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Development of a Multi-Frequency Dielectric Sensing System for Real-Time Forage Moisture Measurement

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Introduction

Moisture content usually shows the hay quality which affects harvesting, storing, buying, and selling of hay and forage (Eubanks and Birrell, 2001). Hay and forage is marketed on a wet weight basis so profits are optimized when harvesting in the optimal moisture range. More leaves fall off during the harvest of low moisture content hay making it a lower quality and producers will have a lighter product yielding lower profits. At the other extreme storing hay too wet can cause spoilage and possibly internal combustion.

A preservative needs to be added during harvest to successfully harvest and store wet hay. Unfortunately, hay preservatives are relatively expensive so they are not economical for everyday use. However, preservatives may become a more profitable option when avoiding rain on the crop. If the crop mass flow rate and the moisture content are known, then preservative application can be applied in a variable rate fashion thus saving the producer money. The most common hay preservative to reduce storage losses is propionic acid which is supposed to reduce microbial growth and subsequent heating (Shinners, 2000).

Various methods to determine moisture content that are developed or being developed includes oven drying, electric meters, NIR spectroscopy, and dielectric measurements. The baseline for hay moisture measurement comparisons is oven drying using ASAE Standard S358.2 (ASAE, 2003). This standard requires a representative sample to be in the oven for 24 hours at 103 degrees Celsius or for 72 hours at 60 degrees Celsius. Electronic meters are currently the most widely used method commercially to determine hay and forage moisture content (Henson et al., 1987). NIR spectroscopy using microwave reflections and capacitive systems can also predict forage moisture content (Kormann and Auernhammer, 2002). Dielectric moisture measurement sensors have shown potential in the radio frequency range (Eubanks and Birrell, 2001). Many of the current moisture sensors available determine the moisture content after bale formation. These capacitive sensors operate at a single frequency making them sensitive to hay density. Therefore, field calibrations are required to account for varying bale density and ambient conditions.

For a number of years grain moisture sensors using capacitive type methods and other impedance measurements have been in widespread commercial use. The dielectric properties of several grains are specified in ASAE Standard D293.2 (ASAE, 1998). Measured impedance depends on both the moisture content and the bulk density of the sample. Many of these moisture sensors require also field calibrations to account for the changes in sample density. The development of density-independent functions of the dielectric properties of grains has been and still is being investigated in both the radio and microwave frequency ranges (Gillay and Funk, 2003a; Nelson and Trabelsi, 2002). It was also found that dielectric constants vary according to temperature and frequency for grains (Nelson, 2003).

A previous study at Iowa State University has shown the determination of hay and forage moisture content prior to compaction was possible using impedance measurements of capacitive type sensors at multiple frequencies (Eubanks and Birrell, 2001). Impedance measurements of each sample were taken at sequential frequencies from 5 Hz to 13 MHz at a rate of one frequency every three seconds. A multiple linear regression to predict moisture content was used to obtain an equation utilizing multiple frequencies. Multiple linear regressions were used because the R^2 values generally increased the moisture prediction accuracy using many frequencies. For density independent alfalfa moisture predictions R^2 = 0.2249 using the best single frequency. Using additional frequencies R^2 increases as follows: R^2 = 0.7163 for 2 frequencies, R^2 = 0.7758 for 3 frequencies, R^2 = 0.8538 for 4 frequencies, and R^2 = 0.9532 for 5 frequencies (Eubanks and Birrell, 2001).

It takes many seconds to record a multi-frequency measurement using the sequential frequency method. A real-time moisture sensor must be capable of predicting moisture at the speed which material flows through the machine. A real-time sensor does not have many seconds to take a measurement. Large amounts of material will have passed through the sensing volume in a few seconds. The first frequency would measure one sample mass and the final frequency would measure an entirely different sample mass. Taking multi-frequency dielectric measurements simultaneously would ensure all measurements are from the same sample mass. This would minimize the effects of material flow on moisture prediction.

Objective

The objective is to develop a system capable of real-time hay and forage moisture sensing. A previous study taking sequential frequency measurements took many seconds which is impractical for a real-time moisture sensor. A real-time moisture sensor should have multiple frequency measurements taken simultaneously to ensure all measurements are from the same sample mass. Specific objectives include:

1. Develop sensor hardware and signal conditioning circuits required for simultaneous multi-frequency dielectric impedance measurements.

2. Determine if sequential frequency measurements are comparable to measurements taken from extracted frequencies of a multiple frequency signal.

Theory

Impedance measurements taken in a known sensing volume on a particular material determines the material's dielectric properties. The complex permittivity, ε, is defined as,

$$\varepsilon = \varepsilon' + j\varepsilon'' \quad (1)$$

where ε' is the real part known as the dielectric constant and ε'' is the imaginary part known as the dielectric loss factor. The dielectric constant is associated with the energy storage of the electric field in the material and the dielectric loss factor is associated with energy dissipation in the material or the conversion from electric energy to heat energy (Nelson 2003). The loss tangent is,

$$\tan(\delta) = \frac{\varepsilon''}{\varepsilon'} \quad \text{(2)}$$

where δ is known as the loss angle. The capacitance of a parallel plate sensor is determined from the dielectric constant, area of the sensor plates, A, and the distance between the sensor plates, d, as follows,

$$C = \frac{\varepsilon' A}{d} \quad \text{(3)}$$

The dielectric constant is composed of a relative material dielectric constant, ε_r', and the permittivity of free space, ε_0, as shown,

$$\varepsilon' = \varepsilon_0 \varepsilon_r' \quad \text{(4)}$$

where ε_0 is equal to 8.854×10^{-12} F/m. The free space capacitance, C_0, for a particular parallel capacitor is determined as,

$$C_0 = \frac{\varepsilon_0 \varepsilon_{air}' A}{d} \quad \text{(5)}$$

where the relative dielectric constant of air, ε_{air}', is equal to one. A material's capacitance, C_{mat}, is used when the sensing cell is filled with that material as shown,

$$C_{mat} = \frac{\varepsilon_0 \varepsilon_{mat}' A}{d} \quad \text{(6)}$$

where, ε_{mat}', is the relative dielectric constant of the material. The real part of the complex admittance is the conductance, G, and is determined as,

$$G = 2\pi f C_0 \varepsilon'' \quad \text{(7)}$$

where G is a function of frequency, f, empty cell capacitance, C_0, and the dielectric loss factor, ε". The susceptance, B, is the imaginary part of the admittance and related to the capacitance as follows,

$$B = 2\pi f C_{mat} \quad \ldots\ldots (8)$$

When modeling the Device Under Test's (DUT) complex impedance as a parallel resistor and capacitor, the conductance, G, and susceptance, B, are related to DUT impedance, Z_{DUT}, as follows,

$$\frac{1}{Z_{DUT}} = G + jB \quad \ldots\ldots (9)$$

After substituting the conductance and susceptance into equation 9 the DUT impedance becomes,

$$Z_{DUT} = \frac{1}{2\pi f \varepsilon'' \frac{\varepsilon_0 \varepsilon'_{air} A}{d} + j2\pi f \frac{\varepsilon_0 \varepsilon'_{mat} A}{d}} \quad \ldots\ldots (10)$$

Sensor Circuit Development

The overall sensor circuit is shown in Figure 1 and is designed to find the DUT impedance. The equivalent impedance, Z_{eq}, is a resistor, R_1, in series with the DUT impedance and from this relationship Z_{eq} can be determined as,

$$Z_{eq} = Z_{DUT} + R_1 \quad \ldots\ldots (11)$$

The signal going to the DUT is driven by operational amplifier (OP-AMP) 1 and this driven signal, $\mathbf{V}_1$, is recorded by the data acquisition system via buffer amplifier OP-AMP 4 shown in Figure 1.

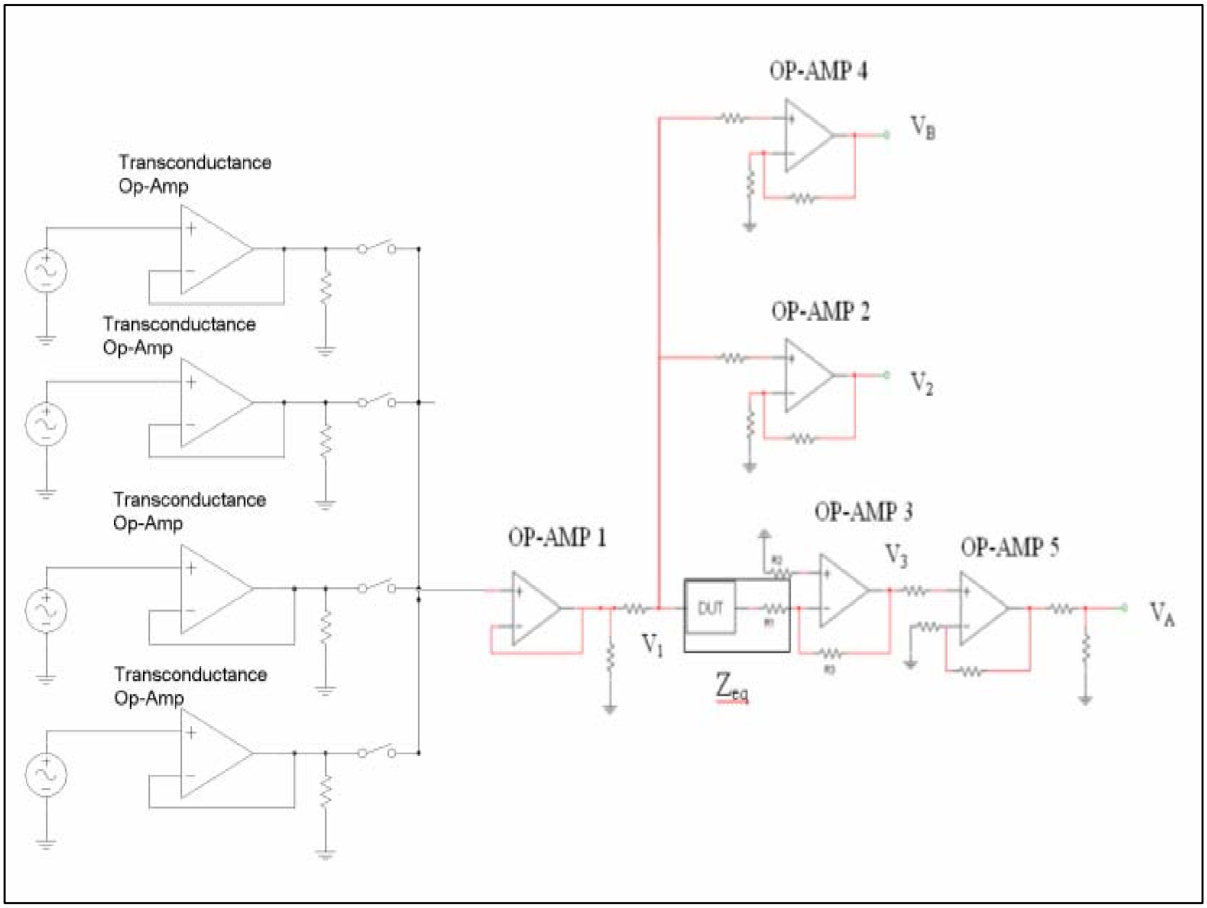

Figure 1. Schematic of auto-balancing bridge sensor circuit with buffer operational amplifier drivers for the sensing signal, guard signal, and buffered data acquisition signals.

The auto-balancing bridge is the standard method of measuring impedance at frequencies less than 40 MHz and shown as OP-AMP 3 which is the operational amplifier after Z_{eq} (Agilent Technologies, 2003). The auto-balancing bridge is based on the flow of current. For all operational amplifiers both the inverting and non-inverting inputs are always at the same voltage, unless saturated. The non-inverting input of OP-AMP 3 is connected to ground through a resistor which makes the inverting input a virtual ground. With the inverting input a ground the voltage drop across Z_{eq} is related to the current flowing through it as follows,

$$I = \frac{\mathbf{V}_1}{Z_{eq}} \quad \text{...} (12)$$

An equal amount of current also flows through a feedback resistor, R_3, because amplifier input current is negligible. This current is related to R_3 and the voltage after the auto-balancing bridge, $\mathbf{V}_3$, as follows,

$$I = \frac{-\mathbf{V}_3}{R_3} \quad \text{(13)}$$

The current in equation 12 is equal to the current in equation 13 allowing,

$$\frac{\mathbf{V}_3}{\mathbf{V}_1} = -\frac{R_3}{Z_{eq}} \quad \text{(14)}$$

The attenuation is measured by dividing the signal output from the auto-balancing bridge by the driven signal to the first sensor plate. The phase shift can be found by subtracting the input phase from the output phase. Both the attenuation and phase relationship are shown as,

$$\frac{\mathbf{V}_3}{\mathbf{V}_1} = \left|\frac{V_3}{V_1}\right| \angle(\phi) \quad \text{(15)}$$

where phase shift, ϕ, is equal to the phase of the driven signal, ϕ_3, minus the phase of the signal output from the auto-balancing bridge, ϕ_1. Signals measured with the data acquisition system correspond to the attenuation and phase shift as follows,

$$\frac{\mathbf{V}_A K}{\mathbf{V}_B} = \frac{\mathbf{V}_3}{\mathbf{V}_1} \quad \text{(16)}$$

where $\mathbf{V}_A$ is the signal coming from OP-AMP 5 going to channel A of the data acquisition, $\mathbf{V}_B$ is the signal coming from OP-AMP 4 going to channel B of the data acquisition, and K is a constant which equals 0.3282 and accounts for the amplifier gains of both data acquisition measured signals. The signals measured with the data acquisition are related to the equivalent impedance as,

$$Z_{eq} = -\frac{R_3 \mathbf{V}_B}{K \mathbf{V}_A} \quad \text{(17)}$$

From equations 11 and 17 the material dielectric constant and dielectric loss factor can be determined.

Apparatus

The method used in this study to measure impedance is based a parallel plate setup. A pre-determined signal goes to the first sensor plate while the second sensor plate connects to the auto-balancing bridge. From research performed by another researcher in this area it was determined that the sensing area should be shielded to protect it from outside influences (Gillay and Funk, 2003b). It was decided for this study to have the sensor plate insulated from the hay bale using acrylic material. The sensor plate is also shielded with a guard area around the outside edge and back side of it. The guard signal for both plates is connected to the guard plate through the screws of the SMA flange connector as shown in Figure 2. The guard plate of the first sensor plate assembly was driven by a buffered voltage signal, V_2, equal in magnitude and phase, as the sensor signal, V_1, driving the sensor plate. The second sensor plate assembly guard is connected to ground at the circuit boards. The sensing section area is 297.3 cm^2 and the guard section area is 305.0 cm^2. Stands were made to hold the sensor plate assemblies vertical and parallel to each other. The sensor plates are placed 49.6 cm apart with a hay bale between them oriented with its strings down. The hay bale analyzed was 54.7 percent moisture content wet basis.

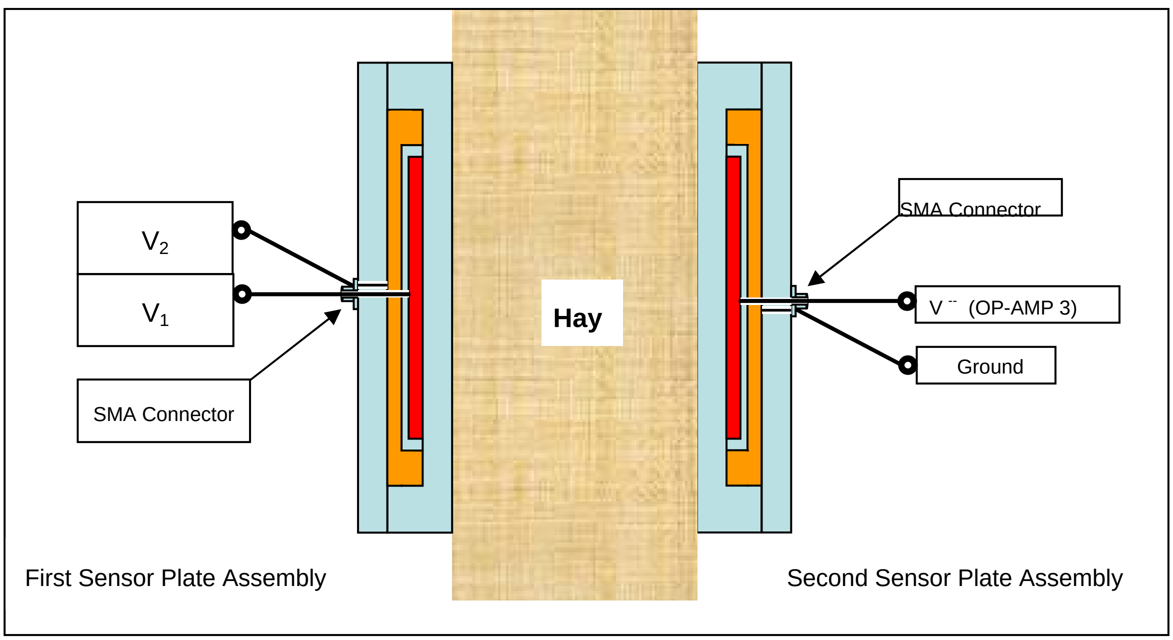

Figure 2. Cross sectional view of the sensor plate configuration showing the sensor plates (in red), acrylic insulators (in blue) and guard plates (in orange).

Two different circuit boards were developed to make the multi-frequency impedance measurements. The first circuit board developed is a frequency generating board which outputs a sine wave at a particular set frequency. The second board developed is an analog signal board used to combine the individual frequencies signals and contains the buffered drivers and auto-balancing bridge circuit. Circuit boards are designed to be stackable and connect together through a header. The stackable circuit boards are shown in Figure 3 with one analog signal board connected to two frequency boards. The analog board can sum together a maximum of four frequencies coming through the header. If less than four frequencies are desired fewer frequency boards are needed.

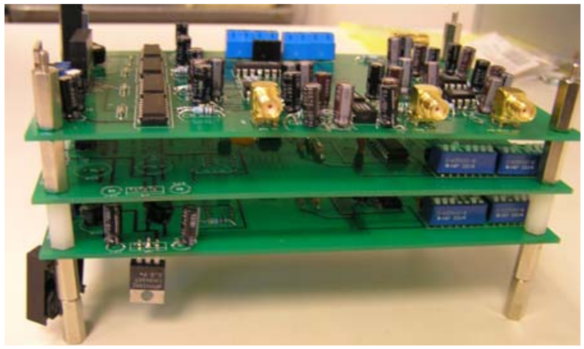

Figure 3. Stackable circuit boards.

Based on a previous study performed at Iowa State University four frequencies were chosen and are 1 MHz, 3 MHz, 7 MHz, and 13 MHz (Eubanks and Birrell, 2001). The analog circuit is capable of selecting any combination of these four frequencies, providing up to fifteen different frequency combinations. The actual frequencies used are 1.035 MHz, 2.863 MHz, 7.132 MHz, and 13.431 MHz but are referred to as 1 MHz, 3 MHz, 7 MHz, and 13 MHz throughout this paper. Electrical testing circuits were developed using Multisim 2001 and circuit layouts were made using Ultiboard 2001 (Electronics Workbench). Circuit boards were composed of FR-4 material with two copper layers and were produced by a supplier.

Each frequency board contains a frequency generating chip, MAX038, to create the set frequency which is output to the header. Dip switches adjust the output voltage of a multiplying D/A converter, MX7541. This output voltage is converted to a current which adjusts the frequency output of the MAX038 frequency generating chip. The dip switches ensure a repeatable frequency selection thus minimizing frequency drift. Dip switches were also used in order to make all frequency boards the same while still being able to output various frequencies.

The analog signal board takes each individual frequency from the header into a trans-conductance amplifier, MAX436. Each MAX436 output is connected to an input on an analog switching chip, PS392. The PS392 allows for any frequency combination to be summed together and output on one line. The selected frequency combination is controlled by four digital bits on a PMD-1208LS USB data acquisition board connected to a computer. Possible frequency combinations are limited by the number of frequency boards connected to the analog board. The combined frequency output from the PS392 is connected to the input of an OPA388P buffer amplifier, shown as OP-AMP 1 in Figure 1. The output of OP-AMP 1 is connected to the sensing area of the first sensor plate. This signal is also duplicated separately through two more buffer amplifiers OP-AMP 2 and OP-AMP 4. The output of OP-AMP 2 connects to the guard area of the first sensor plate and the output of OP-AMP 4 is connected to A/D channel B on the data acquisition.

The sensing section of the second sensor plate assembly is connected to the auto-balancing bridge input on the analog signal conditioning board. The output of OP-AMP 5 is connected to A/D channel A on the data acquisition system. The guard area of the second sensor plate assembly is connected to ground on the analog signal board.

The data acquisition system consists of two boards connected together with a header. One board is a dual channel, 12-bit, 105 MSPS IF sampling A/D converter with analog input signal conditioning (Analog Devices 10200 Evaluation Board). The other board has 32768 sample readings of buffer memory for each channel and communicates to the computer via a parallel cable (Analog Devices High-Speed Analog-to-Digital Converter FIFO (A) Evaluation Kit). The data acquisition system simultaneously records both analog channels of data at 100 MHz until 32768 readings are stored in FIFO memory. After A/D conversions the data is transferred to the computer and written to a file for further analysis.

Type RS-316 cables with SMA connectors were used to connect the signal board to the sensor plates with a cable length of 1.2 m. Two RS-316 type cables 304 mm long connected the signal board to the data acquisition system. Another two RS-316 type cables 304 mm long connected the 100 MHz clock signal to the data acquisition board. The 100 MHz clock was required to sampling trigger the ADC 10200 A/D.

Analysis and Discussion

Many different signals can be created using the developed instrumentation. The system could be used to sequentially output and record the response for each individual frequency, in the same manner as a standard impedance analyzer. In addition, the system was capable of developing different frequency combinations, where individual frequencies are summed together creating a multiple frequency signal where all frequencies are simultaneously superimposed on each other. Bandpass filters where developed to extract the individual frequencies from the multiple frequency combined signal. Unfiltered sequential signals for 1MHz, 3 MHz, 7 MHz, and 13 MHz are shown in Figures 4, 5, 6, and 7 respectively. Figure 8 shows an unfiltered multiple frequency signal containing all four frequencies tested.

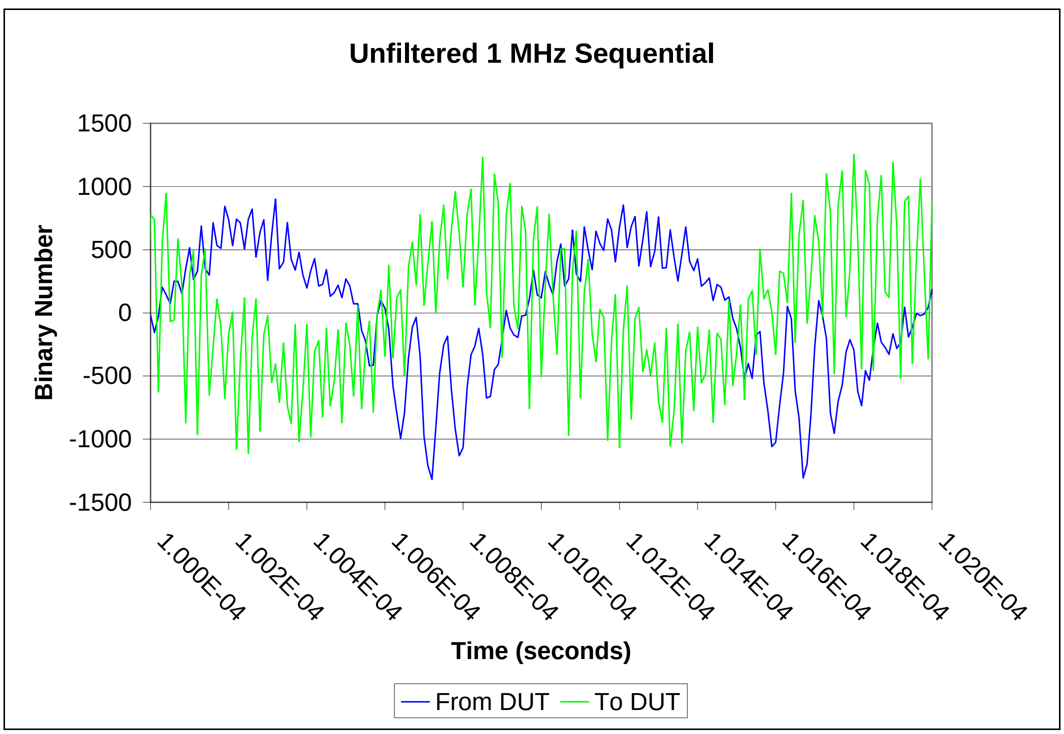

Figure 4. Unfiltered 1 MHz signal measured sequentially.

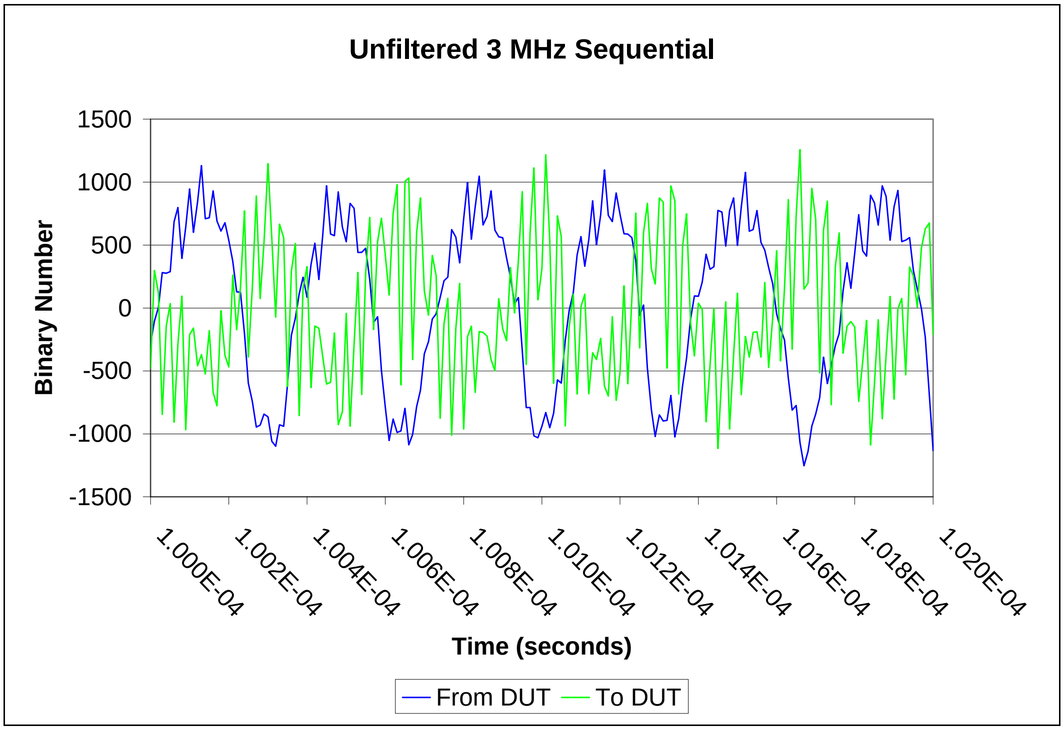

Figure 5. Unfiltered 3 MHz signal measured sequentially.

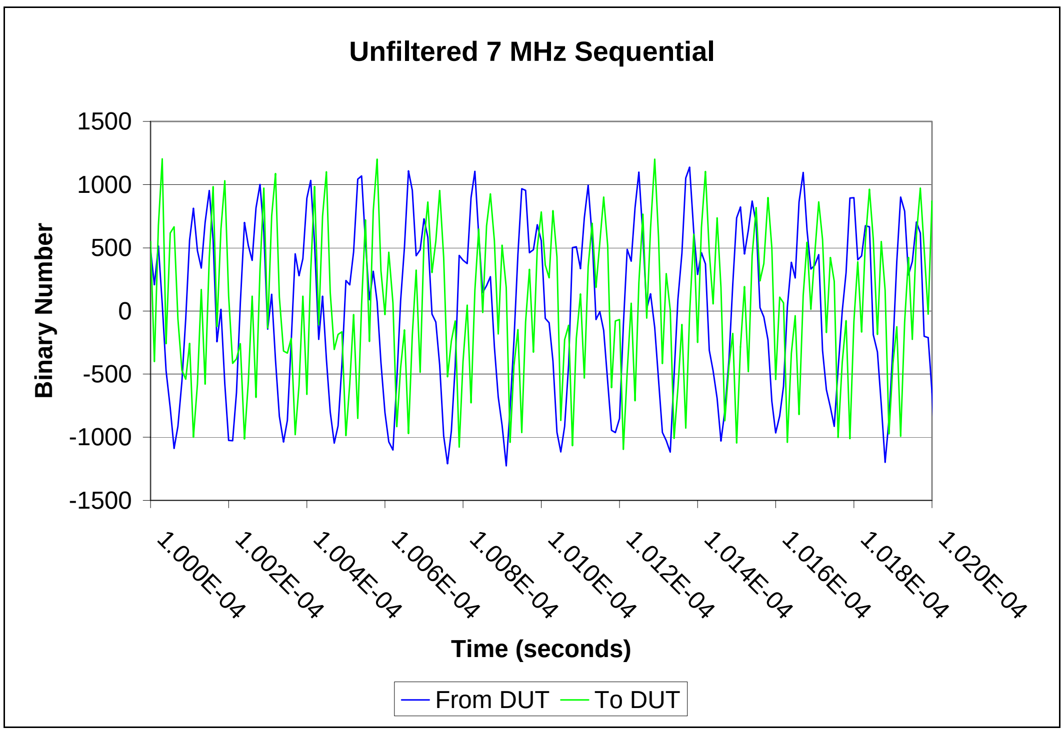

Figure 6. Unfiltered 7 MHz signal measured sequentially.

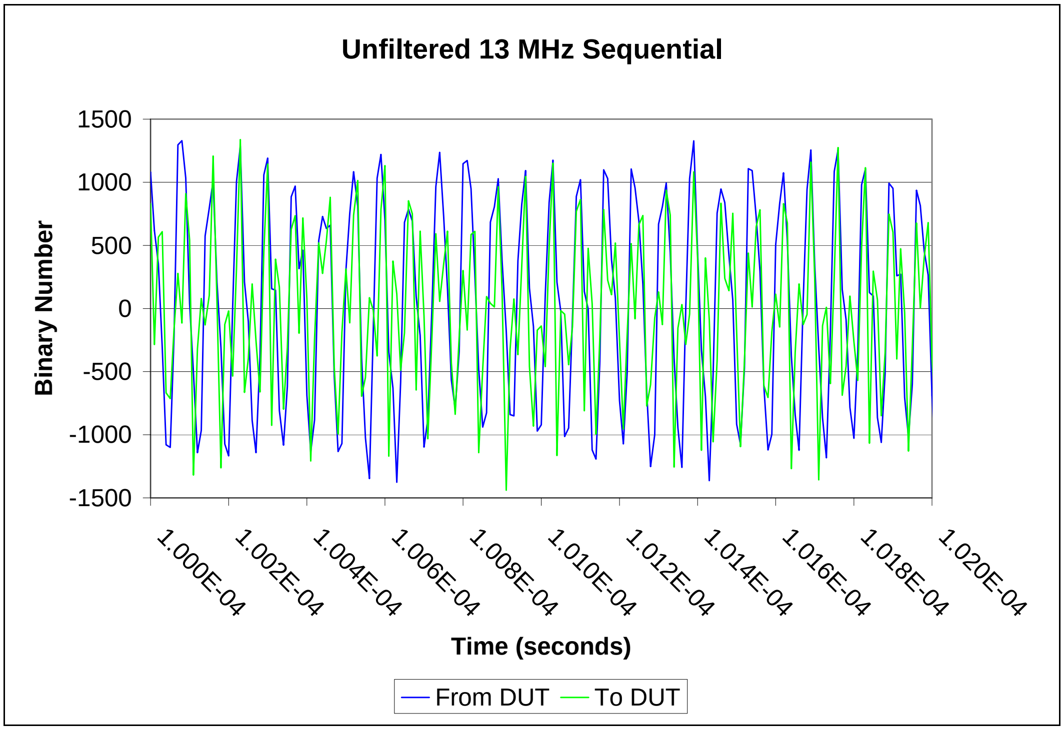

Figure 7. Unfiltered 13 MHz signal measured sequentially.

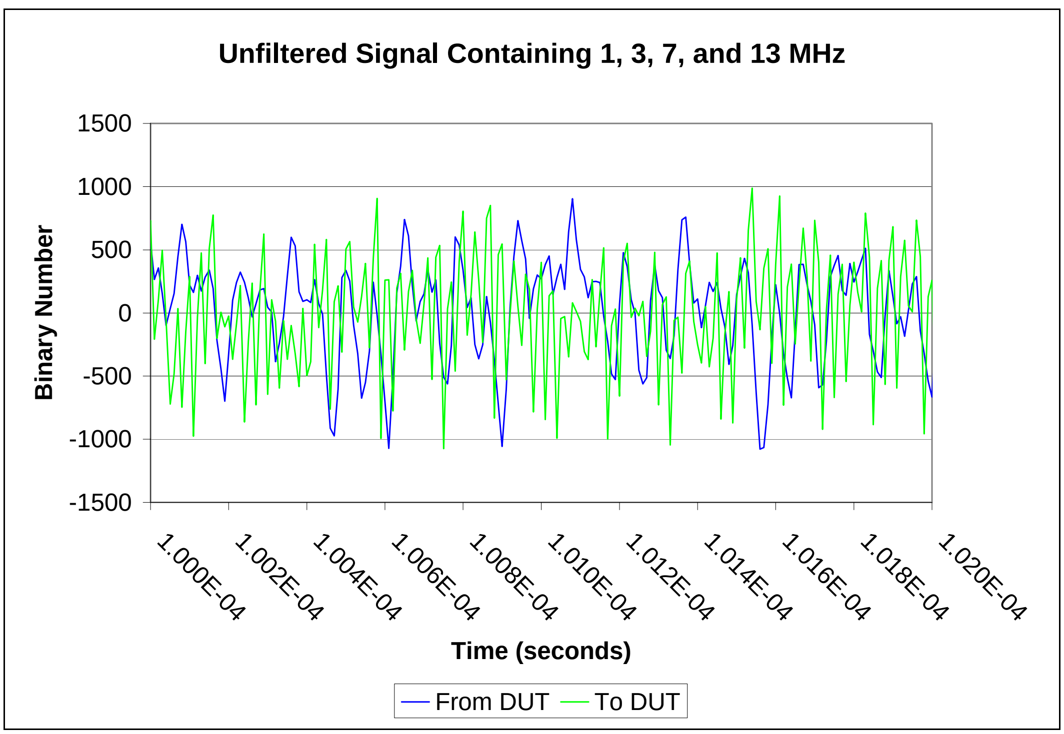

Figure 8. Unfiltered multi-frequency signal containing a sum of 1, 3, 7, and 13 MHz individual signals.

With the sample rate of 100 mega samples per second it takes 0.0003268 seconds to fill the buffer memory of the FIFO board of 32768 points. In this time period 339 cycles are collected for the 1 MHz signal, 938 cycles for the 3 MHz signal, 2337 cycles for the 7 MHz signal, and 4401 cycles for the 13 MHz signal. Since unfiltered signals going "To DUT" and "From DUT" all contained noise they were filtered using Matlab. Both individual frequencies and multiple frequency signals were filtered for desired frequencies using Bandpass FIR Equiripple filters with limits specified in Table 1.

Table 1. Matlab Bandpass FIR Equiripple filter parameters.

	Nominal Frequency			
Filter Parameters	**1 MHz**	**3 MHz**	**7 MHz**	**13 MHz**
Passband Center Frequency	1.035	2.863	7.132	13.431
Low Stop Band Frequency	0.91	2.738	7.013	12.211
Low Pass Band Frequency	0.9725	2.8001	7.0755	12.2735
High Pass Band Frequency	1.035	2.9255	7.2005	14.3985
High Stop Band Frequency	1.0975	2.988	7.263	14.461

After signal filtering the first 6000 collected points were not used because the signals were unstable in this region from the filtering process. Therefore, signal information is based from 277 cycles for 1 MHz, 766 cycles for 3 MHz, 1909 cycles for 7 MHz, and 3595 cycles for 13 MHz. Assume the average bale length is 91.44 cm (36 inches) and it takes 10 seconds to make one bale. This allows the entire sensing area to be in contact with the bale for 8.1 seconds. If only 0.0003268 seconds of data is collected and analyzed every second for 8.1 seconds then the average bale moisture is based on 2244 cycles for the 1 MHz signal, 6207 cycles for the 3 MHz signal, 15463 cycles for the 7 MHz signal, and 29121 cycles for the 13 MHz signal. In the time required to fill the buffer memory the hay bale will travel 0.03 mm showing this sensor is definitely fast enough to be considered a real-time sensor.

Filtered sequential frequencies of 1, 3, 7, and 13 MHz are shown in Figures 9, 10, 11, and 12 respectively. Sequential frequencies 1, 3, and 7 MHz show very clean signals after filtering. The filtered 13 MHz sequential frequency shows amplitude modulation on the signal.

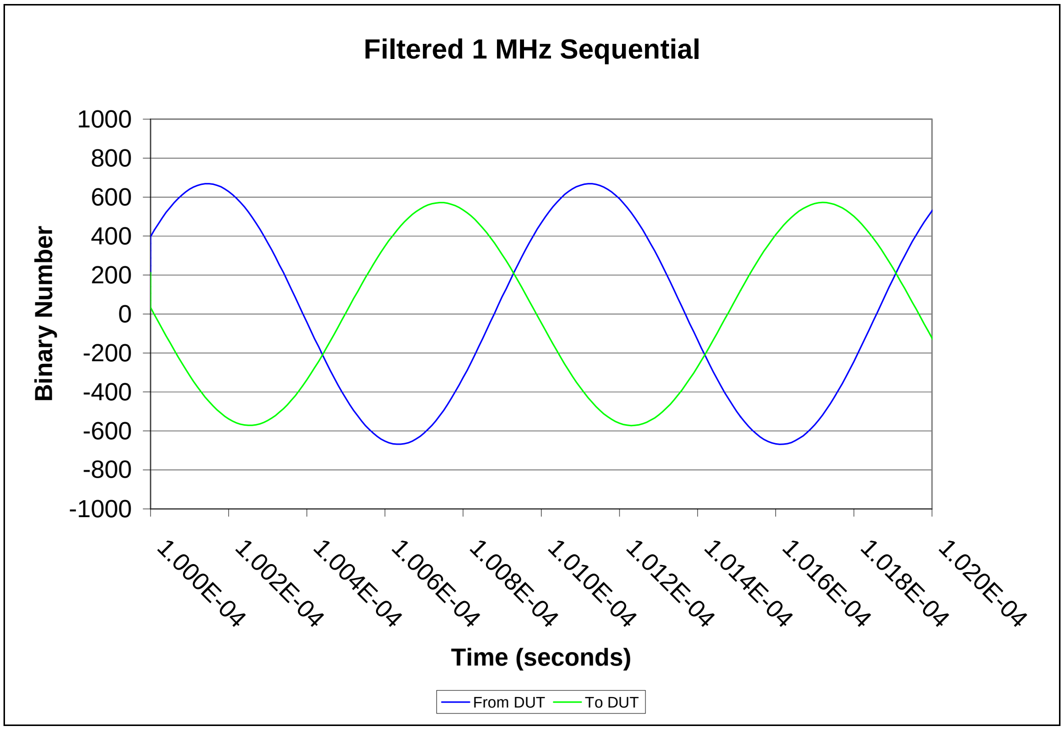

Figure 9. Filtered 1 MHz signal measured sequentially.

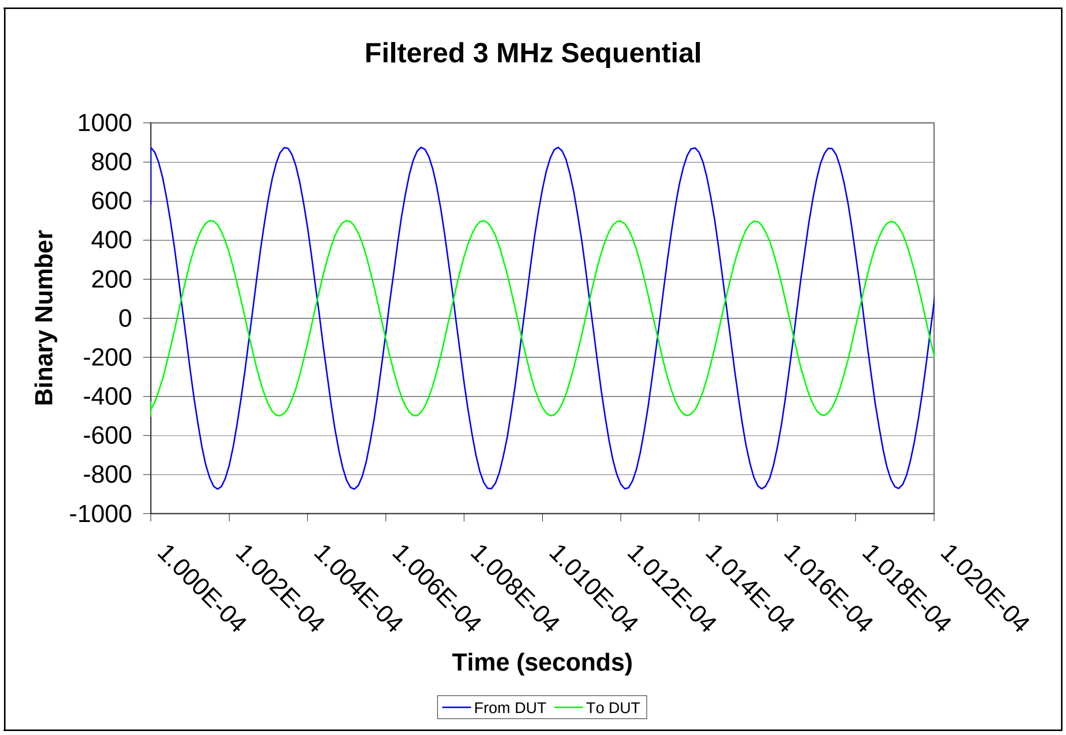

Figure 10. Filtered 3 MHz signal measured sequentially.

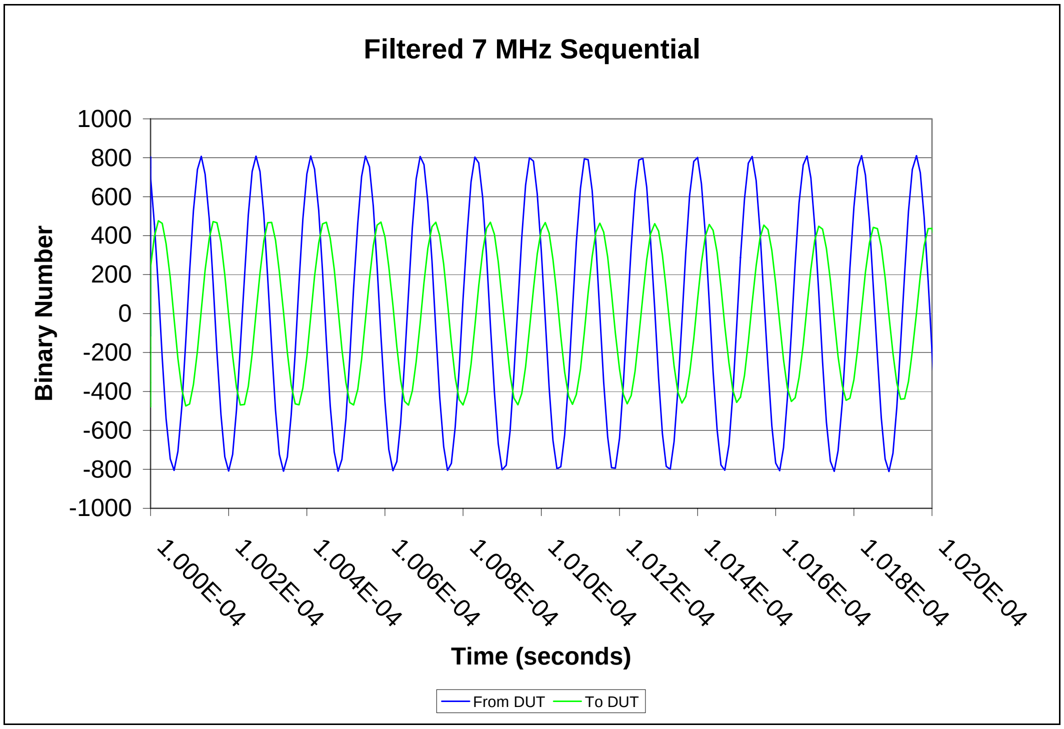

Figure 11. Filtered 7 MHz signal measured sequentially.

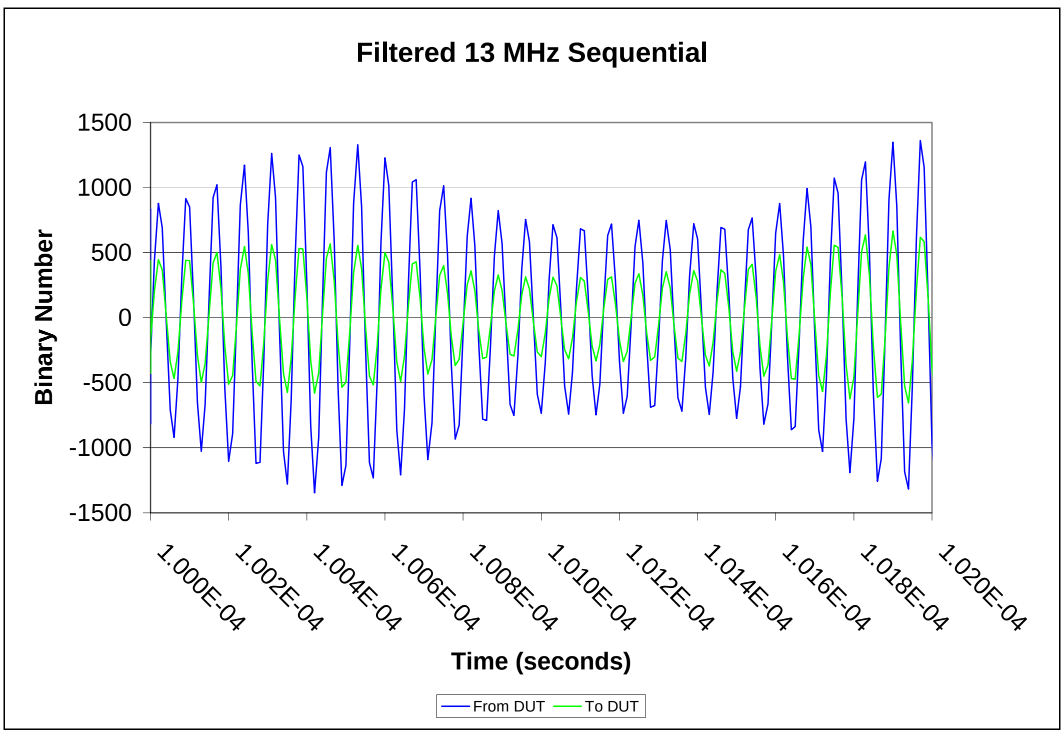

Figure 12. Filtered 13 MHz signal measured sequentially.

The multi-frequency signal containing the superimposed 1, 3, 7, and 13 MHz signals, was filtered to extract each frequency from the signal. Figure 13 shows a clean 1 MHz frequency extracted from the multi-frequency signal. Figure 14 shows a clean 3 MHz frequency extracted. Figure 15 shows a clean 7 MHz extracted. Figure 16 shows a 13 MHz extracted having amplitude modulation on the signal. This may have been caused by a number of factors including: sensor plate separation distance, improper cable terminations, improper circuit board terminations or trace widths. To achieve maximum resolution of the data acquisition the amplitudes of each frequency are reduced proportionally to the number of frequencies making up the multi-frequency signal. Since four frequencies make up the multi-frequency signal the amplitude of each extracted frequency is reduced to one-fourth of its sequentially scanned amplitude.

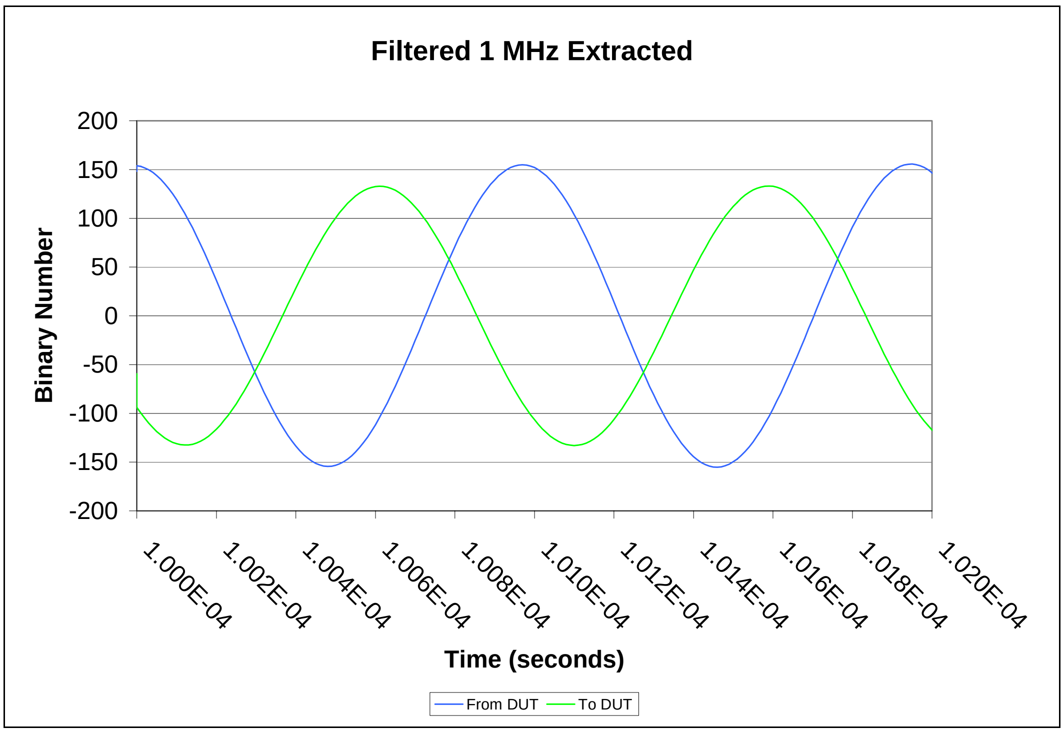

Figure 13. Filtered 1 MHz signal extracted from multi-frequency signal containing all four frequencies.

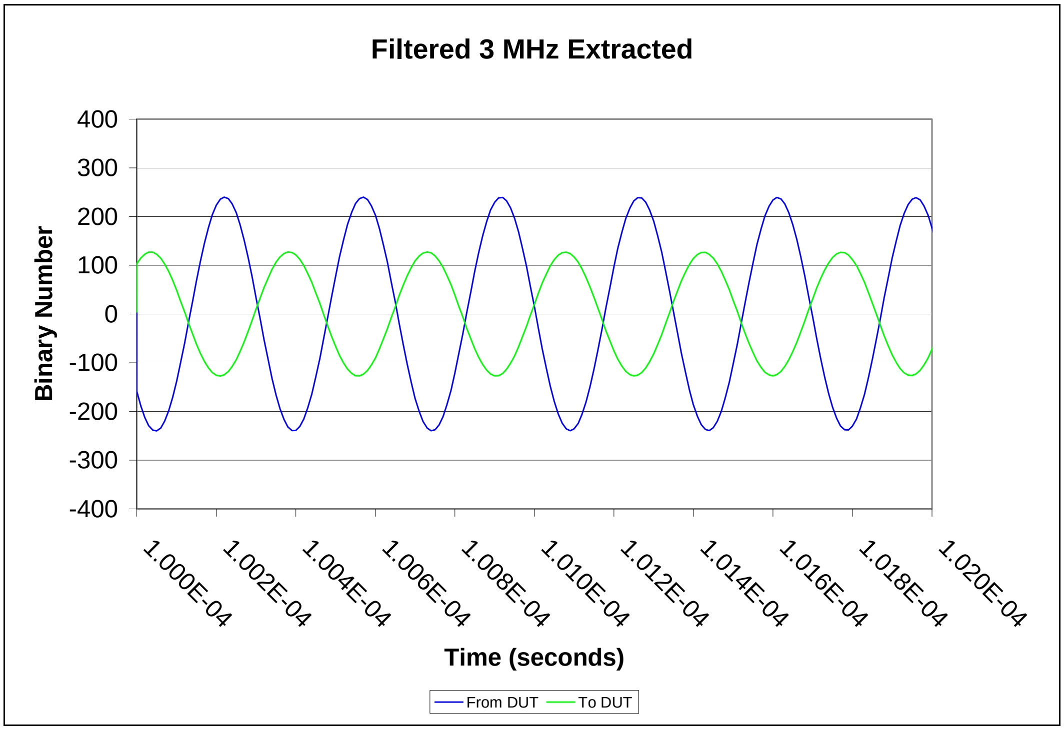

Figure 14. Filtered 3 MHz signal extracted from a multi-frequency signal containing all four frequencies.

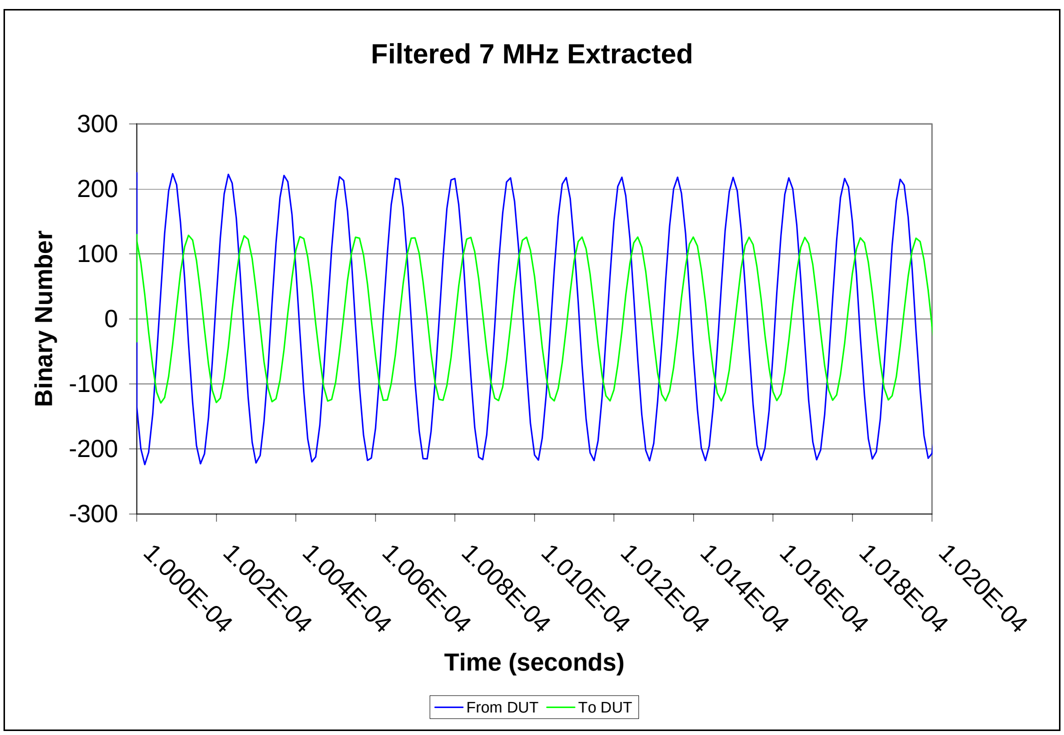

Figure 15. Filtered 7 MHz signal extracted from a multi-frequency signal containing all four frequencies.

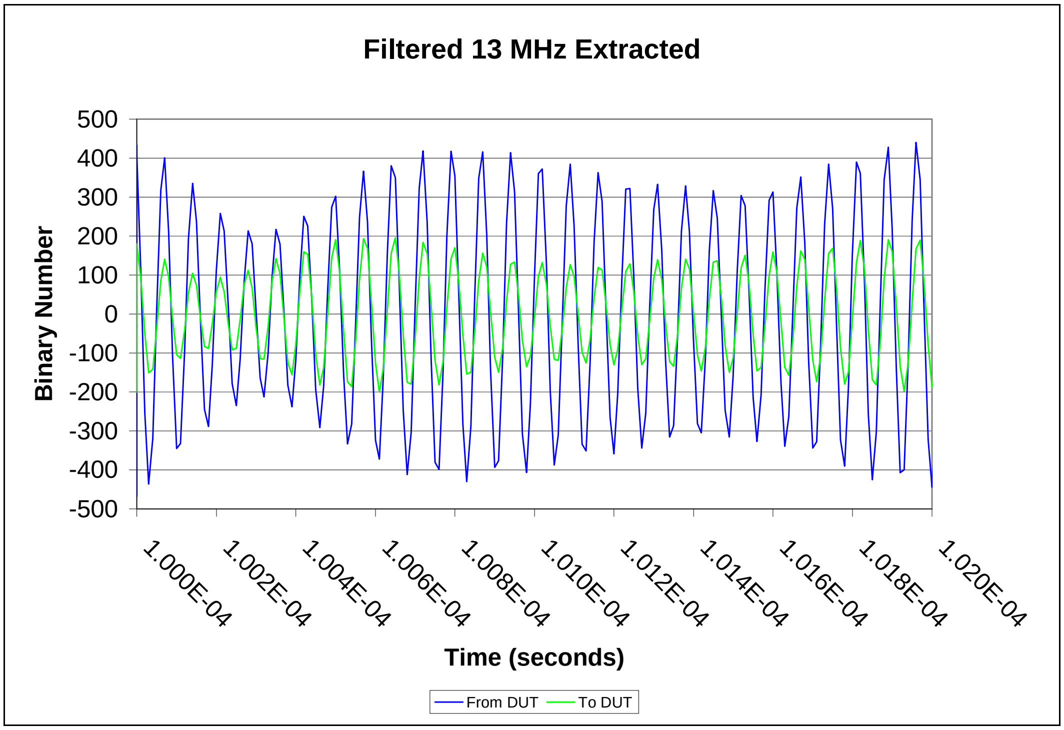

Figure 16. Filtered 13 MHz signal extracted from a multi-frequency signal containing all four frequencies.

The amplitude of sequential frequencies is approximately 4 times the amplitude of the same frequency extracted from a multi-frequency signal. This is expected with the data acquisition configuration for summing together four frequencies.

Conclusion

This study has shown frequencies extracted from a multi-frequency signal are capable of providing the same signal information as sequentially scanned frequencies. A previous study at Iowa State University has shown the determination of hay and forage moisture content prior to compaction was possible using impedance measurements of capacitive type sensors at multiple frequencies (Eubanks and Birrell, 2001). These impedance measurements were taken using sequential frequencies taking many seconds. In this study a multi-frequency signal made up from summing four frequencies took 0.0003268 seconds. A hay bale 91.44 cm long taking 10 seconds to make would only move 0.03 mm in the time required to acquire 339 cycles for 1 MHz, 766 cycles for 3 MHz, 2337 cycles for 7 MHz, and 4401 cycles for 13 MHz of unfiltered data. After filtering the signals moisture prediction is based on 277 cycles at 1 MHz, 766 cycles at 3 MHz, 1909 cycles at 7 MHz, and 3595 cycles at 13 MHz. These high numbers of cycles acquired for a bale moving 0.03 mm provides a sample rate which is above and beyond the requirements to be a real-time sensor.

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