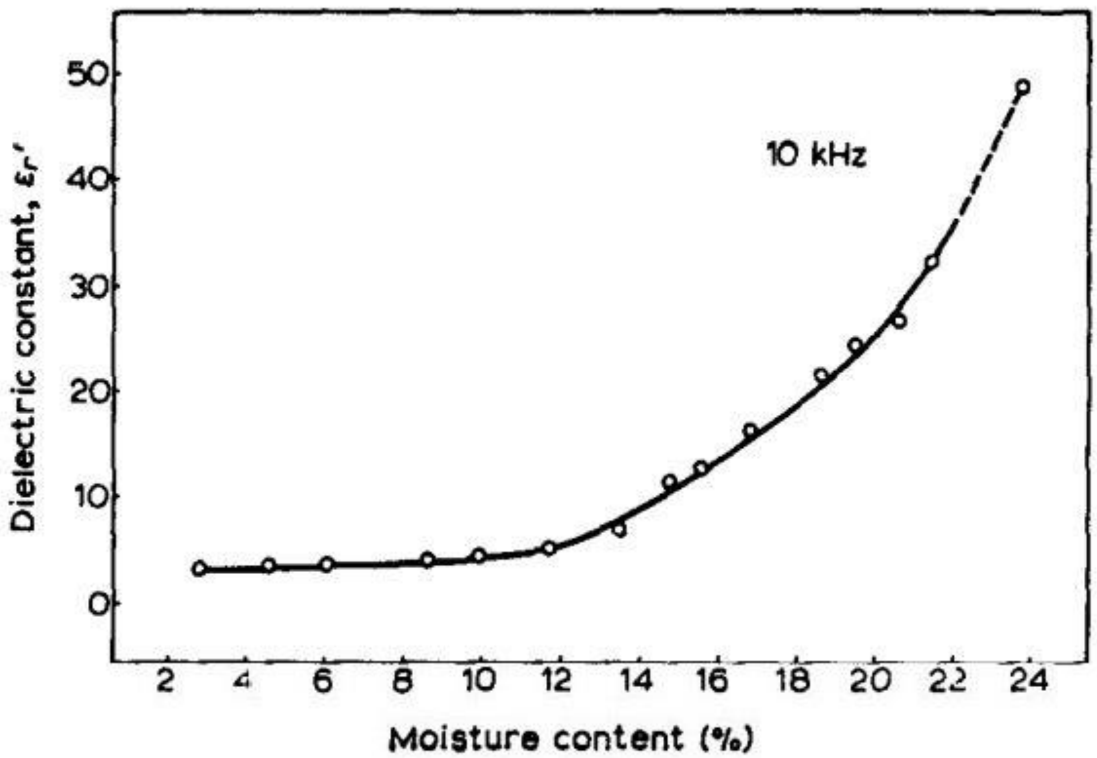

Figure 2.5: Moisture dependence of the dielectric constant of hard red winter wheat at 24 °C and 10 kHz [19]

The test results for 250 Hz (Figure 2.3), 1 kHz (Figure 2.4), and 10 kHz (Figure 2.5) have a linear flat response for lower moisture contents and then rise sharply. Differentiating between moisture contents in the flat region will be very difficult and the resolution of the measurement will be limited.

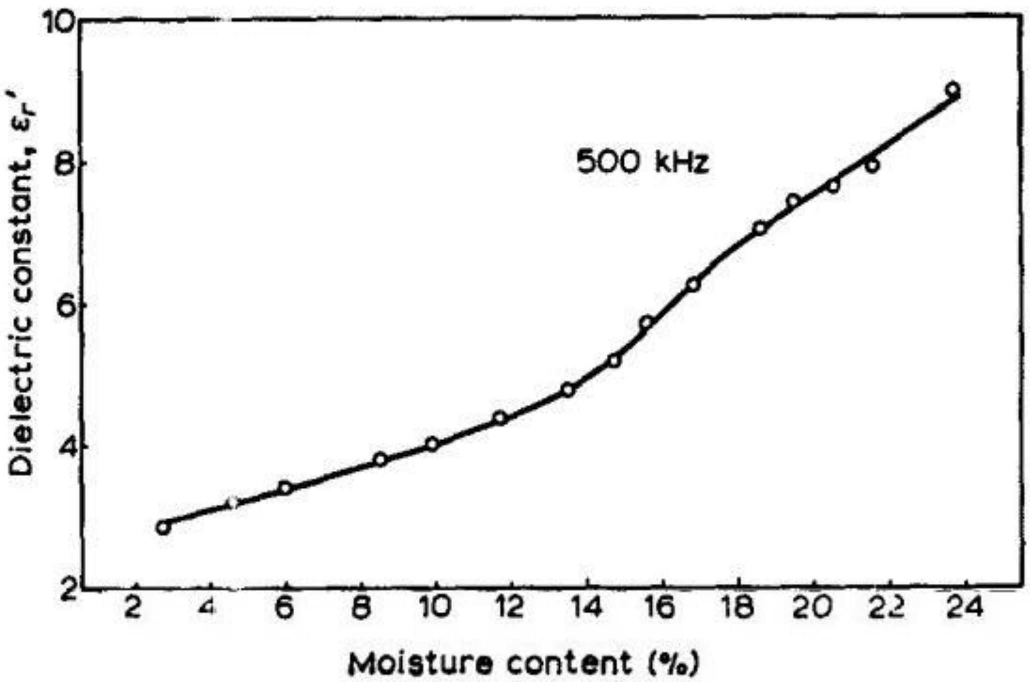

Figure 2.6: Moisture dependence of the dielectric constant of hard red winter wheat at 24 °C and 500 kHz [19]

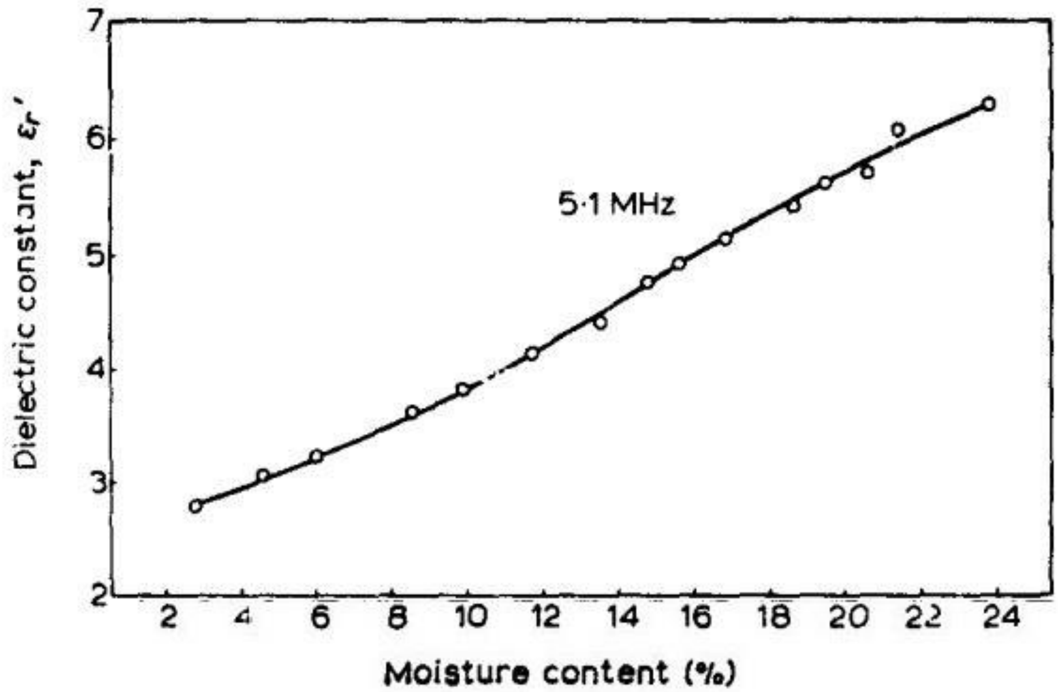

Figure 2.7: Moisture dependence of the dielectric constant of hard red winter wheat at 24 °C and 5.1 MHz [19]

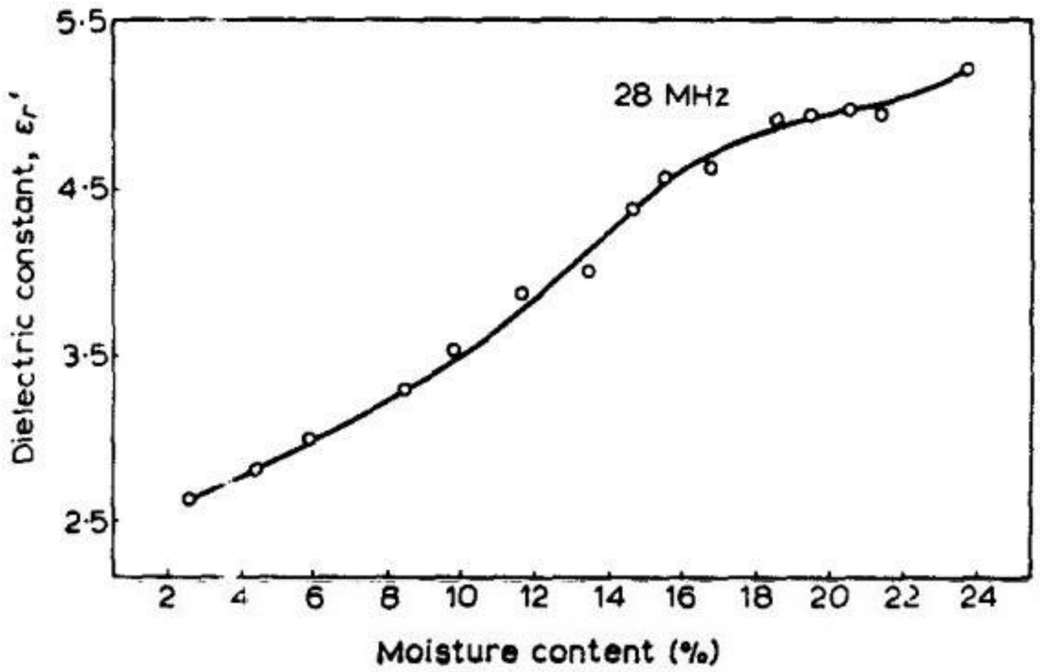

Figure 2.8: Moisture dependence of the dielectric constant of hard red winter wheat at 24 °C and 28 MHz [19]

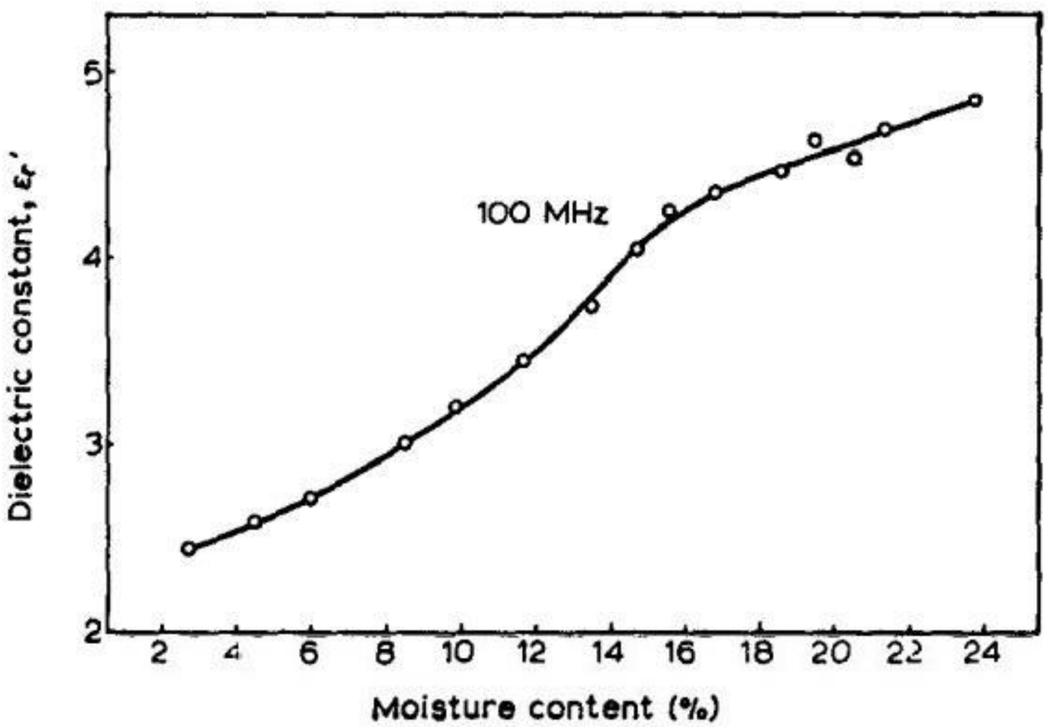

Figure 2.9: Moisture dependence of the dielectric constant of hard red winter wheat at 24 °C and 100 MHz [19]

The results for 500 kHz (Figure 2.6), 5.1 MHz (Figure 2.7), 28 MHz (Figure 2.8), and 100 MHz (Figure 2.9) show a linear slope. The best result from this range is 5.1 MHz, although any of these frequencies should work.

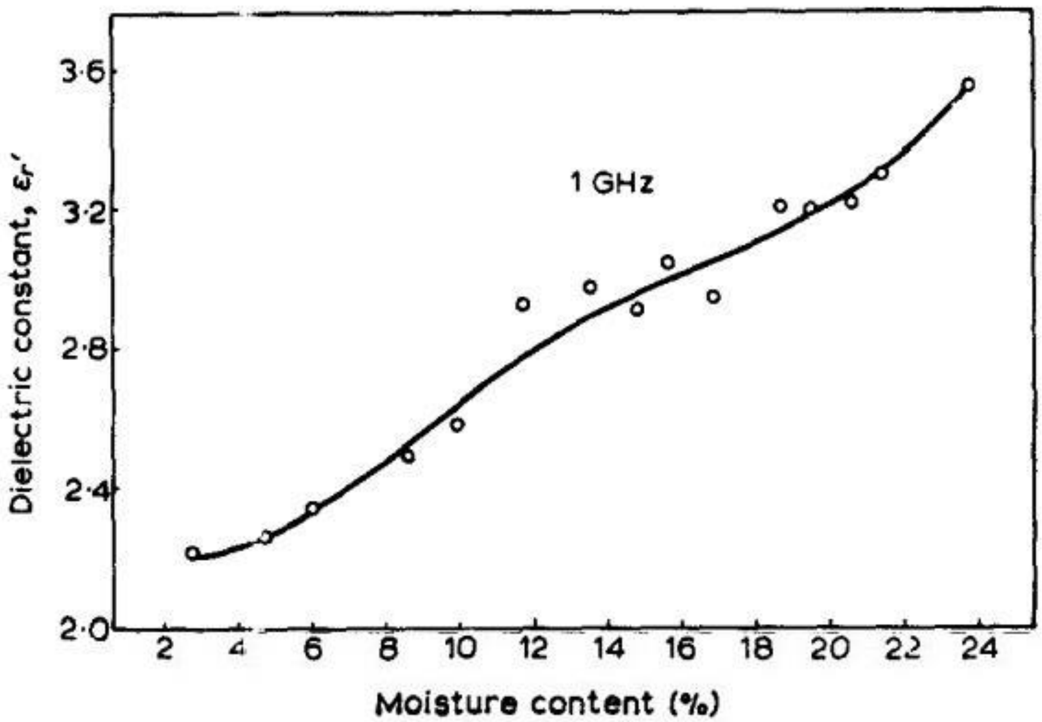

Figure 2.10: Moisture dependence of the dielectric constant of hard red winter wheat at 24 °C and 1 GHz [19]

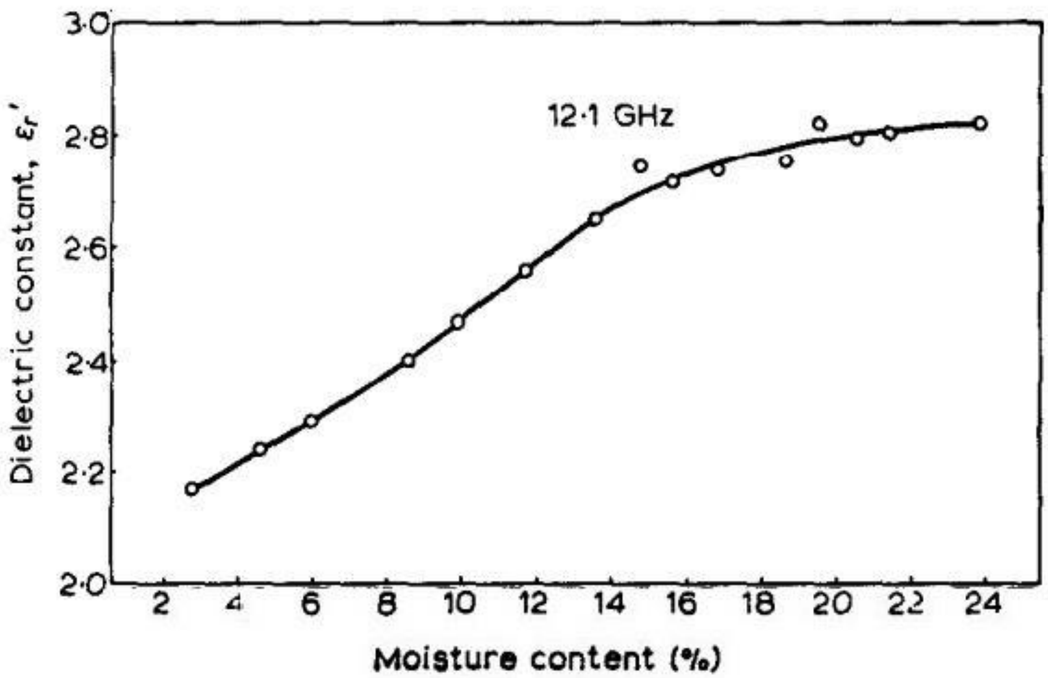

Figure 2.11: Moisture dependence of the dielectric constant of hard red winter wheat at 24 °C and 12.1 GHz [19]

Once the frequency has been increased to 1 GHz (Figure 2.10) and 12.1 GHz (Figure 2.11) the dielectric constant does not change significantly. Therefore, differentiating different moisture contents would be difficult. Another consideration is manufacturing cost. As the frequency increases so does the cost of transmitting and terminating the signal to ensure that reflections are not occurring. Above a certain frequency coax cables should be used and all connections will need to be impedance matched. One solution is to generate the sine wave on each board. However, the duplication of integrated circuits would increase the cost. Considering the results from Nelson, the cost to construct, and previous projects, the range of frequencies that would be expected to work are between 500 kHz and 10 MHz.

2.5. Previous Work

A previous instrument was developed, tested, and a thesis "Low-Cost Multi-Element Capacitive Monitor for Measuring Levels of Substances in Storage Tanks at Oil Fields" [16] was written about the instrument. While the oil level project was being developed, it was discovered that the same instrument might be able to measure the moisture content of grain. The oil tank capacitive monitor was modified for use with grain. The dielectric variation for different grain moistures are much less than the changes in dielectric for measuring water and oil. Therefore, this project needed to improve the capacitance measurement sensitivity of the sensor that was developed for determining the level of oil and water in an oilfield tank.

3. DESIGN

The measurement objective for the grain bin moisture sensor is to be able to measure moisture content inside of a grain bin to ±0.5% w.b. In addition, the design must be low cost and low power. To achieve the design objective, lower frequency electronics were used because they use less power and are less expensive. Another reason to use lower frequencies was to avoid the need for coax cabling.

The instrument developed and discussed in this thesis could be part of a larger grain monitoring system. The larger system would include a wireless network so that temperature and moisture could be reported from each bin to a central user interface. In a further advanced system the fans for each bin could be automatically controlled by the central system or set up to be controlled by the user. These other components are outside of the scope of this project.

3.1. Circuit

The sensor uses a resistor-capacitor voltage divider circuit to measure the capacitance of the substance that the sensor is surrounded by. The resistor, R, is fixed and C_{eq} represents the capacitor created by the substance to be measured between the anode plates and the cathode. The resistor-capacitor voltage divider circuit is shown in Figure 3.1.

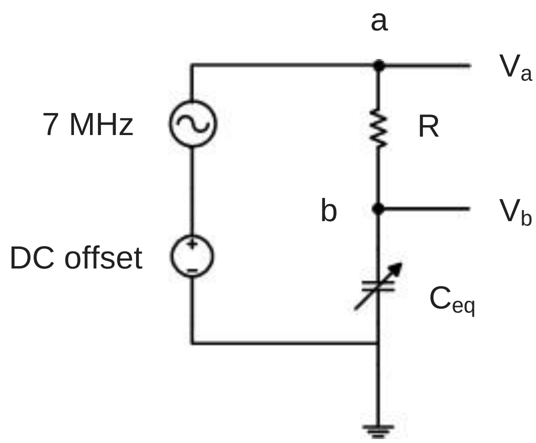

Figure 3.1: Resistor-capacitor voltage divider

There is an inverse relationship between the measured voltage and the capacitance value. As the capacitance (C_{eq}) increases the measured voltage will decrease. Since the geometry is fixed, an increase in capacitance can only occur by an increase in the relative permittivity of the substance under observation. The measurement circuit is a peak detector circuit.

Five boards connected together make up the grain moisture instrument. The bottom four boards are all the same, as shown in Figure 3.2. There are two capacitor anode plates labeled C1 and C2. Each anode plate is connected to a peak detector circuit. Each channel consists of one anode plate and peak detector circuit. In total, the five foot instrument has ten channels labelled channel 0 through channel 9. The microprocessor receives the voltage level from the A/D converters and temperature data from an on board temperature sensor.

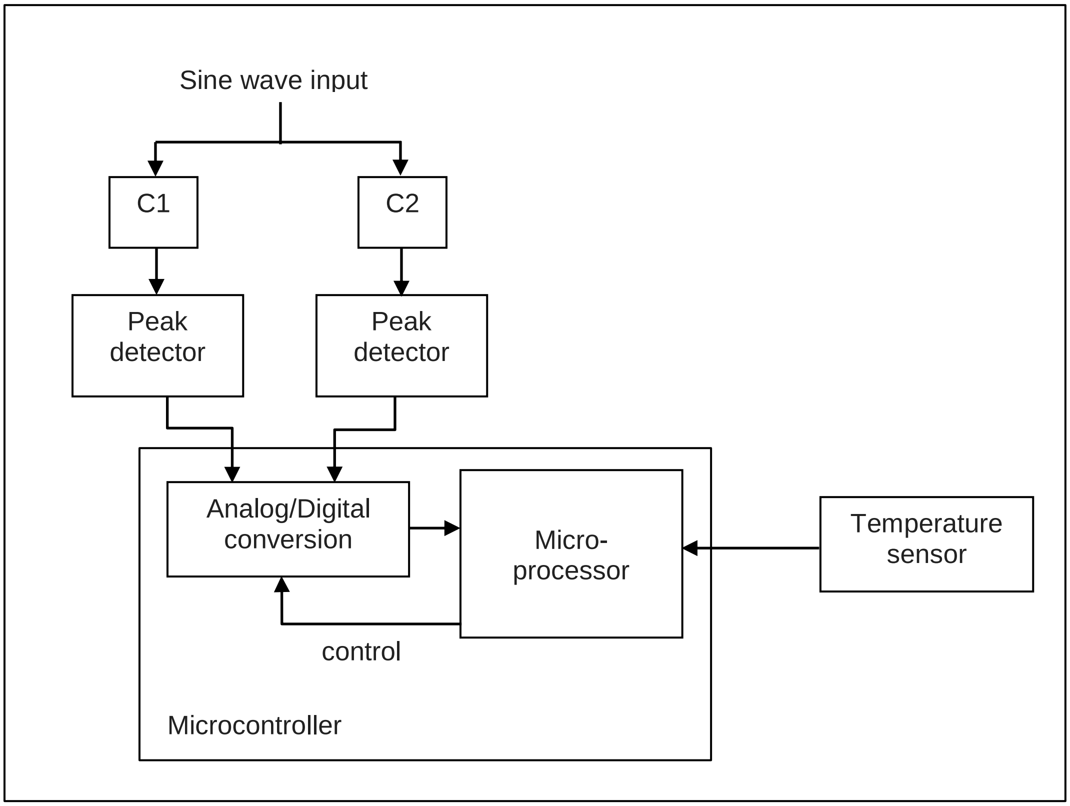

Figure 3.2: Block diagram of circuit for one board

Different substances (air, canola oil, grain, and water) will affect the sine wave by loading the circuit. The voltage measured across the substance being measured must be compared to the current sine wave. The reference sine wave is measured at the top sensor, board 0 channel 0; therefore, the top board is different from the bottom boards as shown in Figure 3.3. The top anode plate has been disconnected from the circuit, so the sine wave input can be measured as a reference.

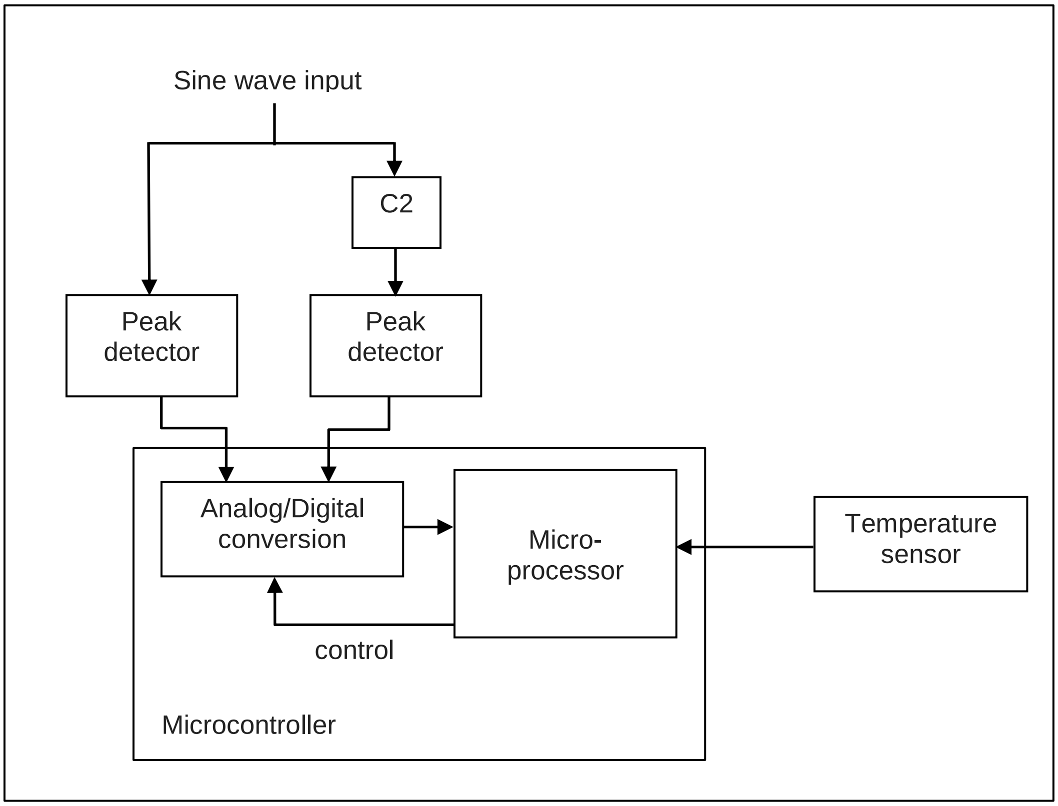

Figure 3.3: Block diagram of circuit for the top board

3.2. Instrument Changes for Grain Moisture Measurement

This project builds on the work “Low-Cost Multi-Element Capacitive Monitor For Measuring Levels of Substances in Storage Tanks at Oil Fields” [16]. Through testing the sensor was found to be improved by making a number of changes to the geometry of the anode plates and the layout of the board. One of the main goals of this project was to increase the sensitivity and accuracy of the previous instrument. Some of the changes suggested in [16] have been implemented in this project.

3.2.1. Increase Sensitivity of Sensors

The variation in dielectric values for grain at different moisture contents was expected to be small and the goal of the project was to measure the moisture of grain to ±0.5% w.b. Therefore, it was decided that the sensors needed to be made at least twice as sensitive as they were for measuring the differences in dielectric for air, oil, and water for the oilfield tank project. Changes to the board include increasing the size of the circuit board from 1 inch wide and 12 inches long to 1.5 inches wide and 12 inches long. The anode plates in the previous version were 0.25” x 2” copper strips, for an area of 0.5 inches squared. The new anode plates are 0.25” x 5.75” copper strips, for an area of 1.4375 inches squared. By area the anode plates have been increased by a factor of 2.875. In addition to making the plates larger, the separation between the anode plates has been reduced from 1 inch to 0.25 inches because this area had little to no sensitivity.

Figure 3.4 shows the top side of one printed circuit board (PCB) and Figure 3.5 shows the bottom side of one PCB. The anode plates are on both sides of the PCB and are connected together to constitute a single plate. The cathode plate is the stainless steel angle iron and runs the length of the five foot sensor. The cathode plate is at the top of Figure 3.4 and at the bottom of Figure 3.5.

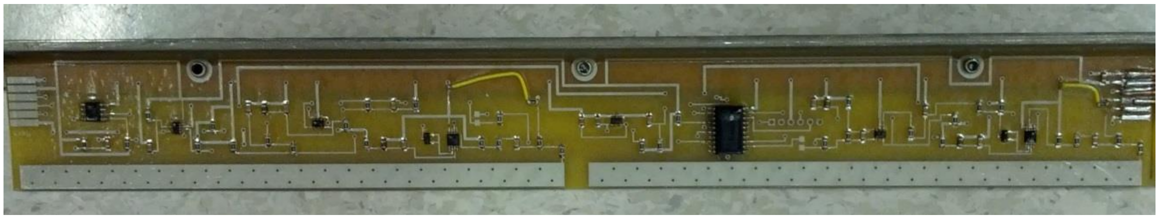

Figure 3.4: Circuit board top side (original in colour)

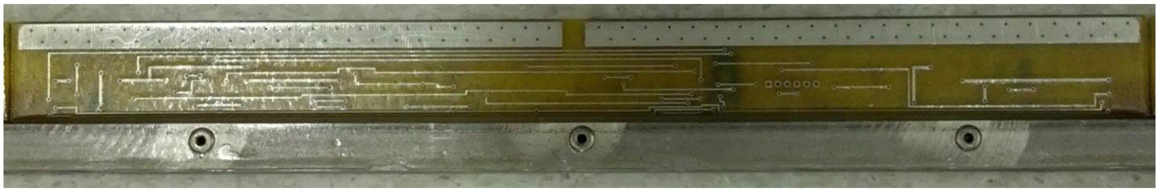

Figure 3.5: Circuit board bottom side (original in colour)

3.2.2. Sine Wave Termination

Another recommendation to improve the sensor was to change the way the sine wave was terminated [16]. The previous termination used analog switches to allow only the sensor that was currently being polled by the microprocessor to be connected to the sine wave. It was found that this could be a source of inconsistent readings. In this version of the board, all of the anode plates are attached to the sine wave and terminated at all times. The switches that were used in the past have been eliminated, which also reduced the cost.

3.2.3. Layout of the Board

In the previous version of the PCB, there was a correlation between the readings of each channel and the position of the anode plate on the PCB. Since this is a very sensitive measurement of a very small capacitance, in the order of picofarads, parasitic and stray capacitances can influence, and, in some cases, completely dominate the capacitance being measured. To minimize the effects of parasitic and stray capacitances special care was taken with the layout of the new PCB, to ensure, as much as possible, that the components directly connected to the anode plates were the same and the traces used were of minimal length for each channel. The complete five foot moisture sensor is shown in Figure 3.6.

Figure 3.6: Five foot moisture sensor (original in colour)

3.3. Cost

In addition to these changes, and because the anode plates were made larger, there was another opportunity to decrease the cost of the overall instrument. One of the most expensive components required is the microcontroller. Each microcontroller can be used to measure four sensors (anode plates). In the first version of the instrument each one foot board had four sensors. With the increase in size of the anode plates each board now has two sensors. Therefore, only half of the boards are required to be populated with a microcontroller and other components. The price for the components on a board with the microcontroller is $16. On the boards without a microcontroller the cost of components is $8.

One of the most important considerations for the moisture sensor is the cost to produce. The five foot prototype unit included $190 in parts and about $450 in labour to construct, at $20 per hour. For large scale production, it is estimated that the parts and assembly would cost about $200 for each five foot instrument.

4. CALIBRATION OF INSTRUMENT

Similar to the previous instrument [16]; air, water, and canola oil were used to calibrate. Air has a relative permittivity of 1, water has a relative permittivity of 80, and canola oil has a relative permittivity between 3 and 4. In addition, mineral oil, which has a relative permittivity of 2.2 [20], was used to verify that the calibration was correct. Mineral oil was not used to calibrate the instrument; it was only used as a reference. By testing with mineral oil it was discovered that the canola oil used had a relative permittivity of 3. Previously, a value of 4 was used for canola oil.

Since the instrument has geometries similar to the previous instrument [16] the same modeling equation was used. Equation 4.1 is the dielectric modeling equation for each channel.

$$dielectric_j = \frac{1}{\frac{1}{k_1 * \sqrt{\left|\left(norm.AD_j\right)^2 - k_2\right|}} - \frac{1}{k_3}} \tag{4.1}$$

where $dielectric_j$ is the dielectric value measured at channel j

$norm.AD_j$ is the normalized values at channel j

j is the current channel that is being measured

k_1, k_2, and k_3 are constants

For each test of a substance, data must be recorded twice. As shown in Figure 3.1 the 7 MHz AC sine wave includes a DC offset to ensure that the sine wave does not include a negative voltage. Therefore, the first run is with the sine wave at 1.5 V peak to peak with a 1 V offset. For the second run of the same substance the sine wave generator is set to 0 V peak to peak with a 1 V offset. The values from the second run are the offset values. Using Equation 4.2, the normalization equation, the DC offset is removed.

$$norm.AD_j = \frac{ave.SinPk - offset_0}{ave.AD_j - offset_j} \tag{4.2}$$

where $norm.AD_j$ is the normalized values at channel j

ave.SinPk is the average of the peak of the offset sine wave input

$ave.AD_j$ is the average A/D value for the j^{th} channel

$offset_0$ is the offset at channel 0

$offset_j$ is the offset at channel j

Once the data has been normalized an iterative process is used to find the constants k_1, k_2, and k_3. As an example, the normalized values from channel 4 ($norm.AD_4$) are 1.155 in air, 1.574 in canola oil, 12.431 in water. The three simultaneous equations that need to be solved to find the constants are: Equation 4.3, the calibration equation for air; Equation 4.4, the calibration equation for canola oil; and Equation 4.5, the calibration equation for water.

$$1 = \frac{1}{\frac{1}{k_1 * \sqrt{|(1.155)^2 - k_2|}} - \frac{1}{k_3}} \tag{4.3}$$

$$3 = \frac{1}{\frac{1}{k_1 * \sqrt{|(1.574)^2 - k_2|}} - \frac{1}{k_3}} \tag{4.4}$$

$$80 = \frac{1}{\frac{1}{k_1 * \sqrt{|(12.431)^2 - k_2|}} - \frac{1}{k_3}} \tag{4.5}$$

To find the best fit, a fitness function, Equation 4.6, was used for the iteration. Canola oil was given priority as the sensitivity was increased by a factor of 6 because the relative permittivity of canola oil is close to the relative permittivity of grain.

$$Best\ fit = \frac{|air - 1| + 2 * |canola - 3| + \frac{|water - 80|}{80}}{3} \tag{4.6}$$

where air, canola, and water are the calculated values from Equation 4.1.

For channel 4 the constants were found to be 1.6 for k_1, 1.3339 for k_2, and 28.1 for k_3. Using these k values the dielectric value for mineral oil for channel 4 was calculated to be 2.3. The average measured value for the dielectric of mineral oil across all nine channels was 2.26.

5. TEST METHODS

5.1. Test Setup

A small five foot grain bin was constructed using a pipe with a diameter of six inches to test the instrument with grain. A six foot computer networking rack on wheels was used to support the bin and allow it to be easily moved around, see Figure 5.1. To ensure that the instrument is centered in the bin wooden dowels were used as shown in Figure 5.2. The bin was equipped with a valve for ease of removing the grain.

The test setup for grain is the same as the procedure for calibration. For each test of grain, data must be recorded twice. As shown in Figure 3.1, the 7 MHz AC sine wave includes a DC offset to ensure that the sine wave does not include a negative voltage. Therefore, the first run is with the sine wave at 1.5 V peak to peak with a 1 V offset. For the second run of the same grain the sine wave generator is set to 0 V peak to peak with a 1 V offset. The values from the second run are the offset values. The normalized values, calculated using Equation 4.2, remove the DC offset.

Figure 5.1: Test grain bin (original in colour)

Figure 5.2: Test grain bin showing wooden dowels and moisture sensor (original in colour)

All of the grain used for testing was moisture tested at a grain terminal using a Labtronics 919 moisture meter. These moisture values are taken to be the known moisture values and were compared to the values produced by the moisture sensor. The terminals visited included Richardson Pioneer at White City, Richardson Pioneer at Balgonie, Viterra at Balgonie, and Cargill at Congress. The 919 meter is the standard meter accepted by the Canadian Grain Commission and is accurate to 0.1% w.b., as reported in this 2006 article by the Western Producer, “The Canadian Grain Commission allows 0.2 percent in their regulations. The 919 meters, even the 55-year-old units with tubes, give a reading that is accurate to 0.1 percent. The basic technology we use in our 919 today is the same technology still in use by the grain commission since the early 1950s.” [21]

Nyborg relates, “The Labtronics 919 grain moisture meter determines moisture content using the capacitance principle. This principle is based on the change in the dielectric properties of grain with changes in moisture content.” [22]

Even though a Labtronics 919 is accurate to 0.1% w.b. there are a few factors that can cause errors in measurement. The 919 uses reference charts to determine the moisture content of grain. The 919 meter requires that the sample weigh exactly 250 g and a precise temperature of the sample is also required.

Throughout the many tests of grain it was found that different 919 meters could provide different moisture readings on the same sample on the same day. The typical variation was ±0.3% w.b. or less, another sample had a variation of ±0.5% w.b. and the worst sample had a variation of ±0.5% w.b., ±0.7% w.b., and ±1.0% w.b. As can be expected, the tests in the lab for these particular samples were the most challenging to get accurate results.

Temperature can have an effect on the moisture of grain. To limit this variation the lab tests were performed in a temperature controlled environment. The range of temperatures recorded by the moisture sensor was from 20°C to 22°C. Using the 919 charts for a reference, a 2°C temperature change can mean a difference of 0.2% w.b. moisture content. [23]

5.2. Grain Testing Procedure

One of the important considerations when testing grain moisture is how tightly the grain is packed. For this reason the Labtronics 919 drops a premeasured amount of grain from a known height allowing the meter to get a consistent, even distribution. The lab tests on the grain moisture sensor did not have the same level of control as the Labtronics 919 meter. However, the moisture sensor is designed to be installed in a grain bin where control over the distribution of the grain would not be possible. In a grain bin the grain is loaded from the top with a grain auger, so in practice the grain bin moisture sensor will not be able to control how tightly the grain is packed.

In the lab, a grain auger was not available. Instead, the grain was loaded with a pail and a ladder. The test grain bin had a capacity of approximately 30 L of grain. A bucket is a 5 gallon (20 L) pail. Each bucket was moisture tested at one of the elevators, using a Labtronics 919 moisture meter, and then paired with another bucket of grain that had the same, or at least a similar, moisture content. Since a bucket was too heavy to carry up the ladder safely, a 10 L pail was used. Therefore, to fully immerse all 10 sensors, 3 pails or 1.5 buckets of grain were required. The grain was poured into a large funnel which loaded the test grain bin with a consistent and similar flow of grain for each test. To ensure that the flow of grain was consistent the entire pail was dumped into the funnel at once. Therefore, even though the compaction of the grain was not specifically controlled, it was consistent for all tests.

In total 20 different grain tests were performed. All of the tests are summarized in Appendix A. “Test Name” is the label for the test. This will be used on the graphs in chapter 6 and Table 6.1. “Bucket Labels” indicates which bucket or buckets were combined for the test. “919 Moisture” is the reference moisture as measured by the elevator using a Labtronics 919 moisture meter. In the case that the two buckets did not have the same value, the average moisture between the two buckets is used. “Description” includes any details which describes the test. In total, the lab acquired 18 buckets of grain from three different farms at three different times. Each bucket was labelled with a letter from A to T. Bucket K was acquired from an organic farm in the fall of 2008, buckets O, P, Q, and R were acquired in the fall of 2013, and all other buckets were acquired in the spring of 2010 but were harvested in the fall of 2009. The grain from each farm was Hard Red Spring Wheat.

5.2.1. Initial Moisture Test With No Water Added (9.7% w.b. - 12.6% w.b.)

The first run of 10 tests was labelled A to J and had a moisture range of 9.7% w.b. to 12.6% w.b. This was not a significant enough range so the next step was to add water to a couple of the buckets of grain.

5.2.2. Increased Moisture by Adding Water (9.7% w.b. - 14.8% w.b.)

Water was added to each bucket individually as a percentage of the weight of the grain in the buckets. The water was added and allowed to sit overnight. When the grain was tested at the elevator and in the lab, it was not apparent that any water had been added; each bucket of grain was uniform. Buckets C & M, which were used for test C) 11.7%, had 1% water added and were then tested as M) 12.5 - 12.7% with an average moisture of 12.6% w.b. At the same time buckets G & N, which were used for test G) 11.9%, had 2% water added and were then tested as O) 13.3 - 13.4%.

To further increase the range of moisture tested, a second round of adding water to the grain commenced. Buckets C & M, which were used for test M) 12.5 - 12.7%, had 1% water added and were then tested as N) 12.9 - 13.4% with an average moisture of 13.1% w.b. At the same time, buckets G & N, which were used for test O) 13.3 - 13.4%, had 2% water added and were then tested as P) 14.6 - 14.8%.

5.2.3. Increased Moisture Range By Collecting New Grain Samples (9.7% w.b. - 16.0% w.b.)

To further increase the range of moisture being tested, four buckets of new grain were collected. One set, buckets O and P, were moisture tested between 15.3% w.b. and 16.0% w.b., for an average of 15.6% w.b., and another set, buckets Q and R, tested from 14.0% w.b. to 14.3% w.b. and then a month later tested at 14.5% w.b. for all samples. With this grain, the range of moisture was from 9.7% w.b. to 16.0% w.b.

6. RESULTS AND ANALYSIS

6.1. Grain Dielectric Results

The data collected from the 20 different tests was entered into Equation 4.1 and Equation 4.2 using the k values found by calibrating the instrument with air, canola oil, and water. This provided dielectric values for the grain which are shown in Figure 6.1. Dry grain has a relative permittivity between 2 and 3 [18]. The range of dielectric values calculated was 2.8 to 3.6, which is within the expected range of values. The two points that are below 2.8 are channels that are partially in air. As expected, it was observed that higher moisture content corresponded with a higher dielectric value. However, it was also observed that the dielectric value varied from channel to channel. Some channels, for example channel 7, tended to measure a lower dielectric value and other channels, for example channel 8, measured a higher dielectric value. Two theories were tested to see if they caused this phenomenon.

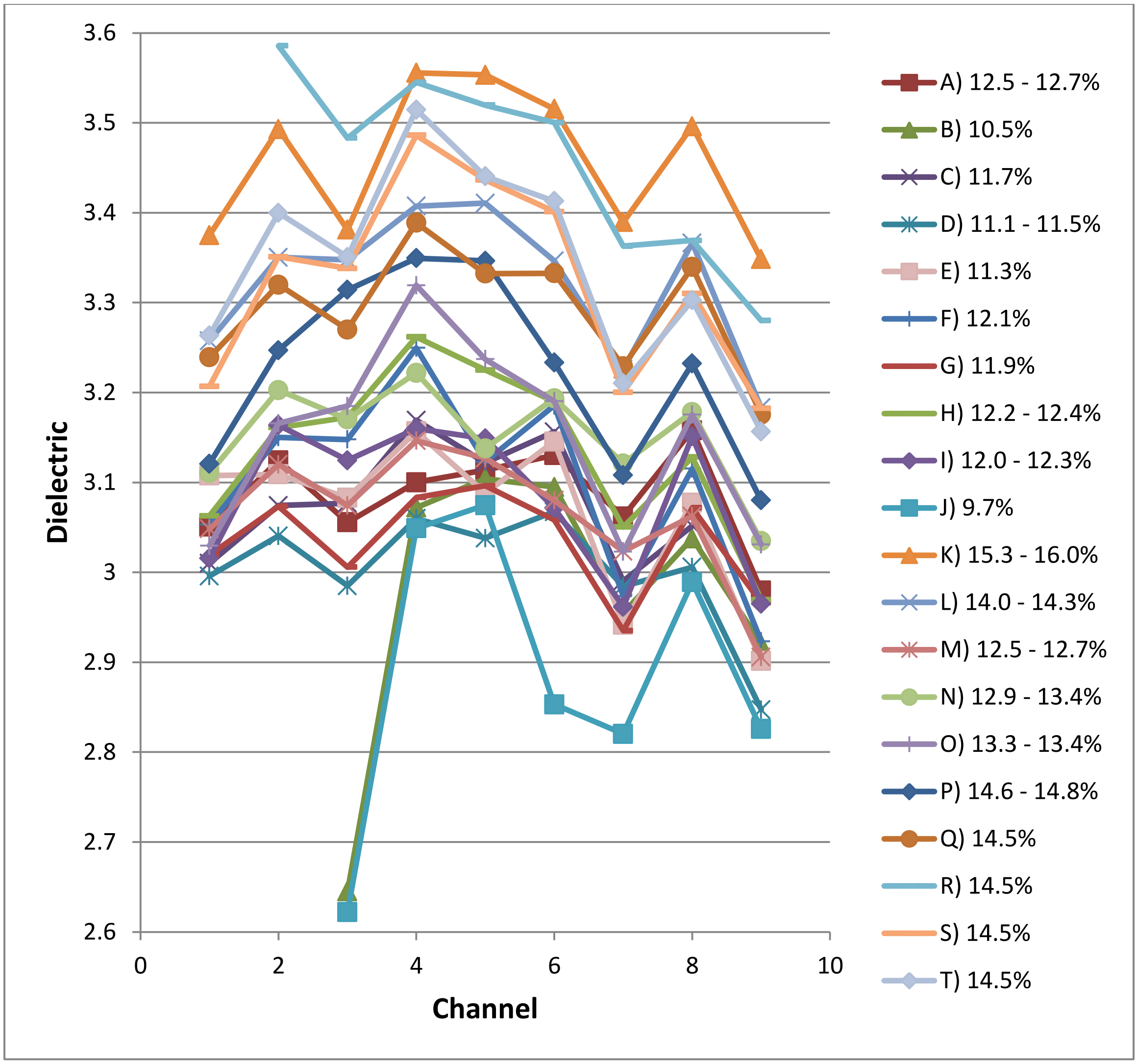

Figure 6.1: Dielectric values for grain tests (original in colour)

The first theory was that the grain was not mixed very well and even though samples were tested at the elevator there was a difference in moisture content within most of the tests. The second theory was that the wooden dowels, as shown in Figure 5.2, were displacing grain and affecting the measurements. To test these theories a couple of extra tests were run. Buckets Q and R were selected for the testing. First a larger container was used to mix all of the grain from buckets Q and R together. After the grain was mixed it was loaded into the test grain bin using the 10 L pail. As mentioned in section 5.2 it takes three pails to fill the test grain bin. A sample of grain was taken from each of the three pails of grain used to fill the test grain bin. Additionally a fourth sample was taken from the grain that was leftover and did not fit in the test grain bin. All four samples were tested at the Cargill Grain Terminal at Congress, and they all tested at 14.5% w.b. All extra tests on buckets Q and R, mixed together, are shown in Figure 6.2.

For reference the test L) 14.0 - 14.3% has also been included in Figure 6.2. This was a test using buckets Q and R but the grain was not mixed together. Bucket Q is on the bottom and bucket R is used to fill up the top. The reason the moisture content is listed as a range is because the samples were tested at two different grain terminals and bucket Q tested 14.0% w.b. and 14.2% w.b., bucket R tested 14.2% w.b. and 14.3% w.b. This is a great example of how the same grain can test differently with two different Labtronics 919 moisture meters. The test at Cargill occurred about a month after the tests that were used for L) 14.0 - 14.3% w.b. and the same grain tested 14.5% w.b. even though it was sealed in a bucket. For more details on each of these tests refer to Appendix A.

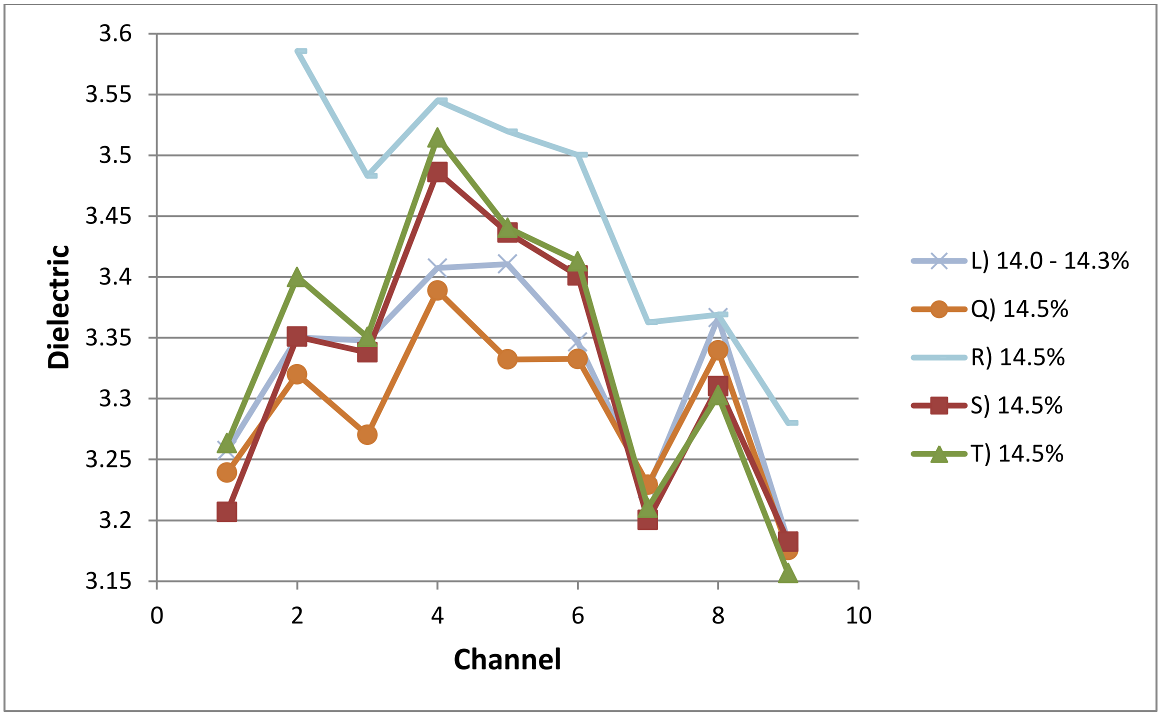

Figure 6.2: Buckets Q & R dielectric results (original in colour)

The first test was Q) 14.5% and as can be seen from the graph above the measured dielectric was not flat. Therefore, the theory that the previous tests contained different moisture contents throughout the test grain bin was disproven.

The second theory that the wooden dowels were displacing the grain and affecting the measurement required another test. Without dumping the grain from test Q) 14.5%, to ensure that the five foot sensor would stay centered in the six inch tube, the sensor was lifted 10 inches and the test R) 14.5% was started. By lifting the sensor the wooden dowels would line up with different channels, so if they were causing a problem then channels that read high should likely read low and channels that read low should read higher. However, the data indicates that the wooden dowels were not causing an issue.

To be absolutely sure that the wooden dowels were not causing a problem with the measurement two additional tests were run. After test R) 14.5% the grain was dumped so the sensor could be placed back in the test grain bin. The grain was then loaded back into the test bin and test S) 14.5% was begun. This was a test with the wooden dowels in place. Once the data was collected for test S) 14.5% the wooden dowels were removed from the test grain bin, and duct tape was placed over the holes. Since the test grain bin was full the sensor was not able to move from its position and it remained centered. Test T) 14.5% was run without the wooden dowels. The results, as shown in Figure 6.2, for test S) 14.5% and T) 14.5% were very similar; six of the nine channels were virtually identical. Therefore, the wooden dowels were not causing the issue of different moisture readings from channel to channel. It was concluded that this must be a systematic error.

6.2. Relationship Between Measured Dielectric and Moisture Content

The ability to measure the dielectric of grain is very interesting, but the goal of this project is to measure grain moisture. Therefore, a relationship between the measured dielectric and the moisture content is required. To find this relationship, the moisture measured at the grain terminal was plotted against the average dielectric. The nine channels on the sensor were averaged to determine the average dielectric value for the 16 corresponding test runs. Four of the tests were not used to find this relationship because an issue was identified with them that led to inconsistent results. Tests B) 10.5% and J) 9.7% were excluded because the test grain bin was not full since these tests were a single bucket of grain. For these two tests the top three and a half sensors were not surrounded by grain and were measuring air. The third test excluded from the dielectric to moisture relationship was R) 14.5%. This was a test where the sensor was lifted 10 inches out of the grain and therefore channel 0 was surrounded by air and channel 1 was partially surrounded by air. Finally, test P) 14.6 - 14.8% was not used because the dielectric value measured did not fit well. This was the second attempt at adding 2% water to the grain and it did not produce a result that fit well. A full description of all tests can be found in Appendix A.

The relationship between moisture content and dielectric was unknown. Therefore, both linear (first order) and quadratic (second order) relationships were explored. Using Excel the data was plotted and regression analysis was used to determine the best relationship based on the coefficient of determination (R^2). The linear relationship had an R^2 of 0.9309 as shown in Figure 6.3. The quadratic relationship had an R^2 of 0.9347 as shown by Figure 6.4. Therefore, either the first order or second order method could be used. The first order best fit equation was found by the graph shown in Figure 6.3 and is shown in Equation 6.1. The second order best fit equation was found by the graph shown in Figure 6.4 and is shown below as Equation 6.2. Both of these equations were used to convert dielectric (x) to moisture (y).

$$y = 9.3946x - 16.761 \tag{6.1}$$

$$y = -5.3509x^2 + 43.816x - 72.013 \tag{6.2}$$

where y is moisture content

x is the measured dielectric

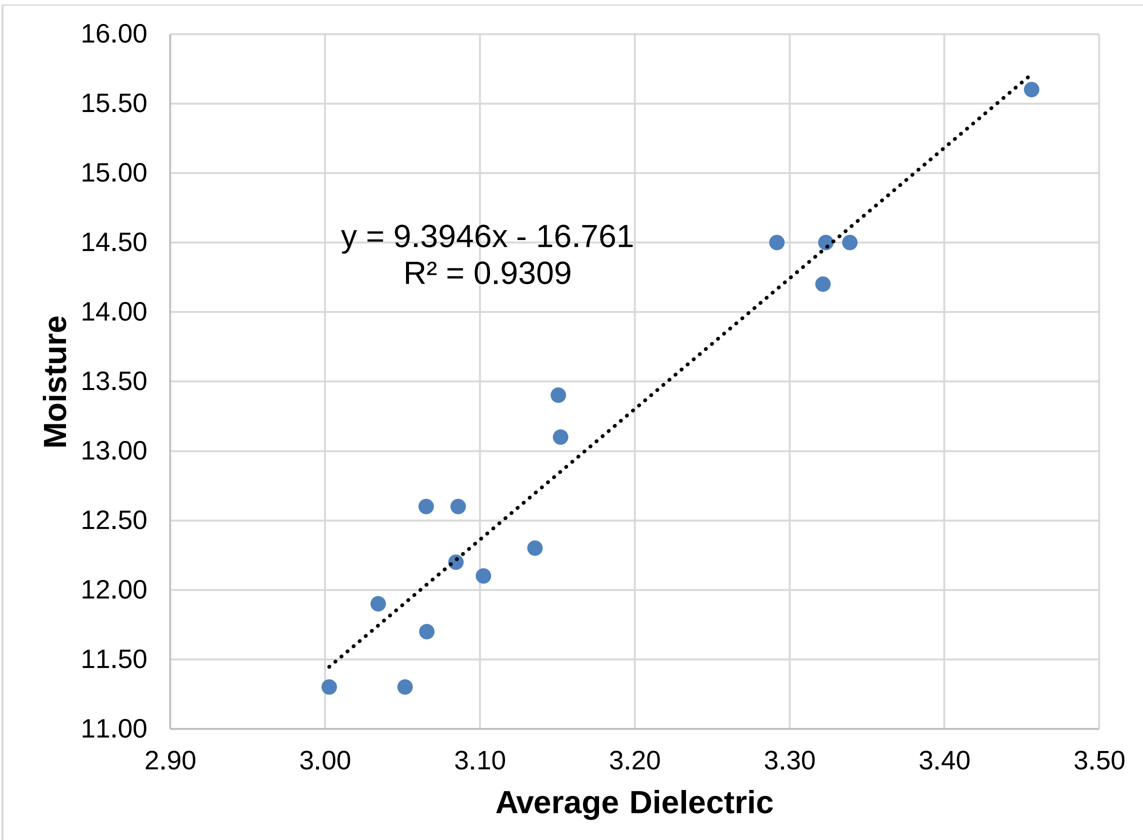

Figure 6.3: Linear best fit equation of moisture and average dielectric

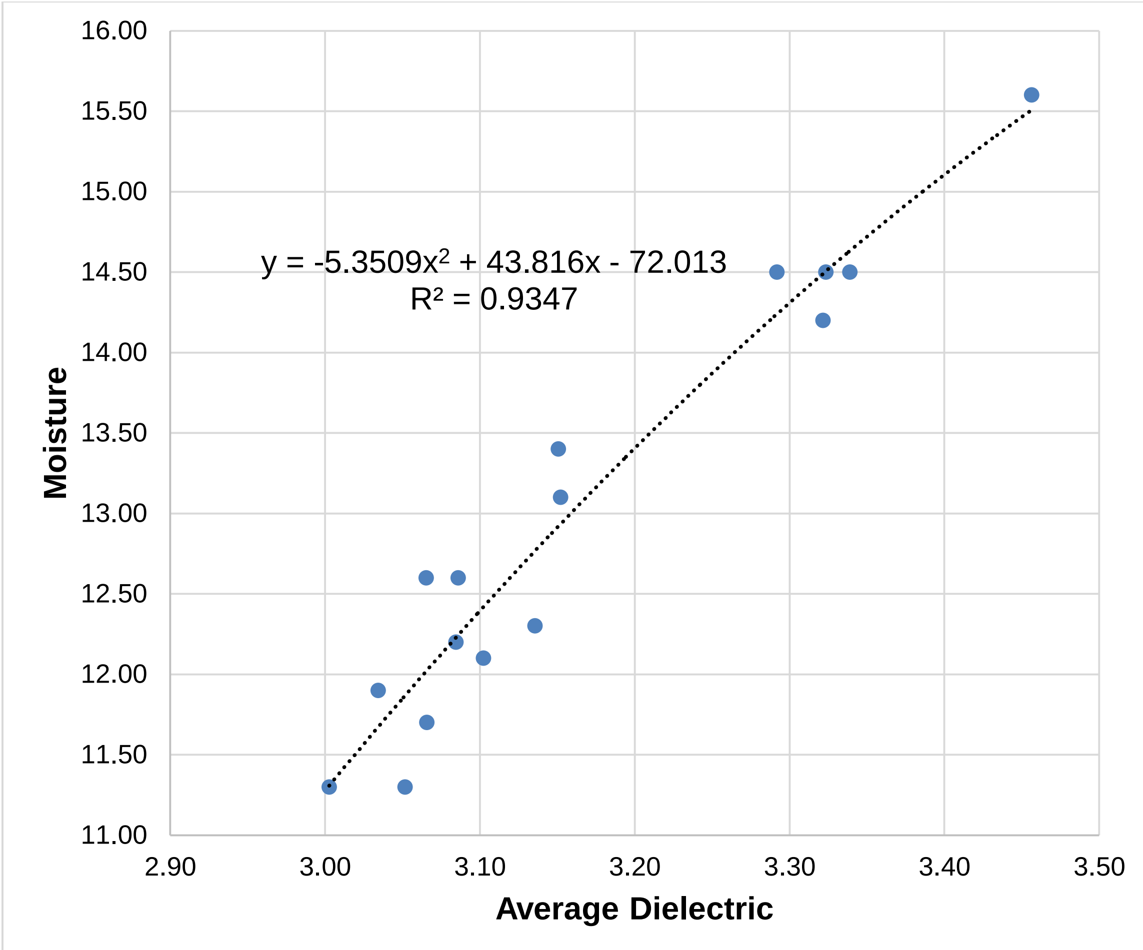

Figure 6.4: Quadratic best fit equation of moisture and average dielectric

Using the first order best fit equation, the moisture content of the grain for each test was calculated and is shown in Figure 6.5. That graph is rather busy so a few of the better results are shown in Figure 6.6.

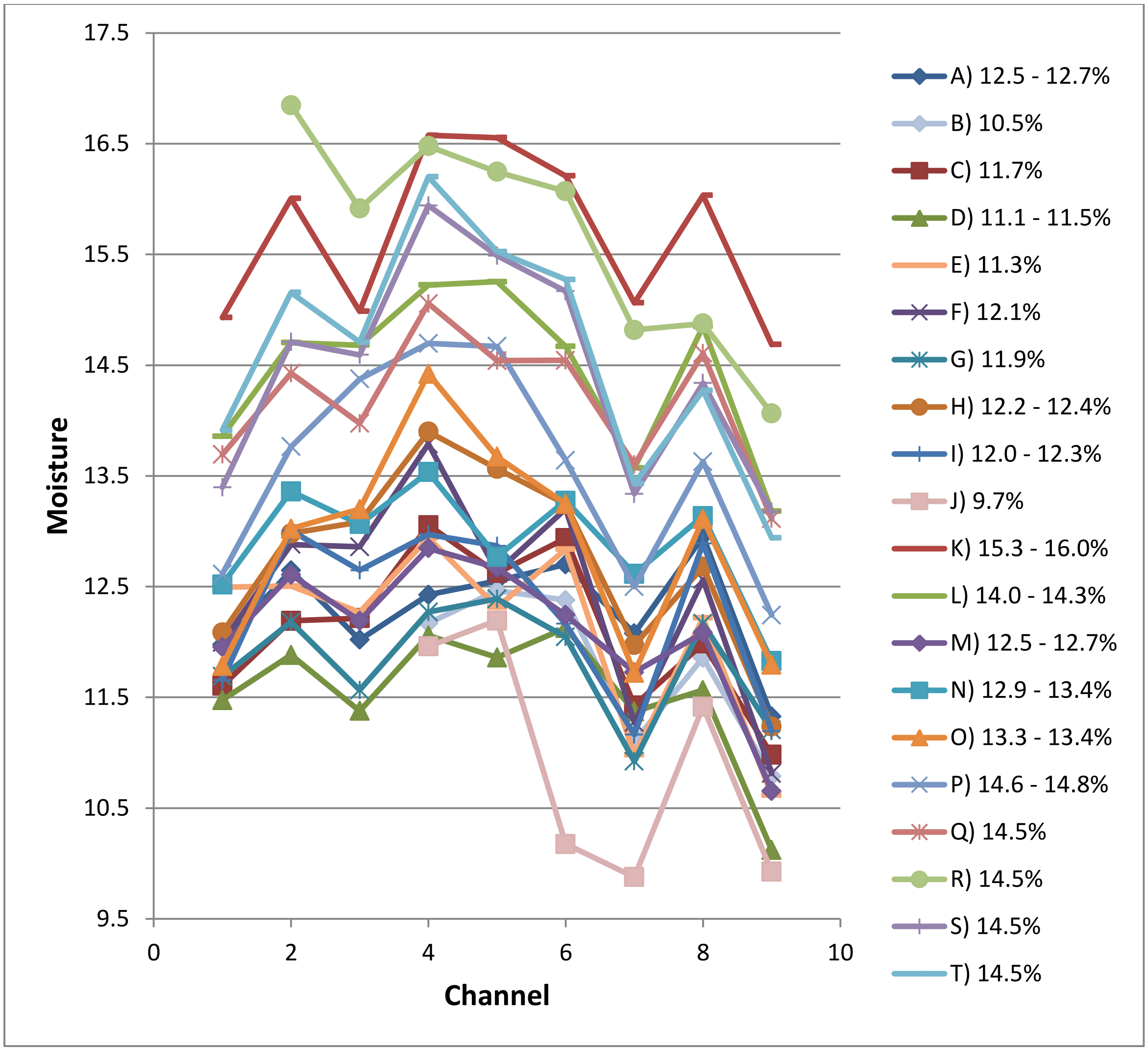

Figure 6.5: Linear fit all tests moisture values (original in colour)

Figure 6.6 shows that the different moisture contents can be distinguished by each channel. However, when the same grain test is compared using different channels there can be overlap in the values. To determine how accurate the grain bin moisture sensor is, the average moisture of the nine channels was calculated. The results for the average moisture for each test, for the first order, are shown in Table 6.1.

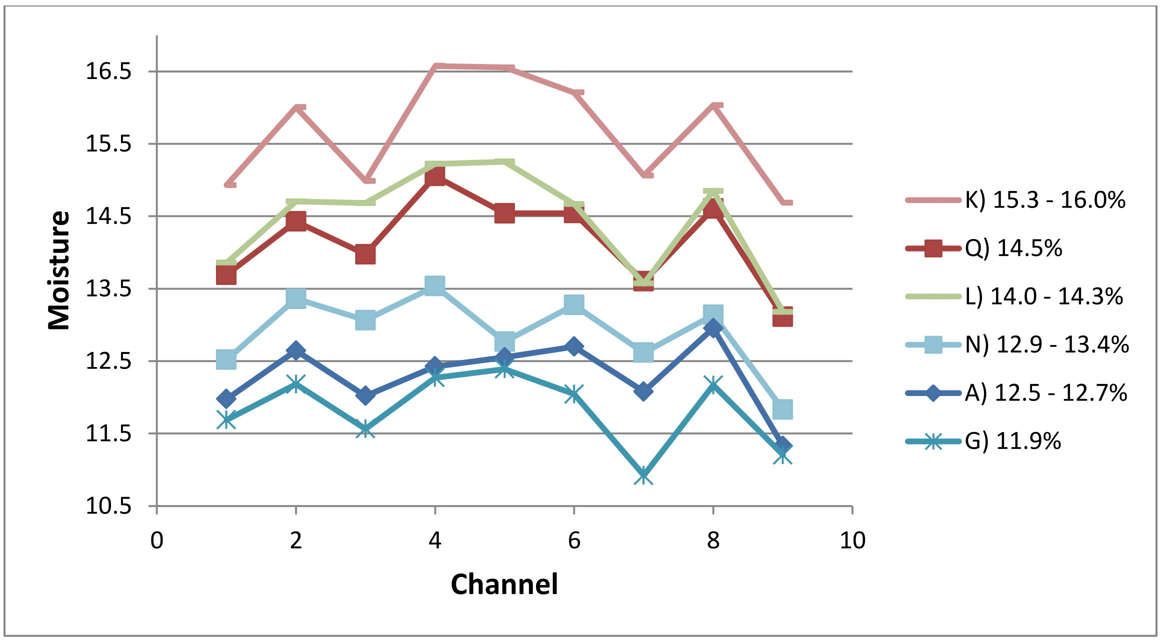

Figure 6.6: Linear fit moisture results (original in colour)

Using the quadratic best fit equation, the moisture content for each test was calculated and is shown by Figure 6.7 below. Since this graph is quite cluttered some of the better test results and are shown in Figure 6.8.

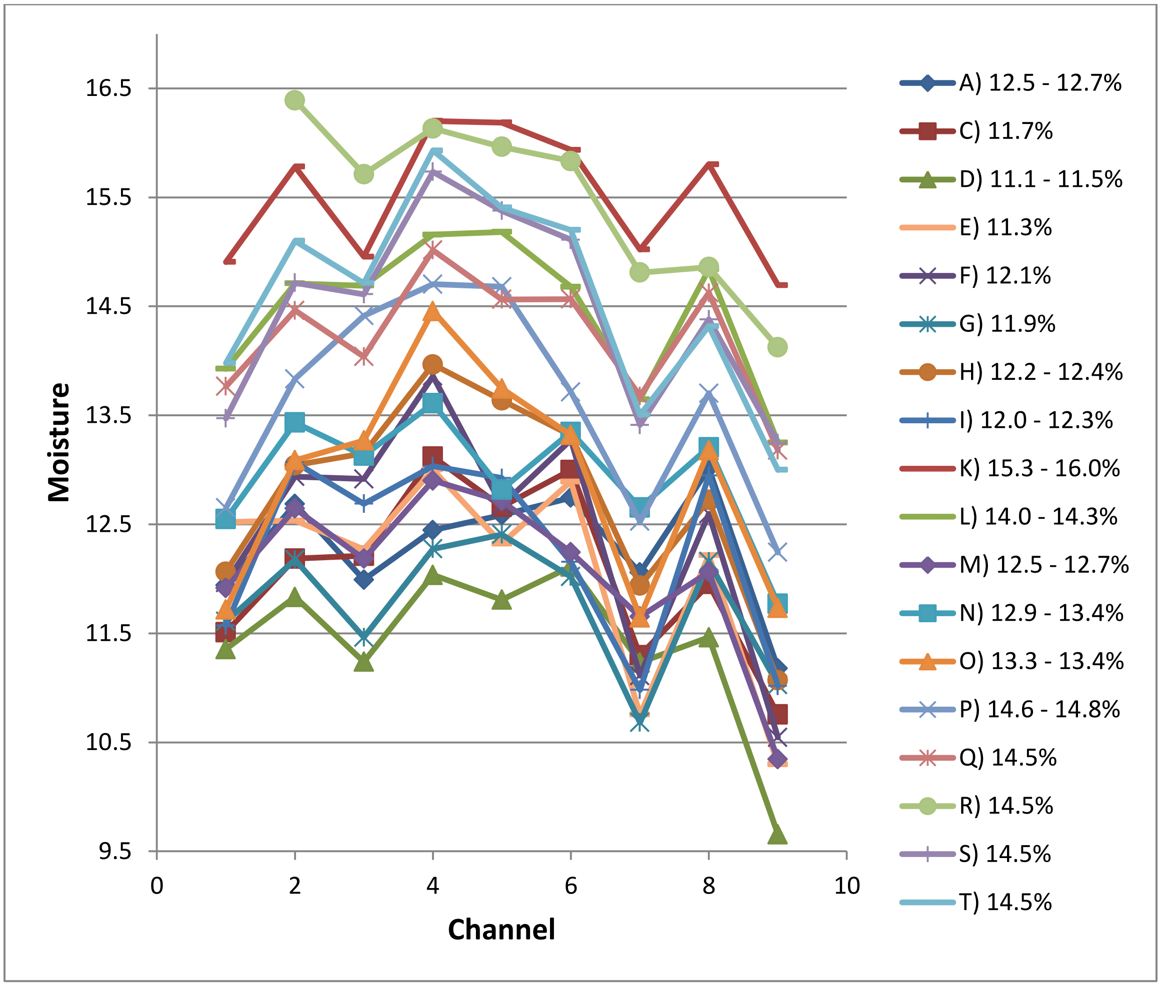

Figure 6.7: Quadratic fit all tests moisture results (original in colour)

The graph below shows the different moisture contents can be distinguished by each channel. However, similar to the first order best fit, when the same grain test is compared using different channels there is often overlap in the values. To determine how accurate the grain bin moisture sensor is, the average moisture of the nine channels was calculated. The results for the average moisture for each test, for the second order, are shown in Table 6.1.

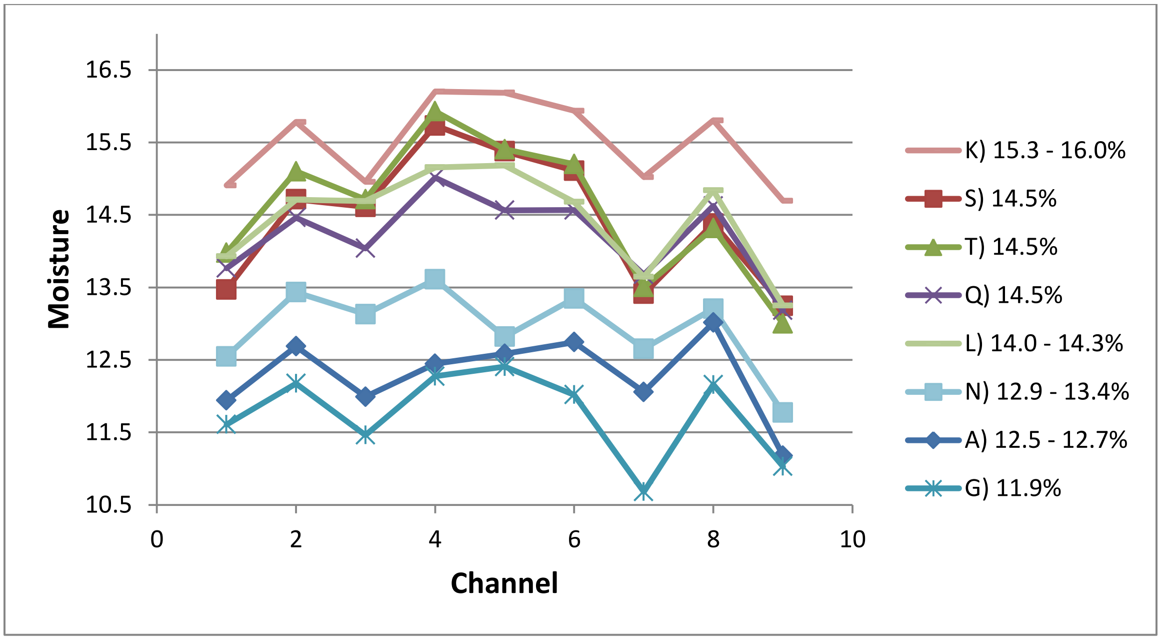

Figure 6.8: Quadratic fit moisture results (original in colour)

Even though the different moisture levels can be distinguished, some channels consistently measured low and other channels consistently measured high. The values for each test run were not as consistent as desired.

Table 6.1: Compare Linear and Quadratic Fit

	Linear Best Fit			Quadratic Best Fit		
Description	Moisture (% w.b.)	919 Moisture (% w.b.)	Error (% w.b.)	Moisture (% w.b.)	919 Moisture (% w.b.)	Error (% w.b.)
A) 12.5 - 12.7%	12.3	12.6	**-0.3**	12.3	12.6	**-0.3**
B) 10.5%	11.8	10.5	**1.3**	11.7	10.5	**1.2**
C) 11.7%	12.1	11.7	**0.4**	12.1	11.7	**0.4**
D) 11.1 - 11.5%	11.5	11.3	**0.2**	11.4	11.3	**0.1**
E) 11.3%	12.1	11.3	**0.8**	12.1	11.3	**0.8**
F) 12.1%	12.4	12.1	**0.3**	12.4	12.1	**0.3**
G) 11.9%	11.8	11.9	**-0.1**	11.8	11.9	**-0.1**
H) 12.2 - 12.4%	12.7	12.3	**0.4**	12.8	12.3	**0.5**
I) 12.0 - 12.3%	12.3	12.2	**0.1**	12.3	12.2	**0.1**
J) 9.7%	10.9	9.7	**1.2**	10.6	9.7	**0.9**
K) 15.3 - 16.0%	15.7	15.6	**0.1**	15.5	15.6	**-0.1**
L) 14.0 - 14.3%	14.4	14.2	**0.2**	14.5	14.2	**0.3**
M) 12.5 - 12.7%	12.1	12.6	**-0.5**	12.1	12.6	**-0.5**
N) 12.9 - 13.4%	12.9	13.1	**-0.2**	12.9	13.1	**-0.2**
O) 13.3 - 13.4%	12.9	13.4	**-0.5**	12.9	13.4	**-0.5**
P) 14.6 - 14.8%	13.6	14.7	**-1.1**	13.6	14.7	**-1.1**
Q) 14.5%	14.2	14.5	**-0.3**	14.2	14.5	**-0.3**
R) 14.5%	15.7	14.5	**1.2**	15.5	14.5	**1.0**
S) 14.5%	14.5	14.5	**0.0**	14.5	14.5	**0.0**
T) 14.5%	14.6	14.5	**0.1**	14.6	14.5	**0.1**

Table 6.1 compares the average moisture (Moisture) of the nine channels against the moisture measured at the grain terminal (919 Moisture) and shows the difference (Error) between the grain bin moisture sensor and the Labtronics 919 moisture meter. Table 6.1 also compares the linear best fit and the quadratic best fit. The results indicate that there is very little difference between the linear best fit and the quadratic best fit.

Table 6.1 shows that the instrument is able to determine the moisture of grain within ±0.5% w.b. for all but five of the tests. The tests with an error greater than ±0.5% w.b. have been highlighted. For the tests that have been highlighted the accuracy rate was ±1.5% w.b. These tests are the four that were not used in finding the best fit equation and test E) 11.3%. Test E) 11.3% consisted of one bucket of grain that was moisture tested at 11.5% w.b. and another that was tested at 10.5% w.b. Even with this mismatch in grain moisture, the test was within ±0.8% w.b.

The results of the testing of the grain that had water added had a slightly lower dielectric value than the tests of grain with the same moisture content that did not have moisture added. These tests include M) 12.5 - 12.7%, N) 12.9 - 13.4%, O) 13.3 - 13.4%, and P) 14.6 - 14.8%. This result is consistent with the results that Nelson observed, “The dielectric properties of wheat that dries naturally after maturation or harvest may be slightly different from those of the same wheat when its moisture content is artificially raised from lower moisture levels by tempering [19].”

7. CONCLUSIONS AND FUTURE WORK

7.1. Conclusions

The grain bin moisture monitor was able to measure the moisture of the grain to within ±0.5% w.b., on 75% of the tests. This level of accuracy met the goal set for the project. Overall, the accuracy was within ±1.5% w.b. on all tests, which is the same as a product currently on the market; therefore, overall, the project was a success. However, with a few improvements the results should be even better. The lab test has proven that the moisture of grain can be measured using capacitance in the grain bin. Even though the lab tests have shown that the grain moisture sensor works, more testing is required and a field study should be conducted.

One of the issues occurred when the test grain bin was not full. On a couple of tests only six of the nine sensors were surrounded by grain and this affected the accuracy of the measurement when channels were compared to each other. Even though the approximate amount of grain in the bin can be determined, the accuracy of the moisture measurement suffers. Another issue with the current design is the connection between the boards. During the testing to see if the wooden dowels were causing an issue there was a communication failure between the boards. In addition, after the first coat of epoxy, a poor connection was discovered and needed to be fixed.

The sensitivity of the sensor could be improved by changing the geometry of the PCB layout. Increasing the size of the anode and cathode plates will help but it would also be useful to place the electronics differently on the board. Currently, the electronics are located between the anode and cathode plates and this could be affecting the measurements. A different board layout could have the electronics in the middle, surrounded by the cathode or ground plate, and further out would be the anode plate. A further improvement would be to generate the sine wave directly on the board. This would ensure that each sensor receives the same input sine wave.

7.2. Future Work

The next step would be to do a field trial. A farming operation that would be willing to put the sensor in a bin that they normally use for drying grain would be an ideal place for an extended field study. These bins are used to dry wet grain for a short time and then, once the grain has been dried, it is moved to another bin or sold. This would create an opportunity to collect a lot of data for grain of various moisture contents. Additionally, the unit could be used to track how the grain is drying.

Initially, it is recommended that the current grain handling methods for monitoring moisture content would continue. Specifically, for the initial field trial, that would mean moisture testing the grain using a Labtronics 919 either on the farm or at the local grain terminal and then comparing this to the moisture measured by the grain bin sensor. The moisture sensor would collect data and be checked against the moisture tests that are part of the normal operation already.

A field trial would also be a convenient place to test the sensor with grains other than wheat. It will need to be determined if the same dielectric values measured in wheat are the same for other crops. A few examples are barley, canola, lentils, and peas. It is very possible that a different relationship between the measured dielectric and moisture content could exist for different crops.

One of the factors affecting grain moisture that was not investigated during this project was the effect of temperature on the moisture measurements. In a field trial, the temperature of the grain will vary and this will need to be explored to see if the moisture meter remains accurate for grain at different temperatures. Since the temperature is recorded by the instrument it could be used as a correction factor if necessary.

To improve the accuracy of the sensor, the size of the anode plates should be increased. It is clear that increasing the size of the anode plate has increased the sensitivity and accuracy of the instrument. Perhaps a single anode plate per 12 inch board would be best. Costs can be controlled by having a passive board, without a microprocessor and support components, on each side of an active board. The current microprocessor could be used to monitor as many as nine channels. The next version of the PCB could be designed in one of two ways. If an 11 inch sensor, one per PCB, is decided on, that means there could be up to four passive boards on each side of the active board with the microprocessor. This would allow a single active board to control up to a nine foot instrument. Alternatively, if it is decided to have two 5.25” channels per board you could have two and half passive boards on each side of the active board. In this scenario, there would be eight channels per active board covering four feet. This improvement would decrease the cost of the electronics which is important for covering the area of a large grain bin.

In addition to increasing the size of the anode plates, a completely different board layout should be considered. Parasitic and stray capacitances have the potential to affect the measurement since the capacitance being measured is in the range of a few picofarads. The current design has the electronics in between the anode and cathode (ground) plates. This creates a situation where there are multiple ground traces between the anode and cathode plates. An alternative design would have the electronics placed in the middle with the cathode or ground plate surrounding the electronics and then the anode plate would be outside of the cathode plate. This change would help to ensure that the capacitance that is measured is only affected by the dielectric between the anode and cathode plates.

Another recommendation would be to improve the durability of the connectors between boards. For grain it might be useful to space them out to cover a bin that is 40 feet high. The current connectors appear to be a weak spot. There was an issue during initial testing where a poor solder joint had to be tracked down and fixed. Additionally, during the wooden dowel tests, when the instrument was lifted 10 inches, the communication from the instrument to the master became problematic. Fortunately, this was a temporary problem and was corrected by wiggling the instrument. However, the instrument should be made more durable before it is manufactured as a commercial product. In addition to making the sensor more durable, the effect of the forces of flowing grain during the loading and unloading of the bin would need to be considered. These forces can be quite high and the product will need to be able to withstand them.

For this test a single frequency of 7 MHz was used. A useful study would be to test a range of frequencies to see if an advantage can be gained. The range of frequencies could be from 1 MHz to 10 MHz to limit the cost of generating the sine wave. In addition, the coating for the boards should also be studied to see if there is something that would work better. The current moisture tester on the market uses a rubber like coating and is a flexible cable. This type of construction would increase the cost but would also increase the durability of the product so it should be considered in the future.

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APPENDIX A: Summary of Grain Tests

Test Name	**Bucket Labels**	**919 Moisture (%** w.b.**)**	**Description**
A) 12.5 - 12.7%	A & H	12.6	Bucket A tested at 12.5% w.b. and Bucket H tested at 12.7% w.b. Bucket A is at the bottom and part of Bucket H was used to fill the top.
B) 10.5%	B	10.5	Not used for dielectric to moisture relationship. Only one bucket of grain so only 6.5 sensors covered. The top 3.5 sensors were surrounded by air. Bucket B tested at 10.5% w.b. Additional notes: Bucket B was first tested on Aug. 30, 2013 at Richardson Pioneer at White City at 10.5% w.b. On Sept. 13, 2013 it was tested again at Richardson Pioneer at White City at 10.7% w.b. It was actually tested a 3rd time on Sept 13, 2013 at Viterra at Balgonie at 10.8% w.b. Since the grain was pretty much sealed in the buckets it should not have increased or decreased in moisture content. Therefore, the actual moisture content for Bucket B was probably about 10.7% w.b. the whole time.
C) 11.7%	C & M	11.7	Both Buckets C and M tested 11.7% w.b., Bucket C is at the bottom and Bucket M was used to fill the top.
D) 11.1 - 11.5%	D & E	11.3	Bucket D tested at 11.1% w.b. and Bucket E tested at 11.5% w.b. Bucket D is on the bottom and Bucket E is used to fill the top.
E) 11.3%	E & B	11.3	Bucket E was tested at 11.5% w.b. and Bucket B tested at 10.5% w.b. In this test Bucket E is on the bottom and Bucket B was used to fill the top. Additional notes: Bucket B was first tested on Aug. 30, 2013 at Richardson Pioneer at White City at 10.5% w.b. On Sept. 13, 2013 it was tested again at Richardson Pioneer at White City at 10.7% w.b. It was actually tested a 3rd time on Sept. 13, 2013 at Viterra at Balgonie at 10.8% w.b. Since the grain was pretty much sealed in the buckets it should not have increased or decreased in moisture content. Therefore, the actual moisture content for Bucket B was probably about 10.7% w.b. the whole time.

Test Name	**Bucket Labels**	**919 Moisture (%** w.b.**)**	**Description**
F) 12.1%	F & L	12.1	Both buckets tested 12.1% w.b. Bucket F is on the bottom and Bucket L is used to fill the top.
G) 11.9%	G & N	11.9	Both buckets tested 11.9% w.b. Bucket G is on the bottom and Bucket N is used to fill the top.
H) 12.2 - 12.4%	I & J	12.3	Bucket I tested 12.4% w.b. and Bucket J tested 12.2% w.b. Bucket I is on the bottom and Bucket J is used to fill the top.
I) 12.0 - 12.3%	I & J	12.2	Bucket I tested 12.0% w.b. and 12.3% w.b. and Bucket J tested 12.2% w.b. and 12.3% w.b. (two different elevators were visited this day to verify measurements). Bucket I is on the bottom and Bucket J is used to fill the top.
J) 9.7%	K	9.7	Not used for dielectric to moisture relationship. Only one bucket of grain so only 6.5 sensors covered. The top 3.5 sensors were surrounded by air. Bucket K - 9.7% w.b., Bucket K covers sensors 4 - 9 and part of sensor 3. This bucket of grain came from an organic farm and was the oldest grain in the lab collection. It has the lowest moisture content, and since it was different than any other bucket of grain it was not mixed with any other buckets.
K) 15.3 - 16.0%	O & P	15.6	Bucket O tested 16.0% w.b. and 15.5% w.b. and Bucket P tested 15.6% w.b. and 15.3% w.b. (two different elevators were visited this day to verify measurements). Bucket O is on the bottom and Bucket P is used to fill the top.
L) 14.0 - 14.3%	Q & R	14.2	Bucket Q tested 14.0% w.b. and 14.2% w.b. and Bucket R tested 14.2% w.b. and 14.3% w.b. (Two different elevators were visited to verify measurements). Bucket Q is on the bottom and Bucket R is used to fill the top.
M) 12.5 - 12.7%	C & M	12.6	These buckets are part of the water added testing. 1% water by mass was added to each bucket. Bucket C tested 12.5% w.b. at both elevators and Bucket M tested 12.6% w.b. and 12.7% w.b. (two different elevators were visited to verify measurements). Bucket C is on the bottom and Bucket M is used to fill the top.

Test Name	Bucket Labels	919 Moisture (% w.b.)	Description
N) 12.9 - 13.4%	C & M	13.1	These buckets are part of the water added testing. 1% water by mass was added to each bucket. Bucket C tested 13.1% w.b. and 12.9% w.b. and Bucket M tested 13.4% w.b. and 13.1% w.b. (two different elevators were visited to verify measurements). Bucket C is on the bottom and Bucket M is used to fill the top.
O) 13.3 - 13.4%	G & N	13.4	These buckets are part of the water added testing. 2% water by mass was added to each bucket. Bucket G tested 13.2% w.b. and 13.4% w.b. and Bucket M tested 13.3% w.b., 13.5% w.b. and 14.0% w.b. (two different elevators were visited to verify measurements). Bucket M was a special case that day because it tested as low as 13% w.b. and as high as 14% w.b. This could have been because of temperature readings. Bucket G is on the bottom and Bucket N is used to fill the top.
P) 14.6 - 14.8%	G & N	14.7	The results for this test did not match well with the others therefore this test was not used for dielectric to moisture relationship. When this test was used it significantly effects R^2. These buckets are part of the water added testing. 2% water by mass was added to each bucket. Bucket G tested 14.6% w.b. and 14.8% w.b. and Bucket M tested 14.8% w.b. at both elevators. (Two different elevators were visited to verify measurements). Bucket G is on the bottom and Bucket N is used to fill the top.
Q) 14.5%	Q & R	14.5	As a test to see why the data does not come out flat (grain dielectric) it was decided to see if the grain was not mixed and that was causing the issue. Therefore, two buckets were mixed together in a larger container. Four samples were taken to the elevator, one from each of the top, middle, and bottom as well as one from the leftover grain not used in the test. All samples tested at 14.5% w.b.

Test Name	**Bucket Labels**	**919 Moisture (%** w.b.**)**	**Description**
R) 14.5%	Q & R	14.5	Not used for dielectric to moisture relationship. As a test to see if the wooden dowels were causing a measurement error the instrument was lifted 10 inches so the top 1.5 sensors were in air. Four samples were taken to the elevator, one from each of the top, middle, and bottom as well as one from the leftover grain not used in the test. All samples tested at 14.5% w.b.
S) 14.5%	Q & R	14.5	As a further test to see if the dowels were causing an issue this test was with the dowels in and the next test was with the dowels out. Four samples were taken to the elevator, one from each of the top, middle, and bottom as well as one from the leftover grain not used in the test. All samples tested at 14.5% w.b.
T) 14.5%	Q & R	14.5	This is the second test to see if the dowels were causing an issue. This was the test with the dowels out. Four samples were taken to the elevator, one from each of the top, middle, and bottom as well as one from the leftover grain not used in the test. All samples tested at 14.5% w.b.