NON-DESTRUCTIVE QUALITY ANALYSIS OF IN-SHELL PECANS USING MICROWAVE DIELECTRIC SPECTROSCOPY

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CHAPTER I

INTRODUCTION

Statement of Problem

Over one hundred years of change and forward progress has made the pecan quality grading system what it is today, though pecan grading is still accomplished using the same basic method. Assessed by the buyer, the quality of a pecan batch is determined by the same destructive test—cracking and shelling a pre-weighed sample of the pecans and making either a qualitative (good or bad nuts) or a quantitative (edible kernel percentage based) decision about the entire batch's quality. The grower is then paid for the pecans based on a set price per pound on a qualitative basis or, from a quantitative standpoint, a price per edible kernel percentage point is given which in turn yields a price per pound for the entire batch as stated by Herrera et al. (2003).

In 1903 the National Nut Growers' Association published a loose rating system to measure the quality of pecan batches. After this decree, a load of pecans was sold based on a points system instead of being ranked as before with the merit of sheer volume as Manaster (1994) describes. With the new system in place, batches having the appropriate quality traits such as large kernel amount, good taste, light color, thin shell, and large nut size were awarded more points, and these attributes quickly became the driving factors in the pecan economy.

Today the price per point (the term “point” coming from the original grading system) is agreed upon before the pecans are graded, while the percentage of edible kernel in the pecans is taken into account after a small, random sample of the nuts is shelled and the components are weighed. For example, if the price for pecans is $4.00 per point and a shelled sample yields 54% edible kernels, the price paid for the entire batch of pecans is $2.16 per pound ($4*0.54). With qualitative or quantitative testing, the skill, precision, and personal bias of the assessment personnel compound to form concerns about the fairness of the sale.

In an effort to develop a repeatable, reliable, and simple method of testing pecan quality that has a standard measurement method and accurate results, research regarding the analysis of the dielectric properties of pecans and their correlation to quality will be conducted using a free-space microwave transmission measurement device. Strong correlations between dielectric properties and the overall quality of pecan samples from this research could lead to the development of new automated pecan grading and sorting equipment in the near future.

Objectives of Study

This study has two main objectives. The first is to build a suitable apparatus with which to measure dielectric properties of materials that greatly reduces noise in measurements, has a reliable and easily adjustable sample holder, and allows high gain to give reproducible results. Beyond this specific application, the attachment built for the existing vector network analyzer will be highly adaptable to measure dielectric properties of a wide range of materials, especially biological samples. The second objective is to investigate the dielectric properties (namely signal attenuation and signal phase shift) of four in-shell pecan cultivars with respect to certain physical parameters and to draw conclusions about the dielectric measurements' correlations with overall sample quality and moisture content. Frequencies that give good correlations with measured nut quality values from either signal attenuation or phase shift measurements will be reported, including their ability to repeatedly predict quality and moisture content.

CHAPTER II

REVIEW OF LITERATURE

A Brief History of Pecans in North America

For thousands of years, North Americans have enjoyed its kernel's rich, sweet flavor, despite its shell's tough exterior. The pecan nut is surely one "hard nut to crack," as its name almost literally means in Algonquian. According to Manaster (1994), long after this hickory-type tree's seed was found to be delicious by people worldwide, the tree was given the final name *Carya illinoinensis* by the International Botanical Congress in 1969.

As the heart of America was explored by the Spanish and French, these groups were continually shown by the natives the huge trees that grew by the banks of rivers and streams that yearly rained a crop of hard nuts upon the shores. The Native Americans traded this traditional fall and winter staple by the bushel to the newcomers for new shipments of clothing, coffee, tea, and salt in the mid 17th century, but when the great taste of fresh pecans reached urban American settlers on the east coast, demand rose sharply. As the 1800s came to a close, everyone was accepting cash for the newfound crop.

The amazing rise in pecan demand would soon outweigh the supply that could be found on the river banks. Established groves where many old trees existed were cleaned out for easy access to the nuts on the ground while young pecan trees were transplanted into new orchards. With this transformation from a gathered to a farmed crop, improved accessibility made it easier for locals to experiment with mixing the genes from different native trees together through the grafting process. The biggest and best nuts with the thinnest shells were obtained and their attributes were given to thousands of trees in several orchards. With breeding came the concept of an improved cultivar, and larger pecans with more kernel percentage than ever were finding their way to the public.

Brison (1974) states that today pecan trees can exist in several parts of the United States, with native pecan trees able to grow in the eastern two-thirds of Texas, along with the majority of Oklahoma, Louisiana, Arkansas, and Missouri. Improved cultivars have a larger growth area, including the previously listed regions and extending east to Mississippi, Alabama, Georgia, the Carolinas, and Florida. Improved crops are also grown in northern Mexico and are grown westward in New Mexico, Arizona, and parts of California.

Microwave Dielectric Spectroscopy

Many steps have recently been taken in the field of indirect material analysis using microwaves as the penetrating energy. Microwaves are non-ionizing and are generally safe compared to x-rays, while being relatively efficient and inexpensive to produce compared to new technologies such as higher frequency terahertz waves as mentioned by Yan et al. (2006). With a relatively short history, microwaves moved into the sensing scene in the 1960s but according to Nyfors and Vainikainen (1989) they were so bulky and insensitive that they were pushed aside for more than 20 years until the technology could grow. Currently, a full-range test emitter/sensor can be purchased for under $100,000 while specific frequencies can be emitted by much, much less expensive equipment, often available to the industrial sector in pre-made kits. The frequency range for microwaves lies between 300 MHz and 30 GHz, with a corresponding wavelength of about 1 m at low frequencies down to 1 cm at higher frequencies. Microwaves penetrate most materials that are not conductors and are commonly used in microwave ovens for heating foods.

Sensing equipment is available in many different configurations, including transmission and reflection sensors, resonators, and radiometry equipment. However, to get the best idea of what is inside a slab of matter, the transmission sensing technique is the most appropriate. Setup for a transmission measurement is described by Nyfors and Vainikainen (1989) and includes two antennas—one that emits the microwaves toward the sample, and another that receives that signal on the other side. The information from the receiving antenna is then compared to the emitted signal and two values are produced: signal attenuation and signal phase shift. Signal attenuation is the decrease in intensity of the wave after it passes through the sample, measured in the logarithmic scale as decibels. Signal phase shift essentially measures the lag time of the signal in degrees as it passes through the sample (Figure 2.1).

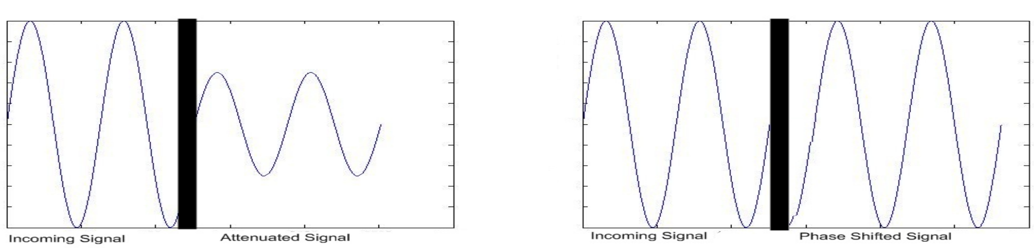

Figure 2.1: Attenuation and phase shift of a propagating wave

Interaction of Microwaves with Biological Matter

When working with microwave analysis, having an idea of the effect of matter on the electromagnetic field is extremely important. While different materials have markedly differing effects on impinging microwaves, several different standard reactions can give great assistance in predicting what will happen to the analyzing wave in different classes of materials.

A material that is good for microwave analysis is usually partially electrically conductive and is known as a dielectric material. This means that electrical signals such as microwaves will interact with the material but will not be easily transmitted in the material or completely reflected back at the emitter. Because the charges in a dielectric material are bound to the structure of the material and only slightly oscillate in the presence of an electromagnetic field, this dampens the wave and physically attenuates or holds back the signal.

Several different materials which vary the dielectric properties of a sample will be covered: water, metals, sugars, salts, oils, bulk density, and surface effects. For each of these materials, the mode of action with respect to impinging microwaves will be analyzed along with the ability of the product to store microwave energy (dielectric constant) and the ability of the product to dissipate microwave energy (dielectric loss factor). Current research work on each division will be covered along with the results found.

Water

Microwaves are extremely sensitive to quantities of water in a given biological sample, and consequently the majority of dielectric property research is based on finding the moisture contents of samples via dielectric properties. Water is a great absorber of microwaves due to its small molecular yet polar nature. The changing electric field that microwaves introduce upon water causes the molecules to spin or to vibrate quickly, creating heat deep within a sample in a short amount of time. This is why microwave ovens are so effective in heating foods with high moisture contents, such as meats, fruits, and vegetables. Relatively, water has the largest dielectric constant and loss factor of all dielectrics, as long as it is not bound too tightly to other components inside a sample.

Two types of water exist in any biological tissue—free water and bound water. Free water is not attached to anything, and is more apt to move when microwaves penetrate the sample. Free water can therefore absorb and transmit the energy from the waves more quickly than the bound water in a sample. Bound water can adhere to a surface, be frozen, or can also attach via hydrogen bonds to a sample, and while it is considered to be part of the moisture content, it has much smaller dielectric properties than those of free water because it is attached to something heavier that inhibits oscillation.

Most of the research relating to dielectric measurements with microwaves features the moisture content of the material being tested. On-line moisture content research and application has been occurring for several decades with many biological applications including apples by Martin-Esparza et al. (2006), pecans by Nelson et al. (1992), cranberries by Eren et al. (1997), and peanuts by Trabelsi and Nelson (2004). Because varying the moisture content of a sample gives the best change in dielectric properties, most research published has something included about the relationship. Due to the large moisture content range in most biological products, a chart with multiple moisture contents and the corresponding dielectric response is a very useful tool for a researcher.

Metals

Though metals do not exist in biological samples in large quantities, it is important to understand their interaction with microwaves. Metals reflect the majority of incident microwaves. This is due to the free electrons inside the conductive metal moving immediately along with the incoming wave and relaying it back toward the emitter as described by Balanis (1989). Microwaves can also cause some eddy currents inside the metals which may cause arcing between small metallic parts thus overheating the microwave emitter. Theoretically metals have almost infinite values for dielectric behavior, however metals are by definition not dielectrics.

Knowledge of the interaction of metals and microwaves is most important when designing a mount or a container in which to test samples. It is necessary to avoid the use of all metals, using plastics and Styrofoam as building materials in their place.

Sugars

Sugars are fairly sensitive to microwaves and can be of great use in correlating sweetness of a high-sugar product to a dielectric response. The hydroxyl groups on sugars in solution bind the water with hydrogen bonds, therefore restraining the molecules from movement caused by microwaves. Concentration of sugars has an upper limit, however, and the saturation point of the solution at a given temperature indicates how much the dielectric properties of the solution can be depressed. Sugars in the crystal form also have important microwave properties and are used in many cooking applications when selective heating is important as explained by Rao et al. (2005). Sugar crystals coating the outside of a food product are great absorbers of microwaves with high dielectric constants, and can cause exterior surface heating. A thin layer of sugar between layers of food can selectively heat the outside part while the inside is shielded from the microwaves. Sugars are also involved in browning foods in reaction to microwaves so that the cooked product may have a more appealing color.

Current research on the sweetness and ripeness of fruits using microwave dielectric measurements is taking place, with differing results. One research paper attempted to correlate the dielectric constant of honeydew melon tissue to the amount of total soluble solids in the tissue. Guo et al. (2007) proposed that because soluble solids are mainly sugars, they are directly related to sweetness of the melon. These attempts so far have led to unsatisfactory results in making a connection between either the dielectric constant or the loss factor and the sugar concentration of the melon, but research continues. Ripeness of other fruits such as peaches and watermelons is being investigated using microwaves, with Nelson et al. (1995) having research in peaches that gives the best results so far.

Fats and Oils

Lipids such as fats and oils have little direct impact on microwaves in biological samples, though they do have indirect effects on the availability of water. When there is sufficiently high fat content, water can be bound in the system, and much like in a sugar system it is restricted from movement caused by the incident microwaves as described earlier in Rao et al. (2005). Dielectric loss factors tend to be greater in liquid oils, while the loss factors are less in tallow fats and fats of higher molecular weight. The mainly non-polar molecules in fats do move slightly in reaction to impinging microwaves, but are less able to do so when they are much larger.

Fairly sensitive measurements can be made to gain the dielectric properties of pure fats and oils. In systems that are completely fats and oils, such as oil in deep frying vats, the dielectric properties of the fats give an idea of the quality of the mixture. Research conducted on the dielectric properties of soybean oil found that there were statistical differences between new oil of good quality and poor quality used oil by utilizing microwaves and dielectric analysis as in Chu (1991). These results could one day lead to a commercial deep fryer that measures the oil inside automatically and alerts the operator when the oil has become unfit for use. A safety feature such as this could make fast food taste better and be safer for the general public, and would be better than relying on a strict schedule for oil replacement.

Salts

Salts, because they are ionic when they are in solution, have a strong effect on the dielectric loss factor in foods. Due to their nature, salts dissolved in any polar solvent give that solution some conductivity, which means that the solution will have a very large dielectric constant and loss factor.

Researchers in Ireland have made an attempt to assess the on-line moisture and salt content of cheese traveling through a processing plant, outlined by Fagan et al. (2005). Using different recipes of cheese that contained different moisture contents and salt contents, dielectric tests were conducted and it was found that while the moisture content could be estimated by using the dielectric constant, the salt content could also be roughly ascertained between frequencies of 300 MHz and 3 GHz by using the dielectric loss factor. Though this equipment is not functional yet, it is very feasible that in the future such non-destructive techniques for salt content analysis will exist.

Bulk Density

The density of a sample being tested has some direct effect on microwaves, but like oils and fats, a more indirect effect of water content overrides most of the measurement. Having a lower bulk density means having less water and smaller dielectric constant and loss values, while higher bulk density in biological samples usually means that there is more moisture in the sample. This is especially important when working with granular materials such as nuts and seeds, because the manner in which they are packed in a measured sample could affect the outcome of the experiment.

Work done with in-shell and shelled peanuts by Trabelsi and Nelson (2004) explains that because the density of the shelled peanut kernel is greater than that of the entire in-shell peanut, the dielectric effects will be more pronounced—first because more water is found in the shelled peanut kernels and secondly because of the increased mass of the less penetrable edible portion of the peanut. The dielectric constant and loss factor both, however, have a linear correlation with the bulk density of each of the samples, even when including both the shelled and unshelled sample responses on the same plot.

Surface Effects

The surface of the matter being tested can also have an effect on impinging microwaves. Stated earlier, sugar on the outside of a material can act as a shield to the material underneath, much the same as a high moisture content layer on the outside of a material. Texture and sample shape will also have an effect on the incident microwaves. A very smooth and flat surface is preferred when analyzing a sample with microwaves because a rough surface will cause the microwaves to reflect in random patterns outside the sample and may cause interference. The shape of a sample is also important because of reflection effects between the microwave and the matter. When working with anything that is not smooth and square, Nyfors and Vainikainen (1989) state that it is good practice to work in an anechoic chamber so that reflected waves do not reverberate inside and add unwanted noise to the measurement.

Current research in quality assessment of different crops found that the rough surface of some fruits causes reflections in the incoming microwaves, thus complicating the measurement. Some measurements of grain crops such as in Guo et al. (2007)

contained multiple reflections in the sample. Mathematical corrections to account for or to reduce the complicated effect of reflections in the sample have been developed as seen in Nyfors and Vainikainen (1989), but much like the problem that they attempt to solve, these equations are very complicated.

Conclusion

Several components inside biological samples can alter the microwaves that are passed through them with water as the dominating force. Most of the other components that do not have strong dielectric properties themselves are responsible indirectly for the binding of water in the sample. Metals and ionic salts independently change microwaves, but in a biological sample, water is the main participant.

Due to the complicated nature of biological tissues under analysis by microwaves, it is quite difficult to correctly predict the change in the signal attenuation or phase shift initially. With all of these components acting together in a multi-layered structure with a complex surface texture and a complicated shape, a real example of microwave analysis is very distant from the theoretical world. Keeping these problems in mind, the research world has been challenged to find solutions by direct measurement.

Quality Assessment using Dielectric Spectroscopy

Much research is in progress concerning the dielectric properties of materials. Initially the measurements were completed for the sake of knowing the properties of a material, but now attempts are being made at analyzing a material for some aspect of quality instead of merely taking measurements. The results for quality measurement are mixed, with measurements for salt content, water content, bulk density and quality of oils correlating well with dielectric properties, but with measurements for sugar and oil content still under inspection.

Dielectric properties of uncooked chicken breasts in a recent study by Zhuang et al. (2007) have been found to be an indicator of muscle type and the chicken's required deboning time. Development of quality analysis sensors by Chen and Sun (1991) in fruits, vegetables, and grains has had limited success, mainly due to the results of analysis not being satisfactory enough to be introduced to practical industrial applications.

There continue to be many applications that are not yet found for this relatively new science in the field of non-destructive analysis, and with knowledge of the effects of materials on microwaves, many more useful ideas for those applications can be developed.

CHAPTER III

METHODOLOGY

Materials Used

Materials used for this study consisted of two types: consumable materials and non-consumable materials. The consumable materials consisted of the pecans and some holding materials for the samples. Non-consumable materials were the measuring equipment and shelling and sorting equipment involved.

Pecan samples were collected from trees located at the Cimarron Valley Research Station north of Perkins, Oklahoma. Samples of four cultivars of good quality pecans were collected immediately after harvest, along with poor quality samples of each cultivar that were separated from the good nuts by a pre-cleaner. The four cultivars selected were the ‘Giles’, ‘Kanza’, ‘Maramec’, and ‘Pawnee’ pecans due to their availability and their differing characteristics.

The Giles cultivar is mainly used as a pollinator for the other trees, but there were adequate samples available at harvest time for this research. ‘Giles’ pecans were the smallest of the four cultivars, with relatively thick shells and a small, slightly shriveled kernel inside. ‘Giles’ samples were collected immediately after harvest.

The Kanza cultivar has seen a great demand increase over the past few seasons in Oklahoma because of its bright kernels that are easily released from the fairly thick shells. The 2008 'Kanza' crop sustained much damage by pecan weevils, but there was still a good crop of quality pecans along with the large amount of completely empty nuts. The 'Kanza' pecans were harvested the day before collection and were therefore drier than the other cultivars.

Maramec and Pawnee cultivars have experienced many years of success in Oklahoma, and both cultivars have thin shells and large kernel percentages. Both of these pecan samples were collected immediately after harvest. Pecan samples were dried using a box fan placed in front of the sample in a large tray.

Measurements of the pecan samples were made using an N5230A PNA-L vector network analyzer (Agilent Technologies, Englewood, CO). The vector network analyzer (VNA) was attached to the samples via two 4 m radiofrequency cables each attached to a double-ridged waveguide horn antenna (Model 3117, ETS-Lindgren). The two horn antennas were mounted to a frame made of 3.8 cm PVC plastic tubing and were oriented toward each other and aligned, one facing upward and the other facing downward (Figure 3.1) with a distance of 70 cm between the antenna emitters.

Figure 3.1: Apparatus used for gaining transmission measurements

The frame was designed so that it could be adjusted for a wide range of operation distances and sample types. The frame was constructed of plastic so that it would not interfere with any electromagnetic waves. In addition, the frame was built to hold a microwave-absorbing box made from four foam sheets of C-RAM LF-79 (Cuming Microwave, Avon, MA) high-loss material to shield the sample from incoming noise as well as to greatly decrease the amount of microwave reflections in the sample measurement area. The box was fastened at the seams with Velcro strips and hinges so that a door was made that could be opened and closed. The apparatus shown in Figure 3.1 has the door in the open position. A sample shelf of Styrofoam was mounted inside the microwave-absorbing box, also with Velcro, and a small Styrofoam sample container was made to be placed between the antennas to hold the sample while it was analyzed.

Additional materials were also used to shell and to measure the pecan samples once they had been measured under microwave fields. The volume of the in-shell pecans was measured using a digital caliper with 0.001 cm sensitivity. A York Nut Sheller (Texan Nut Shellers, San Angelo, TX) was then used to hand shell each pecan into a #18 grain sifting pan which removed the dust from the shell. A laboratory scale sensitive to 0.01 g was used to find the mass of each sample and each constituent part, while several metal trays, labels, and plastic freezer bags of different sizes were employed to keep the samples organized and sealed. Kernel samples were ground in a Waring laboratory blender with both large and small cup attachments and were sized using a #10 sieve with a bottom pan. Samples were also dried in a forced-air oven ranging in temperature from 90° to 105° C.

Measured Values

Measured values were obtained from 71 in-shell samples of four cultivars of new-crop pecans, varying in moisture content and quality. Sample sizes ranged from 20 to 28 nuts per sample. Values logged for each sample are:

1. Signal attenuation through sample (dB)
2. Signal phase shift through sample (degrees)
3. Total in-shell mass of sample (g)
4. Total volume of nuts in sample (ml)
5. Bulk density of sample (g/ml)
6. Number of nuts per kg sample
7. Percent kernel fill (kernel volume/entire nut volume)
8. Edible kernel mass (g)
9. Shell mass (g)
10. Packing material mass (g)
11. Non-edible kernel mass (g)
12. Pecan weevil mass (g)
13. Total non-edible nut mass (includes masses of shell, packing material, non-edible kernel, and pecan weevil larvae) (g)
14. Total kernel mass (includes edible and non-edible kernel mass) (g)
15. Total non-kernel mass (includes masses of shell, packing material, and pecan weevil larvae) (g)
16. Non-edible portion water content (g)
17. Edible kernel portion water content (g)

18. Total sample water content (g)

Values 1-6 were non-destructive tests measured before shelling and the remaining values were destructive measurements made after the non-destructive tests were completed.

Procedure

Collection

As the 2008 pecan crop was harvested from late October to mid November, about 5 kg each of four pecan cultivars were collected from Oklahoma State University's Cimarron Valley Research Station north of Perkins, OK. The cultivars used were 'Kanza', 'Pawnee', 'Maramec', and 'Giles'. Pawnee, Maramec, and Giles cultivars were collected the same day as harvest and required drying to prevent spoilage. The Kanza cultivar had been drying on the research station's dryers for one day before collection. Sample drying will be further discussed in the handling section. These cultivars were of varying quality, giving a wide range of physical properties as a whole and making analysis more thorough.

A portion of each cultivar's sample was taken from the refuse pile next to the research station's field cleaner. These pecans were lighter than the best quality pecans, and were called "pops" because of the way they popped upward and out of the air flume that the nuts were subjected to, while heavier pecans fell down through the flowing air. These pops were assumed to have weevil damage or other disorders, making them unfit for consumption. Complete weevil larvae damage will be defined as a pecan with a small opening where the weevil larva, having eaten the edible kernel inside the nut, has escaped. This completely damaged sample was rated to have no edible kernel due to the damage caused by the weevil larvae.

Handling

Samples of pecans collected in the field had a moisture content of 10 to 15% and required drying to about 5% total moisture content to obtain the best shelf-life. Before drying, one sample of 75 good quality pecans was collected from each cultivar and labeled as “high moisture content.” Another good quality sample was collected after the pecans had been spread on flat trays in front of a box fan set to “high” in the Biosystems Lab for 48 hours and were labeled as “medium moisture content,” and the third sample was collected after at least five days in front of the fan to ensure adequate drying. This final sample was labeled “normal moisture content” and will be almost exactly the same as the finished product of most pecan growers.

The new-crop samples of all moisture contents along with the “pops” samples, dried to normal moisture contents, were kept in a 4° C cooler in closed freezer bags to minimize moisture loss until analysis could take place. The samples were stored in the cooler for one to three months. Storage containers prevented significant moisture loss in samples for this time period (M. Smith, personal communication, 12 September 2008).

Pecan samples were removed from the cooler 24 hours in advance of tests to allow acclimation to the ambient temperature while sealed in the freezer bag. Thus temperature effects were eliminated as a variable in this study because the sample will be the same temperature of the calibrated equipment. This also prevented outside moisture from condensing on the cold pecans to artificially raise their moisture content.

Sample Preparation

Once the samples reached ambient temperature, groups of pecans adequate to cover the 18 cm by 12 cm sample container with one layer were randomly selected by hand from the sample (Figure 3.2).

Figure 3.2: Sample analysis tray containing ‘Giles’ pecans

For the smaller ‘Kanza’ and ‘Giles’ pecans, 28 nuts were required to cover the tray’s surface. Only 20 of the large ‘Maramec’ pecans were required per sample while 24 nuts per sample were required of the medium-sized ‘Pawnee’. Twelve of the low moisture content samples of each cultivar were prepared with the appropriate number of nuts, placed in metal storage containers, and then sealed in freezer bags to guard against moisture loss (Figure 3.3).

Figure 3.3: In-shell pecan samples waiting to be analyzed

For the low moisture pecans, five of the samples were selected to have a high quality and were composed entirely of good pecans while the remaining seven samples were chosen to have varying qualities by mixing different ratios of the good pecans with the "pops" rejected by the field cleaner. The lowest quality sample would be, if possible, all non-edible pecans, and quality would increase toward the range of the high quality pecans.

In the case of the medium and high moisture content pecans, all nuts selected were assumed to be of good quality when they were added to the samples. No inferior quality pecans were purposefully laced into the samples to create a quality gradient.

A chart outlining the organization of the samples is included in Table 3.1.

Table 3.1: Organization of and number of pecan samples analyzed including low, medium, and high moisture contents and quality range combinations separated by cultivar

	Varied Quality	Good Quality			
Cultivar	Low MC	Low MC	Medium MC	High MC	Total
Giles	7	5	4	3	19
Kanza	7	5	3	0	15
Maramec	7	5	4	3	19
Pawnee	7	5	3	3	18
				Grand Total	71

Dielectric Measurement

The VNA must be allowed at least 90 minutes to warm up before measurements are made so that the machine can equilibrate to its surroundings and so that all factory specifications can be accurately applied to the equipment. Samples were prepared while the VNA was allowed to warm up. Calibration followed the procedures listed in the Network Analyzer help manual by Agilent (2008). Calibration used was the short, open, load, and thru measurements, or SOLT calibration. Responses were measured when each of the two ports were shorted, then left open, then attached to the load, and then responses were measured through the antenna system. An appropriate SOLT calibration gives signal attenuation and phase shift responses as values close to zero for the selected frequency range and equipment.

After the VNA was calibrated, the empty container was placed between the antennas. Three measurements of the signal attenuation and phase shift for the empty tray were recorded for the fine calibration measurement. Each measurement consisted of frequency readings ranging from 10 MHz to 2.5 GHz with the average of 100 successive sub-measurements giving the result of each measurement. The data sets had 101 measurement points linearly spaced between the two frequencies and were saved and labeled accordingly. The mean of these three measurements was the initial reading for the change in both the signal attenuation and phase shift caused by the sample. With the same measurement settings, the removable tray was filled with the pecan sample and the pecans were lightly agitated so that they were all on their sides, tightly packed within the sample space. The tray was then returned to the previous measurement position between the antennas. Seven measurements were taken of the pecans within at least ten minutes of starting the empty tray calibration measurements to ensure that the time drift of the VNA's measurements was not a factor. Most of the sample repetitions were completed in five to six minutes.

The previous steps, the three measurements of the empty tray and the seven measurements of the sample, were repeated five times for each sample. Between repetitions, the sample was removed from the sample chamber and the pecans in the tray were dumped into an empty container and repositioned so that their locations and orientations were randomly changed. This scrambling ensured that the position of the individual nuts did not have an impact on the final result and that the measurements were not spatially dependent. When needed for the next repetition, the pecans were poured into the sample holder to be measured once again as stated above.

Additional Measurements

After the pecans had been measured by the VNA, other values needed to be gained from the sample. The mass of the sample was determined and recorded using the electronic balance. Each individual pecan in the sample was measured for length (l) and major diameter (D_m) by the electronic calipers in order to find the volume (V) occupied by the sample, using the equation for volume of a prolate spheroid as a model for a single nut's volume. (Equation 3.1)

$$V = \frac{\pi D_m^2 l}{6} \tag{3.1}$$

The sample was then carefully cracked and separated into five classifications. Nuts were cracked with a hand cracker that snips the pecans apart instead of the more violent impulse cracking method that would decrease the component recovery rate. The classifications are as follows:

1. Edible kernel, which constitutes pecan kernels or broken pieces that are not classified by the USDA (1969) as 'damaged' or 'seriously damaged'.
2. Shell, which makes up the rigid outside of the pecan and houses the kernel. The shell will be made up of the very rigid parts of the pecan and those parts solidly attached to it.
3. Packing material, which is the soft and gritty internal material that surrounds the kernel. Packing material can be found in the grooves along the back of the pecan kernel but is predominantly found between the kernels. The resultant dust from cracking, separated from the shell with a #18 sieve after shelling, will also be classified in this category.
4. Non-edible kernel, which is made up of any kernels that are classified by the USDA (1969) as 'damaged' or 'seriously damaged'. Defects include "stink bug damage, embryo rot, vivipary rot, 50-percent fuzz, 50-percent wafers, black or gray mold, green high-moisture discoloration, weevil damage, or oil-soaked kernels" as described in Pecan South by McEachern (1992).

5. Pecan weevil larvae or animal life, best described by a weevil larva found inside the pecan, either living or dead.

Each of these classifications were weighed and recorded in a file containing all of the measured values for each sample.

The edible portion of the pecan along with the non-edible portion, once they had been weighed, were then measured by the VNA again individually to find their separate dielectric properties. The procedure was conducted as stated for the in-shell pecans, except that the kernels were used in one batch and the non-edible kernels, shell, packing material, and weevil larvae were measured in the other batch.

After measurement, the non-edible portions of the samples were weighed, placed into an oven at 90° C for at least 24 hours, and then immediately weighed again to measure the moisture content of the portion. This method of determining the non-edible moisture content was adapted from the ASABE (2007) standard for determining the moisture content of whole peanut pods because a standard for determining the moisture content of pecan shells does not exist. It was estimated from the standard's chart that drying the non-edible portion of the pecans at 90° C for 24 hours was adequate to determine their moisture content. The edible kernels were also analyzed for moisture content using the standard by Santerre (1994) as outlined in the book, Pecan Technology. The kernel drying standard prescribes drying kernel particles (less than 2 mm) at 105° C until constant mass is reached. This time period was also determined to be approximately 24 hours.

Data Analysis

Stable Frequencies

The first step in analyzing the data was to investigate which frequencies gave stable enough results to be reliable in application. This was done by calculating the 90% confidence interval of each signal attenuation and phase measurement made and dividing that value by the absolute measured value of signal attenuation or phase shift. The resultant value is representative of the theoretical number of statistically significant separate measurements that could be resolved between an empty measurement tray and the measured value with a 90% confidence rate. If the value of theoretical resolution (R_t) is large at a certain frequency, in can be assumed that the combination of a large signal reaction and a small 90% confidence interval results in a frequency that yields repeatable results. Using the low moisture content data from in-shell measurements of the four cultivars of pecans, a grand mean value for R_t was calculated for both signal attenuation and phase shift measurements. A threshold value for R_t was set at 10 to allow for resolution while making measurements. Any frequencies having R_t values above the threshold were included in the results, while remaining frequencies were considered non-responsive and were disregarded.

Correlation Analysis

Of the frequencies selected, signal attenuation and phase shift measurements at each frequency were plotted against each physically measured value, and those frequencies and measured values with the highest coefficient of determination (r^2) value were recorded.

The first analysis held the water content of the pecans constant in the low moisture content range and varied only the quality of the pecans (Table 3.2). Once the r^2 values were calculated for each cultivar, the mean of the four samples was calculated to determine which frequency and indicator of quality best combined to make a quality predictor. The two best frequencies and the two best overall quality indicators with the signal attenuation measurements and the phase shift measurements are presented in Chapter IV.

Table 3.2: Organization of and number of low moisture content pecan samples in quality-variant correlation analysis separated by cultivar

	Low Moisture Content		
Cultivar	Varied Quality	Good Quality	Total
Giles	7	5	12
Kanza	7	5	12
Maramec	7	5	12
Pawnee	7	5	12
		Grand Total	48

The second analysis varies the moisture content in each of the samples while leaving the quality of the samples at a constant high quality. (Table 3.3) Similarly, the two best frequencies and the two best quality indicators will be presented with respect to the moisture content varying in the pecan samples to gain an understanding of what the best predictors of moisture content are in pecans.

Table 3.3: Organization of and number of good quality pecan samples in moisture content-variant correlation analysis separated by cultivar

	Good Quality			
Cultivar	Low MC	Medium MC	High MC	Total
Giles	5	4	3	12
Kanza	5	3	0	8
Maramec	5	4	3	12
Pawnee	5	3	3	11
			Grand Total	43

CHAPTER IV

FINDINGS

Stable Frequencies

Mean values of theoretical resolution for the entire spectrum are plotted by frequency in Figures 4.1 and 4.2.

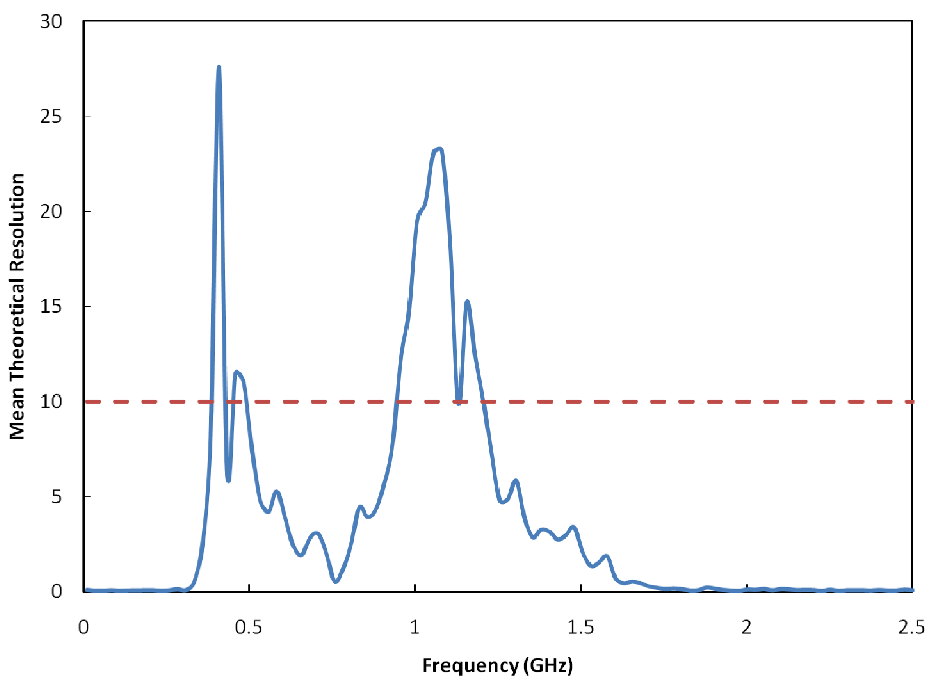

Figure 4.1: Mean theoretical resolution vs. frequency for signal attenuation with the threshold resolution value set at 10

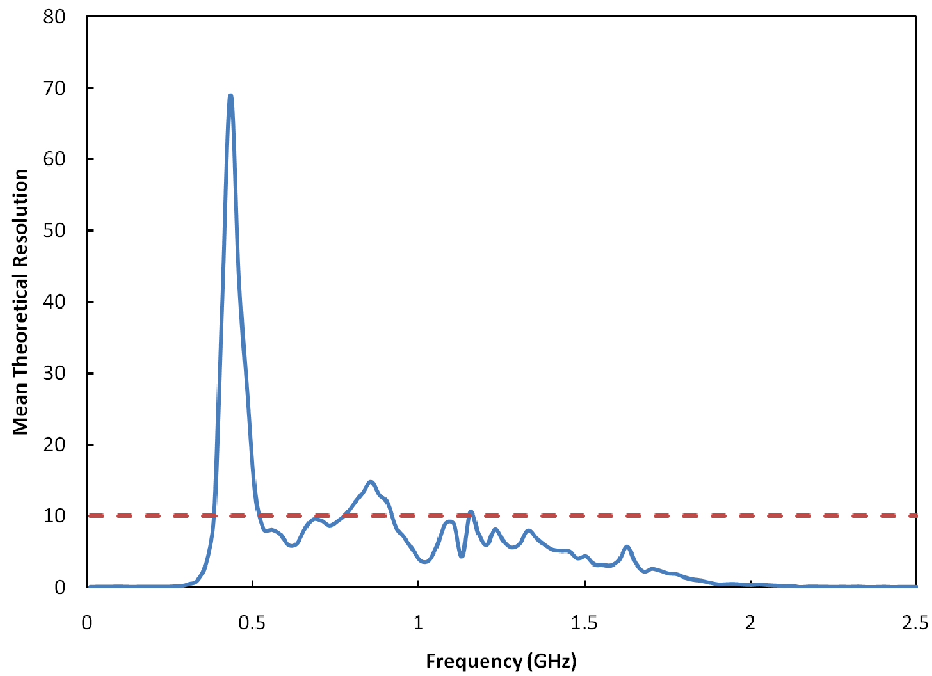

Figure 4.2: Mean theoretical resolution vs. frequency for signal phase shift with the threshold resolution value set at 10

Thirteen frequencies out of the 101 measured yielded signal attenuation measurements that could be used as a quality measurement statistic. One peak occurring at 408.4 MHz yielded the highest value of R_t at 27.6, but the frequency bandwidth is not very wide for that value (Figure 4.1). The important place to look in the signal attenuation measurement set is in the second large peak, which occured from approximately 960 MHz to 1.2 GHz. Because of the larger bandwidth, a less expensive emitter transmitting a relatively wide range of microwaves could be used in this analysis if this frequency range correlates well with quality. For the phase shift measurements, twelve frequencies qualified as possible indicators of nut quality. It is important to note the extremely high mean R_t value at 433 MHz with a value of 68.9. This was the highest measured R_t value for either signal attenuation or phase shift and this frequency or either frequency measured on either side of it would be the best candidates for measurements from either data set. All qualifying frequencies and their R_t values are listed in Tables

4.1 and 4.2. These results reduce the number of frequencies to 25 from the original 202 candidates tested. All other frequencies will be ignored, and these that have been found will be correlated to the physical parameters collected from the pecan samples.

Table 4.1: Qualifying frequencies for signal attenuation and corresponding R_t values for low moisture content samples of 'Maramec', 'Pawnee', 'Kanza', and 'Giles' pecans

Freq (GHz)	Maramec	Pawnee	Kanza	Giles	Mean
0.408	28.93	29.70	29.22	22.58	27.61
0.458	12.21	9.87	13.19	10.62	11.47
0.483	11.42	11.79	11.24	9.45	10.98
0.956	9.37	11.27	18.62	9.45	12.18
0.981	13.46	13.54	20.76	11.20	14.74
1.006	19.06	19.12	25.33	14.46	19.49
1.031	18.58	19.73	26.20	17.39	20.48
1.056	21.95	22.37	27.01	21.15	23.12
1.081	22.45	22.16	24.04	24.17	23.21
1.106	13.93	17.03	19.85	21.74	18.14
1.155	13.61	15.78	16.72	14.82	15.23
1.180	11.22	12.53	13.83	12.14	12.43
1.205	8.71	10.08	11.19	10.24	10.05

Table 4.2: Qualifying frequencies for signal phase shift and corresponding R_t values for low moisture content samples of 'Maramec', 'Pawnee', 'Kanza', and 'Giles' pecans

Freq (GHz)	Maramec	Pawnee	Kanza	Giles	Mean
0.408	43.06	45.05	48.32	25.43	40.46
0.433	79.12	82.13	74.77	39.73	68.94
0.458	48.56	43.80	52.53	29.47	43.59
0.483	28.61	27.46	33.54	20.78	27.59
0.508	12.98	14.37	15.03	9.49	12.97
0.782	10.86	11.54	11.99	6.70	10.27
0.807	12.27	13.19	14.63	7.15	11.81
0.832	13.57	13.91	17.39	8.09	13.24
0.857	14.52	17.16	18.47	8.99	14.79
0.882	11.71	14.33	16.20	9.50	12.93
0.906	7.74	18.96	11.42	9.18	11.82
1.155	9.34	13.81	11.45	7.61	10.55

Pecan Quality Prediction

Physical quality values for each pecan sample were correlated with signal attenuation and signal phase shift at their respective significant frequencies. Linear coefficients of determination (r^2) with probability tests quantified the correlation between the measurements and the physical quality variables. A threshold r^2 value of 80% was used to select only strong correlations among variables. The threshold was chosen based on visual analysis of charts generated with different r^2 values. All correlations with pecan quality were found to have linear relationships.

Signal Attenuation Correlations

As shown in Table 4.3, the two frequencies giving the highest correlation with quality were 408.4 MHz and 1.0309 GHz and the two best quality characteristics were the edible kernel mass and the total kernel mass found in the pecan. Though the characteristic of the entire in-shell sample's mass correlated better than the other two quality characteristics, it was decided that because the total in-shell mass could be determined without the use of this equipment, those results need not be included.

Table 4.3: Coefficient of determination values at significant frequencies for different pecan characteristics with respect to signal attenuation measurements

Frequency (GHz)	0.4084	0.9562	0.9811	1.006	1.0309
Total Inshell Mass	95.34%	87.79%	88.16%	91.29%	91.75%
Total Density	90.82%	83.21%	84.35%	87.90%	89.10%
Nuts/Kg	93.23%	82.86%	82.75%	86.40%	87.33%
Percent Fill	90.44%	82.85%	83.96%	87.79%	88.70%
Edible Kernel Mass	92.42%	86.00%	87.03%	90.03%	89.44%
Total Kernel Mass	93.72%	86.19%	86.80%	90.35%	90.86%
Kernel Water Mass	92.53%	85.02%	86.36%	89.10%	88.41%
Mean	92.64%	84.84%	85.63%	88.98%	89.37%
Frequency (GHz)	1.0558	1.0807	1.1056	1.1554	1.1803
Total Inshell Mass	90.32%	90.07%	85.71%	90.03%	88.04%
Total Density	88.11%	87.27%	83.00%	86.89%	84.96%
Nuts/Kg	85.28%	85.74%	81.63%	88.57%	85.38%
Percent Fill	87.44%	87.01%	82.73%	86.50%	84.58%
Edible Kernel Mass	89.07%	87.40%	82.56%	85.87%	85.53%
Total Kernel Mass	89.39%	89.18%	84.79%	88.97%	87.14%
Kernel Water Mass	88.21%	86.37%	80.62%	85.74%	86.01%
Mean	88.26%	87.58%	83.00%	87.51%	85.95%

After the frequencies and quality characteristics were determined, individual plots of each of the four combinations were plotted on the same chart, separated by pecan cultivar.

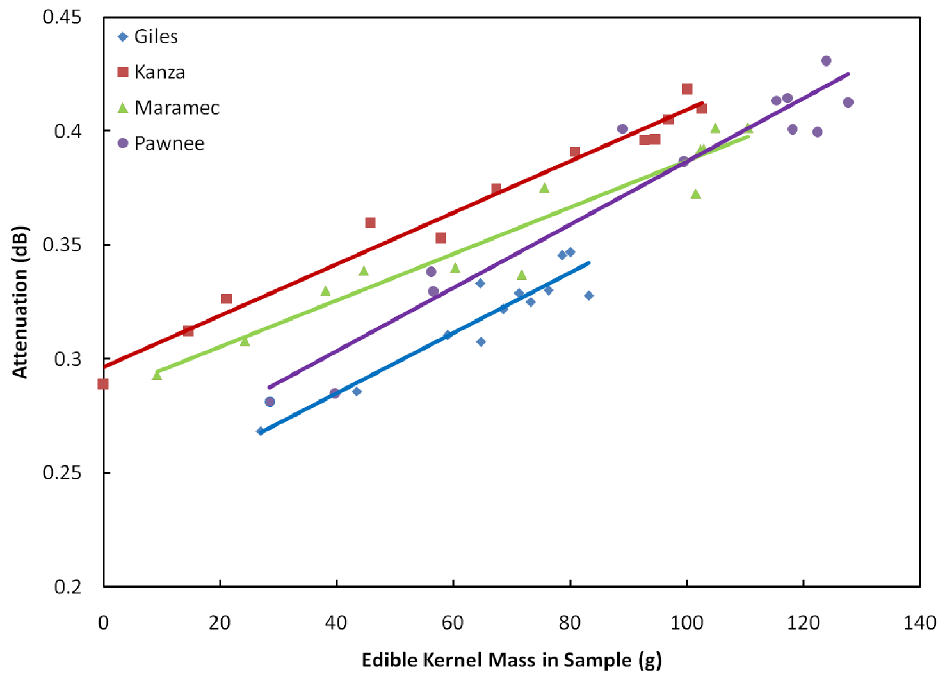

Figure 4.3: Edible kernel mass vs. signal attenuation at 408 MHz

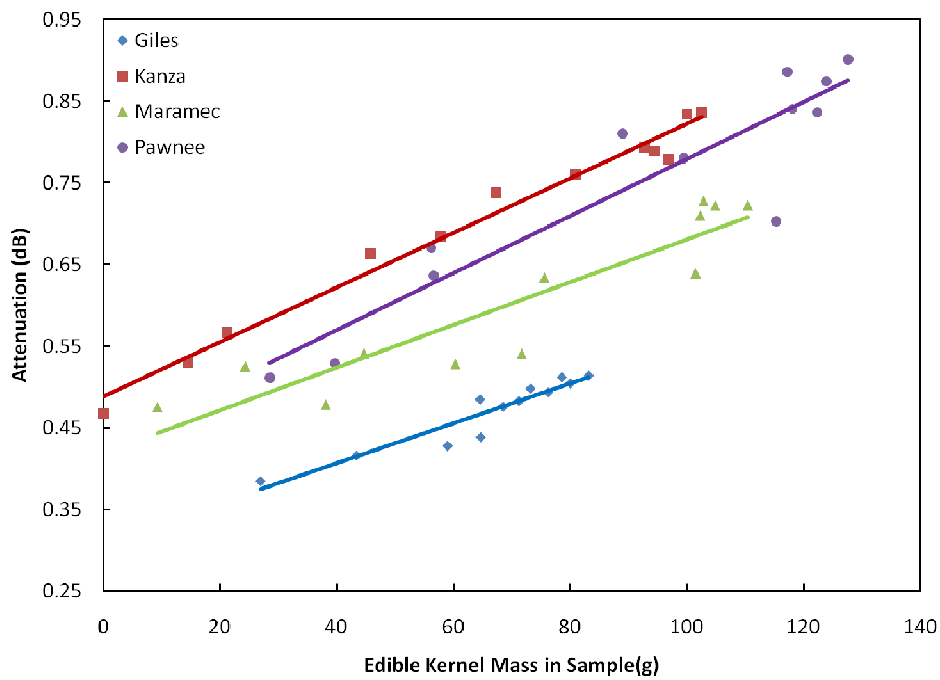

Figure 4.4: Edible kernel mass vs. signal attenuation at 1.03 GHz

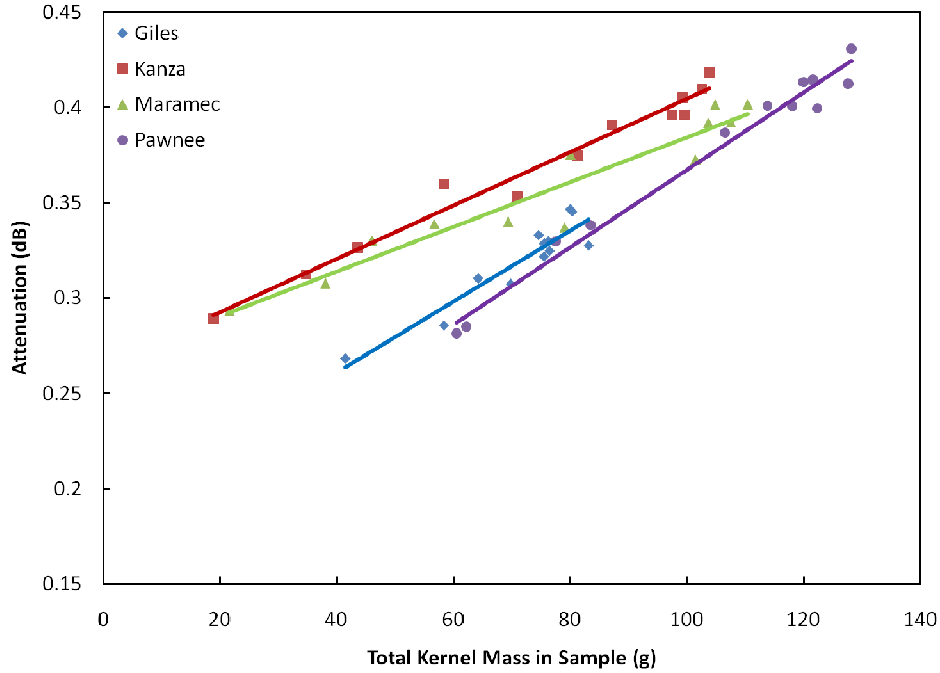

Figure 4.5: Total kernel mass vs. signal attenuation at 408 MHz

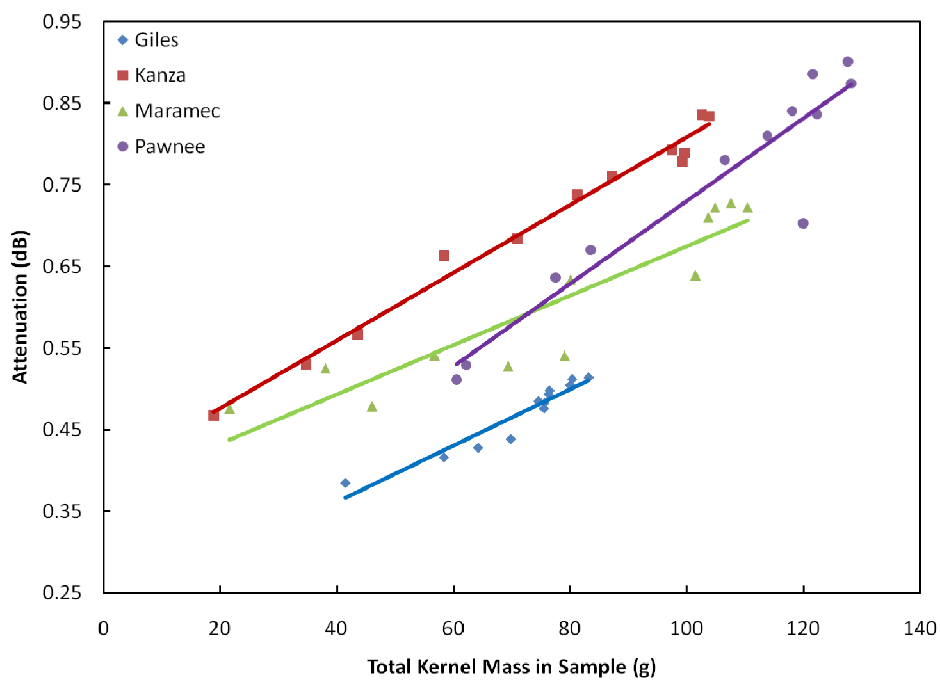

Figure 4.6: Total kernel mass vs. signal attenuation at 1.03 GHz

Table 4.4: Regression line statistics for each pecan cultivar relating signal attenuation measurements to edible kernel mass and total kernel mass at 408 MHz and 1.03 GHz

		Giles			Kanza		
Correlation	Freq (GHz)	Slope (dB/g)	Intercept (dB)	Coeff. of Det.	Slope (dB/g)	Intercept (dB)	Coeff. of Det.
Edible Kernel	0.408	0.0013	0.2320	86.96%	0.0011	0.2965	97.49%
Edible Kernel	1.03	0.0024	0.3088	89.23%	0.0033	0.4882	98.14%
Total Kernel	0.408	0.0019	0.1870	87.78%	0.0014	0.2646	97.37%
Total Kernel	1.03	0.0034	0.2247	90.90%	0.0041	0.3933	98.56%

		Maramec			Pawnee		
Correlation	Freq (GHz)	Slope (dB/g)	Intercept (dB)	Coeff. of Det.	Slope (dB/g)	Intercept (dB)	Coeff. of Det.
Edible Kernel	0.408	0.0010	0.2849	92.50%	0.0014	0.2479	92.73%
Edible Kernel	1.03	0.0026	0.4195	84.64%	0.0035	0.4304	85.77%
Total Kernel	0.408	0.0012	0.2671	91.71%	0.0020	0.1638	98.00%
Total Kernel	1.03	0.0030	0.3728	84.68%	0.0051	0.2231	89.30%

There is a strong correlation between both the total kernel mass and the edible kernel mass and signal attenuation. There is little difference between the r^2 values of the edible kernel and the total kernel correlations, except in the Pawnee cultivar, where the total kernel content correlated better than the edible kernel content at both frequencies. This is mostly due to the green high moisture discoloration in several of the kernels in the samples, disqualifying them from being edible, but still allowing them to be counted in the total kernel mass. Non-edible kernels in the other three cultivars were either shriveled wafers or were damaged by weevil larvae. In either case, these defective kernels had little mass and little water content to attenuate the impinging microwaves. Over the entire data set, non-edible kernel mass was not correlated with the signal attenuation measurements, most likely because of its small mass in relation to the sample masses. The highest r^2 values came from the Kanza cultivar, and this may be due to a combination of the well-developed kernel with a large airspace between the kernel and the shell. The Giles cultivar also had a large airspace, but its kernels were mainly shriveled and had less mass.

From inspection, if cutoff values for the signal attenuation measurements are placed between the pecans deemed as good quality and those that varied in quality, it was found that the highest cutoff value would be the Pawnee cultivar, followed by Kanza, Maramec, and then Giles. The order is the same for both frequencies and for both total kernel mass and edible kernel mass. Reasons for this difference in cutoff value and intercept value for each cultivar could stem from either the bulk density of the kernels or the density of the entire pecan sample. The density of the pecan kernels was high for 'Kanza', 'Pawnee', and 'Maramec' pecans, while it was lower for the less developed 'Giles' kernels. This can partially explain the difference between the 'Giles' pecans and the remainder of the samples, but fails to sort out the remaining differences between cultivars.

Signal Phase Shift Correlations

Table 4.5 shows that the two frequencies giving the highest correlation with quality were 433.3 MHz and 458.2 MHz and the two best quality characteristics were edible kernel mass and total kernel mass found in the pecan. Once again, though the characteristic of total in-shell mass did correlate better than the other two quality characteristics, it was decided that because the total in-shell mass could be determined without the use of this equipment, those results need not be included.

Table 4.5: Coefficient of determination values at significant frequencies for different pecan characteristics with respect to signal phase shift measurements

Frequency (GHz)	0.4084	0.4333	0.4582	0.508
Total Inshell Mass	87.48%	91.58%	92.63%	85.51%
Total Density	82.32%	86.50%	87.02%	82.62%
Nuts/Kg	85.11%	89.47%	89.88%	83.29%
Percent Fill	82.16%	86.77%	86.77%	83.30%
Edible Kernel Mass	84.75%	88.22%	89.39%	82.94%
Kernel Mass	85.63%	90.23%	90.75%	85.46%
Kernel Water Mass	84.41%	87.69%	89.38%	82.50%
Mean	84.55%	88.64%	89.40%	83.66%

The four individual combinations of frequencies and quality characteristics were plotted against each other, separating the data by cultivar.

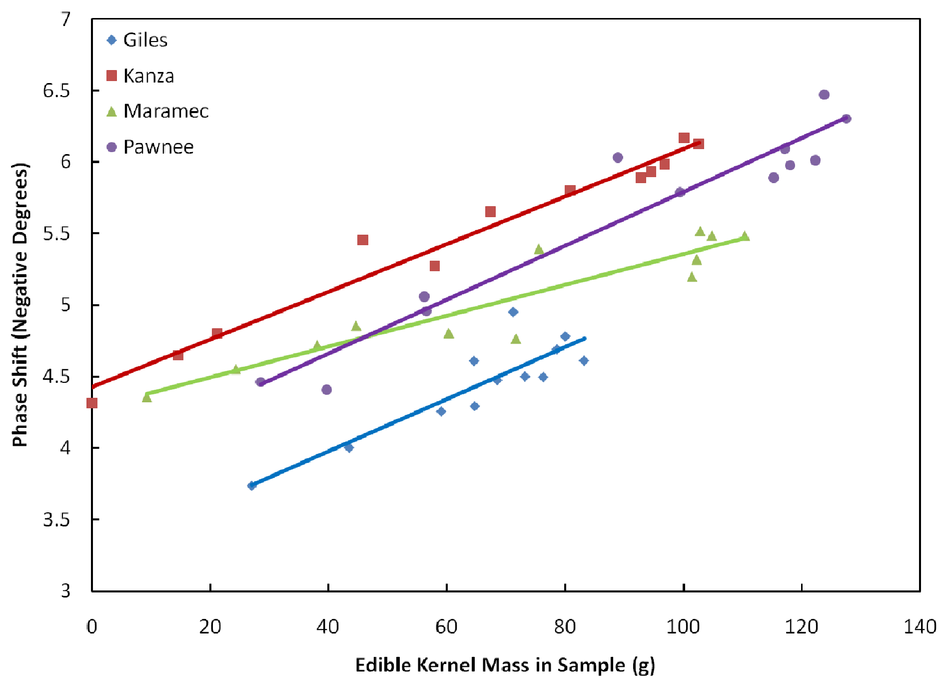

Figure 4.7: Edible kernel mass vs. signal phase shift at 433 MHz

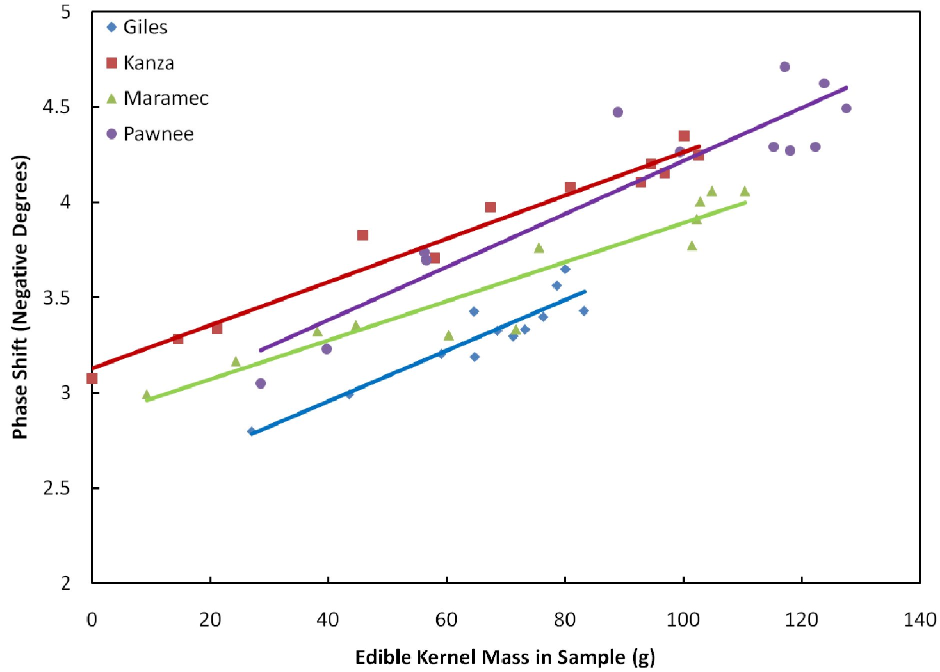

Figure 4.8: Edible kernel mass vs. signal phase shift at 458 MHz

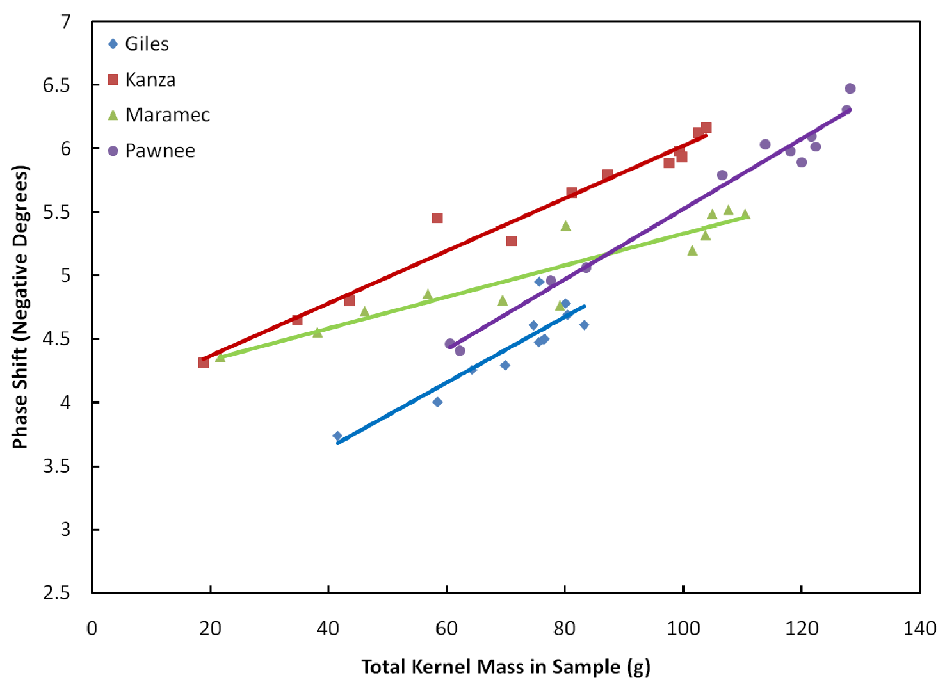

Figure 4.9: Total kernel mass vs. signal phase shift at 433 MHz

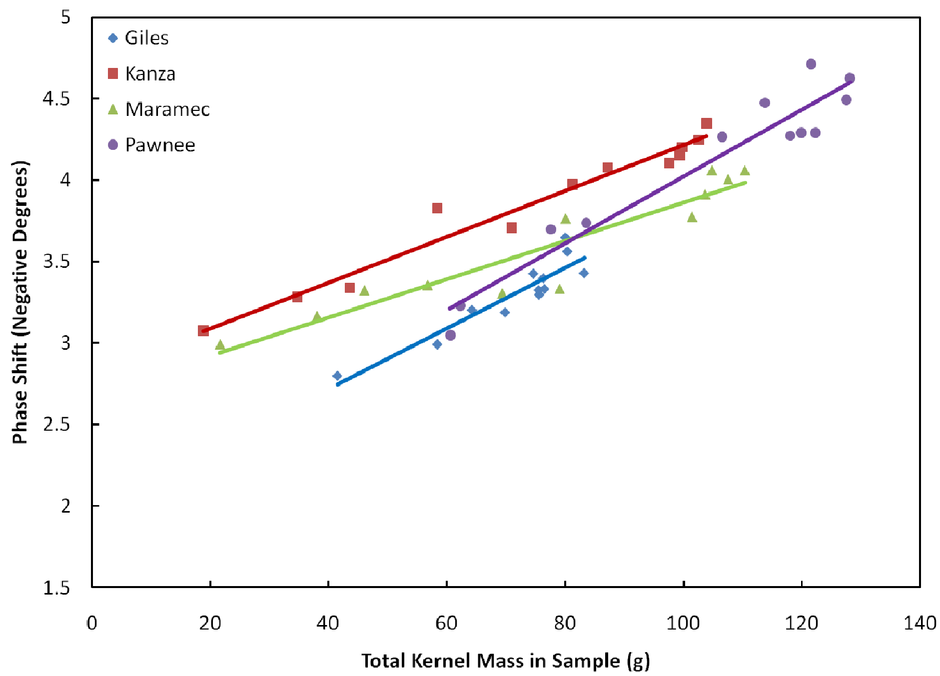

Figure 4.10: Total kernel mass vs. signal phase shift at 458 MHz

Table 4.6: Regression line statistics for each pecan cultivar relating signal phase shift measurements to edible kernel mass and total kernel mass at 433 MHz and 458 MHz

		Giles			Kanza		
Correlation	Freq (GHz)	Slope (deg/g)	Intercept (deg)	Coeff. of Det.	Slope (deg/g)	Intercept (deg)	Coeff. of Det.
Edible Kernel	0.433	-0.0182	-3.2527	77.65%	-0.0167	-4.4262	96.93%
Edible Kernel	0.458	-0.0133	-2.4257	85.71%	-0.0114	-3.1282	96.42%
Total Kernel	0.433	-0.0258	-2.6087	80.59%	-0.0207	-3.9562	96.81%
Total Kernel	0.458	-0.0185	-1.9793	85.80%	-0.0141	-2.8082	96.27%

		Maramec			Pawnee		
Correlation	Freq (GHz)	Slope (deg/g)	Intercept (deg)	Coeff. of Det.	Slope (deg/g)	Intercept (deg)	Coeff. of Det.
Edible Kernel	0.433	-0.0108	-4.2779	85.99%	-0.0188	-3.9081	92.31%
Edible Kernel	0.458	-0.0103	-2.8653	89.23%	-0.0139	-2.8285	86.22%
Total Kernel	0.433	-0.0124	-4.0874	85.59%	-0.0276	-2.7625	97.92%
Total Kernel	0.458	-0.0117	-2.6884	88.03%	-0.0206	-1.9661	92.89%

These results for the signal phase shift in the samples are similar to the signal attenuation measurements. It appears that there is strong relationship between the phase shift of the signal and both the quantity of edible kernel and the total quantity of kernel in the pecans. Once again, little difference is found between the r^2 values for edible kernel mass and total kernel mass except in the Pawnee cultivar data. This is likely due to the same reasons as stated in the signal attenuation results. The Kanza cultivar also has the same result as in the signal attenuation results, likely for the same reason as mentioned before.

Once again, if cutoff values for the signal phase shift are placed between the pecans deemed as good quality and those that varied in quality, it is found that the highest cutoff value would be the Pawnee cultivar, followed by Kanza, Maramec, and then Giles. The order is the same for both frequencies, for both total kernel mass and edible kernel mass, and for both signal attenuation and phase shift.

Pecan Moisture Content Prediction

In addition to the relationship with quality, correlations between signal changes and the moisture contents of the samples were also calculated. Three different moisture contents were measured—moisture in the non-edible portion, the edible portion (or edible kernel), and the total moisture content in the sample. The same frequencies from the quality analysis section were used, but the data followed more of an exponential curve than a linear correlation from the previous section. Also, instead of separating the samples by cultivar, all cultivars were plotted on the same data curve in each chart. Table 4.7 shows the correlation results and coefficients for each chart.

Signal Attenuation Correlations

The two frequencies used in this section are 408 MHz and 1.03 GHz and they are compared with the mass of water found in the edible portion of the pecan samples. The mass of water found in the sample's non-edible portion and the total sample mass of water did fit the curve, but the kernel water mass fit much more cleanly than either of the other two variables. This is most likely due to the way in which the water was bound inside the kernels. Because the water was bound tightly in the shells, it was less reactive to the changing electromagnetic wave. The kernel's water molecules are bound less tightly and thus gave a better result with respect to moisture content.

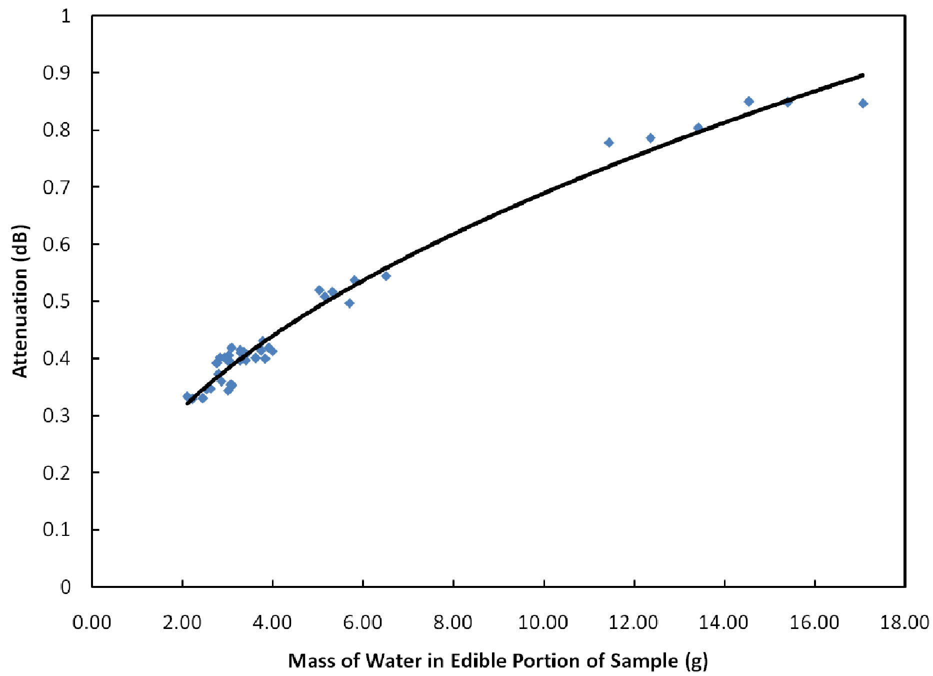

Figure 4.11: Edible kernel water mass vs. signal attenuation at 408 MHz

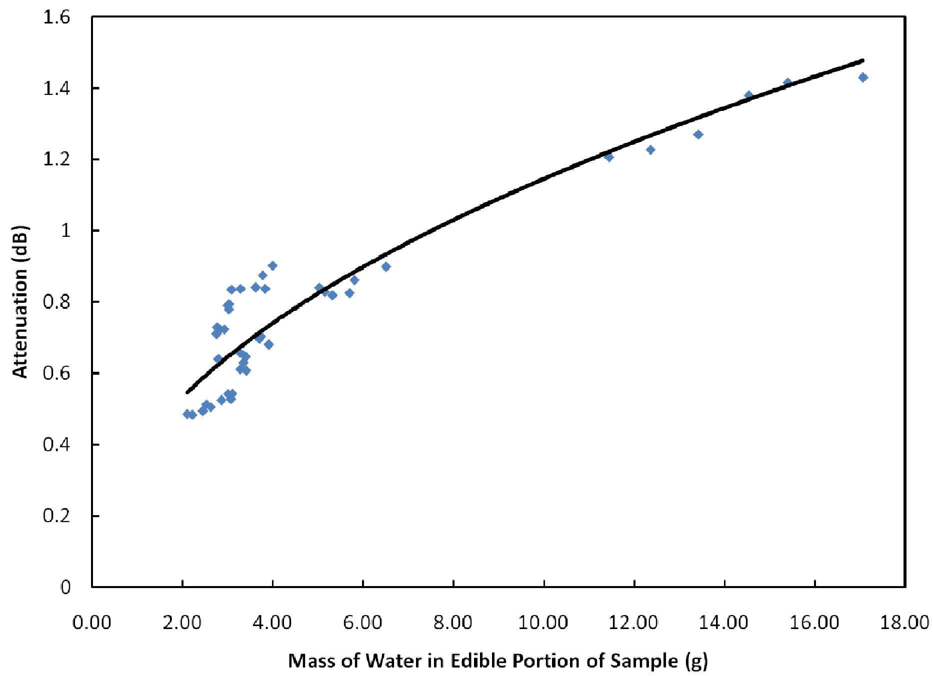

Figure 4.12: Edible kernel water mass vs. signal attenuation at 1.03 GHz

Signal Phase Shift Correlations

To evaluate the correlation between the signal phase shift and the edible portion's water content, the same two frequencies that predicted edible kernel mass were used—433 MHz and 458 MHz. Both of these frequencies fit a curve cleanly, with 433 MHz fitting slightly better than the higher frequency. Once again, the way in which the water is bound in the kernel makes it easy to see a trend in the edible portion's moisture content while there is no clear trend in the non-edible moisture content or total moisture content (data not shown).

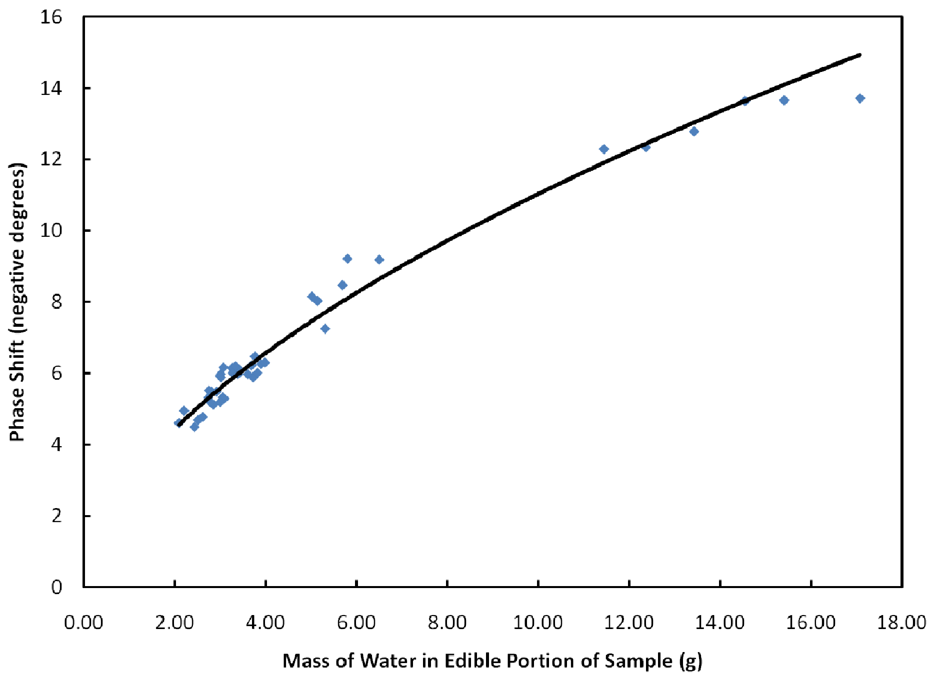

Figure 4.13: Edible kernel water vs. signal phase shift at 433 MHz

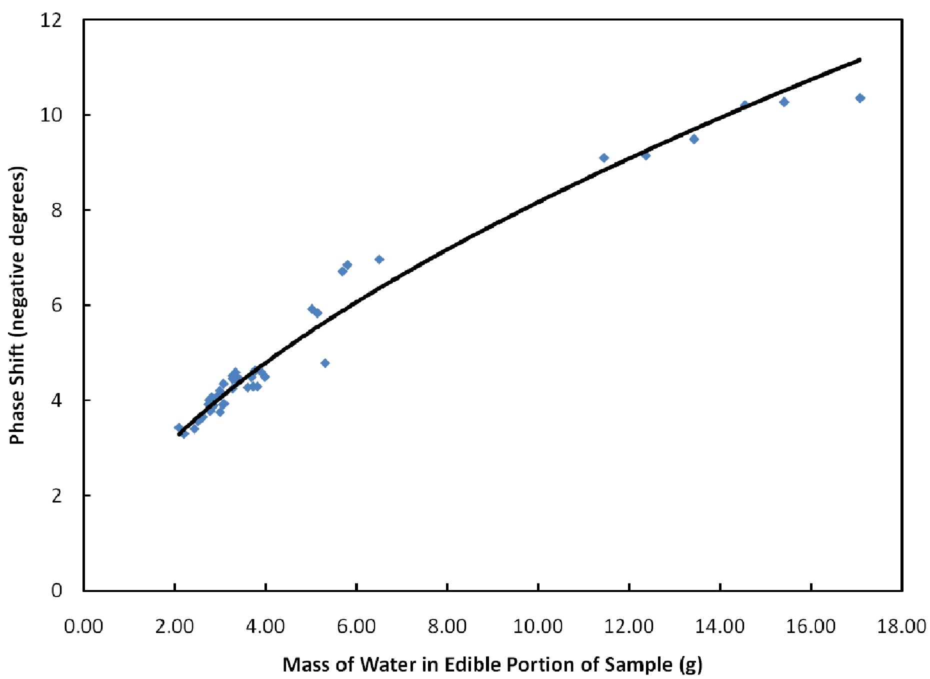

Figure 4.14: Edible kernel water vs. signal phase shift at 458 MHz

Table 4.7: Regression line statistics relating pecan signal attenuation and phase shift measurements to kernel water mass at four frequencies. Variables a and b are coefficients to the equation $y=a*x^b$, where y is the signal attenuation or phase shift and x is the mass of water in the edible kernel of each sample.

		All Cultivars		
Measurement Type	Freq (GHz)	a	b	Coeff. of Det.
Signal Attenuation	0.408	0.2228	0.4904	96.96%
Signal Attenuation	1.03	0.3837	0.4748	79.62%
Signal Phase Shift	0.433	2.9924	0.5666	96.97%
Signal Phase Shift	0.458	2.1348	0.5828	96.79%

CHAPTER V

CONCLUSION

Selection of Quality Assessment Parameter

The pecan quality parameter selected for the overall assessment of the sample was the edible kernel mass because of its very strong correlation with nut quality and market price. The edible kernel mass can be readily converted into a percent edible kernel value which is used by all pecan buyers and sellers as a benchmark value for pecan batch quality. Though several pecan sample characteristics were measured and the total in-shell mass had the greatest correlation values, it was determined that the mass of a sample could be determined by much simpler means such as an electronic balance. The total kernel mass value was ruled out because pecan buyers are not interested in non-edible pecan kernel mass and the total kernel mass and edible kernel mass correlations had similar values.

Pecan Quality Assessment

From the results, the best frequency for predicting the mass of edible kernel inside all of the pecan cultivars using signal attenuation was 408 MHz. Though the frequency 1.03 GHz slightly outperformed 408 MHz for the Giles and Kanza cultivars, the results for the Pawnee and Maramec cultivars gave a much stronger correlation at the lower frequency.

The best frequency found for predicting edible kernel mass of pecans using signal phase shift was 433 MHz. The other frequency presented in the results section, 458 MHz, was very similar in terms of quality correlation, but had a slightly larger confidence interval and was therefore not as stable of an indicator as signal phase shift at 433 MHz. This frequency of 433 MHz, however, did not work as well in correlating the Giles cultivar with quality because it yielded an r^2 value of only 77.65%.

Moisture Content Assessment

The ability to estimate moisture content by use of this method is no surprise, though the interesting data that came from the moisture content assessment was that the kernel moisture content made a much better fit with the signal attenuation and phase shift data than either the moisture mass in the non-edible portion or the total nut moisture content. This is most likely due to the biological way in which the water is bound in each of the materials. Loosely bound water is most likely found in the soft-celled structure of the edible kernel, while the shell’s woody structure binds water more tightly. As a consequence, the fit between the total water content and the signal attenuation and phase shift measurements is not satisfactory because of the uncertainty introduced by the evasive and highly bound water in the pecan’s shell structure.

Overall, the most likely candidate for predicting the moisture content of the kernels within an in-shell pecan is the signal phase shift at 433 MHz. This frequency and measurement type was chosen due to the large resolution possible at this frequency with a signal phase shift measurement as shown in Table 4.2.

Future Work

Much work remains to be done on this subject if a finished pecan grading product is to proceed to the production stages, as this is an initial venture into the plausibility of dielectric measurements of pecans and their correlation to quality. Future work includes a more in-depth analysis of these four cultivars at the specified frequency ranges. This would include having a higher frequency resolution in the 400 to 500 MHz range and the 1.0 to 1.1 GHz range to find more suitable frequencies than the ones presented in this document. Possibly, significant increases in the resolution of measurements can be observed at a more appropriate frequency.

Additional research could also quantify the effect of pecan oil content on the dielectric response of pecan samples. Though the effects may be small, they could be significant in the search for a pecan component that characterizes the quality of a pecan sample through non-destructive means.

More in-depth analysis of the biological structure of each cultivar used in this research and the effects of those structures on the dielectric properties is also an option for further research. After the effect of water content, it is unclear which combination of pecan properties causes the four cultivar calibration lines to diverge from each other. Plausible options are the shell thickness, the amount of air on the inside of the nut, and also the way in which water is bound in both the pecan shells and the kernels. Though it is complicated, more research in this area would assist the pecan industry to provide better technology for future generations.

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APPENDIX I

SIGNIFICANT FREQUENCY DATA

Table A1.1: Theoretical resolution for signal attenuation measurements of low moisture content Maramec, Pawnee, Giles, and Kanza pecan cultivars between 0.01 and 1.0060 GHz. Highlighted lines yielded significant frequencies (mean resolution greater than 10).

	Theoretical Resolution Attenuation				
Freq (GHz)	Maramec	Pawnee	Kanza	Giles	Mean
0.01	0.02	0.13	0.13	0.06	0.08
0.0349	0.01	0.04	0.05	0.06	0.04
0.0598	0.09	0.01	0.00	0.02	0.03
0.0847	0.10	0.03	0.12	0.01	0.06
0.1096	0.02	0.03	0.08	0.00	0.03
0.1345	0.01	0.06	0.11	0.02	0.05
0.1594	0.03	0.02	0.07	0.09	0.05
0.1843	0.09	0.06	0.07	0.03	0.06
0.2092	0.04	0.05	0.06	0.10	0.06
0.2341	0.02	0.06	0.02	0.05	0.04
0.259	0.03	0.02	0.04	0.13	0.06
0.2839	0.11	0.14	0.23	0.02	0.13
0.3088	0.02	0.08	0.11	0.04	0.07
0.3337	0.64	0.54	0.25	0.53	0.49
0.3586	1.98	2.16	3.23	2.37	2.44
0.3835	7.91	7.83	9.19	7.18	8.03
0.4084	28.93	29.70	29.22	22.58	27.61
0.4333	7.06	8.62	5.69	4.10	6.37
0.4582	12.21	9.87	13.19	10.62	11.47
0.4831	11.42	11.79	11.24	9.45	10.98
0.508	7.69	8.61	8.39	5.32	7.50
0.5329	4.91	4.79	5.54	3.94	4.80
0.5578	4.41	4.96	4.56	2.82	4.19
0.5827	5.06	5.51	6.43	4.11	5.28
0.6076	4.01	4.05	4.56	3.01	3.91
0.6325	2.62	2.67	2.69	1.64	2.40
0.6574	2.15	1.92	2.10	1.48	1.91
0.6823	2.77	2.88	3.21	2.37	2.81
0.7072	3.20	3.03	3.55	2.36	3.03
0.7321	1.98	2.16	2.17	1.81	2.03
0.757	0.91	0.61	0.57	0.02	0.53
0.7819	0.67	1.21	1.43	1.32	1.16
0.8068	1.65	2.43	2.54	3.33	2.49
0.8317	3.11	4.46	4.98	5.18	4.43
0.8566	1.91	4.16	3.78	5.83	3.92
0.8815	2.12	4.34	3.74	7.07	4.32
0.9064	3.89	4.87	6.53	7.38	5.67
0.9313	4.96	6.94	11.02	7.69	7.65
0.9562	9.37	11.27	18.62	9.45	12.18
0.9811	13.46	13.54	20.76	11.20	14.74
1.006	19.06	19.12	25.33	14.46	19.49

Table A1.2: Theoretical resolution for signal attenuation measurements of low moisture content Maramec, Pawnee, Giles, and Kanza pecan cultivars between 1.0309 and 2.0020 GHz. Highlighted lines yielded significant frequencies (mean resolution greater than 10). Note: Frequencies greater than 2.0020 GHz were not included due to lack of good results.

	Theoretical Resolution Attenuation				
Freq (GHz)	Maramec	Pawnee	Kanza	Giles	Mean
1.0309	18.58	19.73	26.20	17.39	20.48
1.0558	21.95	22.37	27.01	21.15	23.12
1.0807	22.45	22.16	24.04	24.17	23.21
1.1056	13.93	17.03	19.85	21.74	18.14
1.1305	3.64	7.61	9.08	19.22	9.89
1.1554	13.61	15.78	16.72	14.82	15.23
1.1803	11.22	12.53	13.83	12.14	12.43
1.2052	8.71	10.08	11.19	10.24	10.05
1.2301	7.11	6.75	7.52	7.78	7.29
1.255	4.58	4.56	4.82	5.21	4.79
1.2799	4.68	4.50	5.30	4.97	4.86
1.3048	5.60	5.96	6.92	4.84	5.83
1.3297	3.74	3.64	4.58	3.55	3.88
1.3546	2.56	2.59	3.06	3.21	2.85
1.3795	3.46	2.74	3.84	3.01	3.26
1.4044	3.56	3.14	3.69	2.23	3.16
1.4293	2.96	2.82	3.18	1.98	2.73
1.4542	3.38	2.56	3.25	2.66	2.96
1.4791	4.06	2.99	3.23	3.27	3.39
1.504	2.36	1.69	2.29	2.08	2.10
1.5289	1.54	0.97	1.53	1.40	1.36
1.5538	1.64	1.22	1.70	1.48	1.51
1.5787	1.98	1.65	2.33	1.48	1.86
1.6036	1.01	0.70	1.01	0.16	0.72
1.6285	0.34	0.60	0.45	0.32	0.43
1.6534	0.46	0.51	0.53	0.60	0.52
1.6783	0.28	0.53	0.32	0.61	0.44
1.7032	0.11	0.41	0.21	0.36	0.27
1.7281	0.31	0.24	0.16	0.07	0.19
1.753	0.07	0.20	0.21	0.07	0.14
1.7779	0.21	0.17	0.26	0.02	0.16
1.8028	0.02	0.27	0.17	0.07	0.13
1.8277	0.02	0.06	0.12	0.02	0.05
1.8526	0.16	0.05	0.02	0.02	0.06
1.8775	0.33	0.05	0.16	0.27	0.20
1.9024	0.28	0.09	0.13	0.13	0.16
1.9273	0.07	0.08	0.05	0.13	0.08
1.9522	0.02	0.02	0.00	0.13	0.04
1.9771	0.02	0.06	0.01	0.03	0.03
2.002	0.01	0.20	0.13	0.08	0.10

Table A1.3: Theoretical resolution for signal phase shift measurements of low moisture content Maramec, Pawnee, Giles, and Kanza pecan cultivars between 0.01 and 1.0060 GHz. Highlighted lines yielded significant frequencies (mean resolution greater than 10).

	Theoretical Resolution Phase Shift				
Freq (GHz)	Maramec	Pawnee	Kanza	Giles	Mean
0.01	0.16	0.00	0.00	0.02	0.05
0.0349	0.03	0.14	0.09	0.00	0.07
0.0598	0.03	0.06	0.12	0.03	0.06
0.0847	0.02	0.02	0.27	0.04	0.09
0.1096	0.14	0.05	0.07	0.09	0.09
0.1345	0.07	0.10	0.00	0.02	0.05
0.1594	0.07	0.05	0.12	0.01	0.06
0.1843	0.03	0.11	0.08	0.04	0.06
0.2092	0.08	0.15	0.02	0.08	0.08
0.2341	0.08	0.06	0.02	0.08	0.06
0.259	0.01	0.21	0.14	0.11	0.12
0.2839	0.09	0.17	0.16	0.19	0.15
0.3088	0.34	0.58	0.51	0.43	0.46
0.3337	0.91	0.90	1.13	0.98	0.98
0.3586	3.55	3.87	3.51	1.98	3.23
0.3835	8.92	10.63	10.81	8.91	9.82
0.4084	43.06	45.05	48.32	25.43	40.46
0.4333	79.12	82.13	74.77	39.73	68.94
0.4582	48.56	43.80	52.53	29.47	43.59
0.4831	28.61	27.46	33.54	20.78	27.59
0.508	12.98	14.37	15.03	9.49	12.97
0.5329	8.60	8.82	8.60	6.54	8.14
0.5578	8.28	8.96	9.64	5.37	8.06
0.5827	7.50	8.01	8.89	5.38	7.44
0.6076	5.82	7.00	6.89	4.04	5.94
0.6325	6.46	6.60	7.02	4.34	6.10
0.6574	8.24	8.66	10.24	5.76	8.22
0.6823	9.74	10.08	11.85	6.41	9.52
0.7072	9.58	10.31	10.93	6.46	9.32
0.7321	8.97	9.30	10.28	5.93	8.62
0.757	9.78	10.68	10.74	6.06	9.31
0.7819	10.86	11.54	11.99	6.70	10.27
0.8068	12.27	13.19	14.63	7.15	11.81
0.8317	13.57	13.91	17.39	8.09	13.24
0.8566	14.52	17.16	18.47	8.99	14.79
0.8815	11.71	14.33	16.20	9.50	12.93
0.9064	7.74	18.96	11.42	9.18	11.82
0.9313	6.47	8.46	10.78	8.19	8.48
0.9562	5.25	5.91	10.67	6.13	6.99
0.9811	4.60	3.87	8.63	4.28	5.35
1.006	3.08	2.17	6.85	2.72	3.71

Table A1.4: Theoretical resolution for signal phase shift measurements of low moisture content Maramec, Pawnee, Giles, and Kanza pecan cultivars between 1.0309 and 2.0020 GHz. Highlighted lines yielded significant frequencies (mean resolution greater than 10). Note: Frequencies greater than 2.0020 GHz were not included due to lack of good results.

	Theoretical Resolution Phase Shift				
Freq (GHz)	Maramec	Pawnee	Kanza	Giles	Mean
1.0309	3.54	2.89	6.98	1.63	3.76
1.0558	6.07	5.95	10.04	1.47	5.89
1.0807	8.92	9.74	13.81	3.20	8.92
1.1056	8.26	9.68	11.55	6.00	8.87
1.1305	1.06	2.88	6.49	6.79	4.31
1.1554	9.34	13.81	11.45	7.61	10.55
1.1803	2.11	5.77	14.16	7.94	7.49
1.2052	1.52	4.96	11.23	5.97	5.92
1.2301	8.37	8.49	9.79	5.98	8.16
1.255	7.14	6.88	7.52	4.52	6.51
1.2799	6.33	5.47	6.40	4.05	5.56
1.3048	6.47	5.77	7.08	5.26	6.15
1.3297	8.26	7.78	8.53	7.34	7.98
1.3546	6.85	6.59	7.50	6.62	6.89
1.3795	5.68	4.99	7.25	5.89	5.96
1.4044	5.15	4.49	6.55	4.78	5.24
1.4293	4.98	4.68	6.34	4.33	5.08
1.4542	4.95	4.86	6.27	3.94	5.00
1.4791	5.50	4.67	1.79	4.19	4.04
1.504	0.45	5.28	6.72	5.01	4.37
1.5289	0.35	3.96	4.64	3.94	3.22
1.5538	2.52	3.31	3.76	2.95	3.14
1.5787	2.64	3.23	3.49	2.80	3.04
1.6036	4.35	3.96	3.70	3.14	3.79
1.6285	11.41	3.89	4.51	3.06	5.72
1.6534	3.14	3.63	3.81	3.10	3.42
1.6783	2.74	0.49	3.21	2.40	2.21
1.7032	2.65	2.47	3.22	2.06	2.60
1.7281	2.38	2.24	2.62	1.99	2.31
1.753	2.13	1.81	2.25	1.51	1.92
1.7779	1.98	1.72	1.91	1.63	1.81
1.8028	1.23	1.17	1.64	1.36	1.35
1.8277	1.12	0.98	1.12	1.05	1.07
1.8526	0.98	0.92	0.90	0.82	0.91
1.8775	0.45	0.61	0.78	0.76	0.65
1.9024	0.56	0.02	0.46	0.61	0.41
1.9273	0.07	0.37	0.73	0.62	0.45
1.9522	0.77	0.02	0.70	0.39	0.47
1.9771	0.36	0.21	0.47	0.42	0.37
2.002	0.34	0.36	0.27	0.27	0.31

APPENDIX II

CORRELATION DATA

Table A2.1: Signal attenuation coefficient of determination values for low moisture content Giles cultivar pecans with all measured physical properties at significant frequencies. Highlighted cells have r^2 values that are greater than 80%.

Frequency (GHz)	0.4084	0.4582	0.4831	0.9562	0.9811	1.006	1.0309	1.0558	1.0807	1.1056	1.1554	1.1803	1.2052
Total In-Shell Mass	89.85%	63.24%	57.91%	82.38%	83.80%	88.06%	91.74%	89.26%	95.57%	97.26%	91.51%	84.21%	78.60%
In-Shell Volume	80.86%	43.00%	44.97%	72.02%	67.35%	70.28%	68.90%	66.79%	78.13%	83.60%	80.35%	63.04%	58.76%
Total Density	86.40%	66.21%	58.55%	78.45%	82.36%	86.96%	92.83%	90.40%	94.57%	94.99%	88.27%	85.12%	78.98%
Nuts/Kg	87.22%	59.71%	55.85%	74.74%	76.30%	80.98%	85.46%	82.94%	91.08%	94.16%	87.21%	77.96%	71.44%
Percent Fill	84.69%	64.82%	56.46%	76.49%	79.61%	84.58%	89.96%	87.35%	92.48%	92.57%	86.13%	83.48%	76.36%
Edible Kernel Mass	86.96%	58.42%	57.58%	80.66%	84.15%	87.18%	89.23%	90.33%	92.42%	91.26%	86.99%	87.06%	71.11%
Shell Mass	79.97%	49.93%	51.55%	72.76%	72.16%	73.62%	75.62%	73.97%	80.54%	85.71%	82.01%	65.84%	67.87%
Packing Material Mass	62.43%	36.67%	35.92%	59.60%	64.15%	68.67%	70.98%	70.03%	70.33%	68.68%	62.03%	66.72%	49.11%
Bad Kernel Mass	65.05%	34.70%	45.44%	62.19%	68.41%	67.40%	65.18%	73.31%	67.08%	62.72%	62.16%	72.08%	42.51%
Weevil Larvae Mass	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Non-Edible Mass	7.07%	1.99%	6.75%	7.80%	11.21%	9.79%	7.81%	13.14%	7.45%	4.36%	5.25%	15.90%	1.29%
Kernel Mass	87.78%	64.04%	56.92%	80.48%	82.18%	86.88%	90.90%	88.28%	94.38%	95.10%	89.35%	84.38%	77.77%
Non Kernel Mass	85.11%	52.65%	53.93%	78.02%	78.39%	80.62%	82.89%	81.20%	87.25%	91.59%	86.86%	73.12%	71.40%
Shell Water Mass	1.10%	2.33%	2.04%	2.43%	4.99%	4.13%	3.50%	5.98%	2.14%	0.53%	0.68%	8.53%	0.82%
Kernel Water Mass	89.88%	58.95%	59.71%	80.62%	85.47%	87.66%	90.01%	91.76%	92.92%	89.16%	88.62%	90.88%	74.51%
Total Water Mass	93.24%	57.40%	58.73%	79.93%	80.62%	84.21%	87.74%	85.68%	93.61%	94.70%	93.47%	81.64%	77.60%

Table A2.2: Signal attenuation coefficient of determination values for low moisture content Kanza cultivar pecans with all measured physical properties at significant frequencies. Highlighted cells have r^2 values that are greater than 80%.

Frequency (GHz)	0.4084	0.4582	0.4831	0.9562	0.9811	1.006	1.0309	1.0558	1.0807	1.1056	1.1554	1.1803	1.2052
Total In-Shell Mass	98.48%	86.32%	87.87%	97.62%	97.99%	98.70%	99.21%	98.91%	98.43%	98.66%	90.98%	95.03%	90.10%
In-Shell Volume	76.26%	90.13%	70.29%	81.48%	78.22%	77.14%	73.74%	72.51%	71.34%	70.55%	64.09%	65.62%	65.73%
Total Density	97.08%	79.66%	86.95%	94.94%	96.02%	97.01%	98.45%	98.54%	98.30%	98.69%	91.75%	95.65%	90.41%
Nuts/Kg	95.80%	76.83%	90.96%	94.42%	94.99%	95.22%	97.13%	97.86%	98.03%	98.12%	94.09%	95.55%	92.95%
Percent Fill	96.31%	78.34%	85.50%	94.12%	95.48%	96.33%	97.82%	97.85%	97.53%	97.90%	90.30%	94.75%	89.06%
Edible Kernel Mass	97.49%	84.97%	83.32%	96.40%	97.54%	98.24%	98.14%	97.93%	97.08%	96.89%	87.69%	92.69%	87.09%
Shell Mass	42.20%	61.01%	45.18%	47.65%	43.10%	43.00%	39.89%	39.23%	40.02%	39.33%	40.03%	37.72%	41.17%
Packing Material Mass	58.84%	48.31%	58.85%	58.32%	58.07%	55.93%	55.61%	58.66%	54.28%	53.11%	55.75%	47.03%	54.89%
Bad Kernel Mass	85.84%	84.04%	63.82%	86.43%	87.94%	88.37%	84.46%	84.39%	82.24%	80.31%	68.76%	74.10%	69.85%
Weevil Larvae Mass	6.82%	4.29%	4.49%	4.75%	5.09%	4.52%	6.11%	6.20%	5.70%	4.97%	3.68%	4.10%	6.91%
Non-Edible Mass	60.42%	50.90%	36.71%	58.14%	62.15%	62.91%	60.61%	60.51%	58.34%	56.78%	44.11%	51.85%	44.91%
Kernel Mass	97.37%	82.44%	85.94%	95.87%	96.86%	97.62%	98.56%	98.32%	97.86%	98.17%	89.98%	94.69%	88.90%
Non Kernel Mass	54.57%	70.09%	57.73%	59.99%	55.44%	54.90%	51.61%	51.64%	51.47%	50.59%	52.02%	47.66%	52.64%
Shell Water Mass	41.45%	29.79%	19.48%	35.19%	39.32%	39.66%	41.62%	40.30%	39.73%	40.83%	26.18%	36.56%	24.12%
Kernel Water Mass	96.85%	83.10%	83.83%	96.18%	97.45%	98.17%	98.16%	98.02%	97.59%	97.26%	88.70%	93.81%	87.71%
Total Water Mass	95.29%	84.86%	92.38%	97.82%	97.12%	97.81%	96.78%	97.28%	97.07%	96.10%	93.95%	94.17%	94.04%

Table A2.3: Signal attenuation coefficient of determination values for low moisture content Maramec cultivar pecans with all measured physical properties at significant frequencies. Highlighted cells have r^2 values that are greater than 80%.

Frequency (GHz)	0.4084	0.4582	0.4831	0.9562	0.9811	1.006	1.0309	1.0558	1.0807	1.1056	1.1554	1.1803	1.2052
Total In-Shell Mass	94.38%	66.37%	45.32%	80.89%	84.25%	90.58%	88.41%	84.10%	81.21%	73.38%	91.08%	88.72%	87.12%
In-Shell Volume	14.98%	0.44%	21.89%	17.97%	17.29%	14.74%	14.18%	10.10%	9.81%	7.68%	6.55%	11.38%	7.11%
Total Density	86.64%	67.21%	37.62%	71.87%	75.45%	82.59%	80.44%	77.93%	75.18%	68.19%	86.79%	82.10%	82.48%
Nuts/Kg	91.13%	55.79%	31.24%	74.08%	73.31%	81.65%	78.51%	71.15%	67.14%	59.37%	83.12%	80.94%	76.64%
Percent Fill	87.23%	65.99%	36.12%	71.68%	74.78%	82.23%	79.81%	76.50%	73.63%	66.13%	86.23%	81.54%	81.21%
Edible Kernel Mass	92.50%	66.84%	43.46%	77.66%	81.01%	87.66%	84.64%	81.13%	78.25%	70.02%	89.11%	85.34%	84.42%
Shell Mass	19.60%	5.42%	52.00%	24.61%	28.64%	25.05%	25.90%	25.29%	26.19%	25.01%	13.38%	17.48%	17.36%
Packing Material Mass	32.76%	6.42%	8.41%	41.21%	35.20%	32.79%	33.40%	25.50%	22.19%	23.74%	27.79%	39.53%	27.62%
Bad Kernel Mass	82.16%	60.07%	57.49%	68.86%	74.05%	77.34%	70.90%	72.19%	70.19%	61.25%	74.39%	70.15%	71.38%
Weevil Larvae Mass	0.03%	15.15%	4.54%	0.70%	0.01%	0.00%	0.01%	0.35%	1.02%	0.04%	0.45%	0.17%	0.28%
Non-Edible Mass	47.20%	46.84%	17.83%	32.80%	34.97%	39.72%	34.33%	36.53%	34.93%	28.76%	46.68%	38.53%	40.92%
Kernel Mass	91.71%	66.15%	40.13%	77.01%	79.94%	87.00%	84.68%	80.41%	77.46%	69.59%	89.20%	85.63%	84.35%
Non Kernel Mass	24.83%	6.17%	48.49%	31.29%	34.20%	30.26%	31.22%	29.12%	29.29%	28.58%	17.65%	23.65%	21.70%
Shell Water Mass	68.97%	68.11%	26.92%	54.62%	58.65%	64.73%	62.28%	62.41%	60.58%	53.81%	74.76%	67.27%	69.64%
Kernel Water Mass	92.75%	67.73%	43.55%	79.34%	82.61%	88.46%	85.37%	81.98%	79.15%	71.01%	90.24%	86.92%	85.31%
Total Water Mass	56.01%	14.80%	38.87%	57.19%	55.62%	55.53%	53.98%	46.70%	44.47%	40.91%	40.70%	47.44%	40.18%

Table A2.4: Signal attenuation coefficient of determination values for low moisture content Pawnee cultivar pecans with all measured physical properties at significant frequencies. Highlighted cells have r^2 values that are greater than 80%.

Frequency (GHz)	0.4084	0.4582	0.4831	0.9562	0.9811	1.006	1.0309	1.0558	1.0807	1.1056	1.1554	1.1803	1.2052
Total In-Shell Mass	98.66%	76.15%	25.92%	90.25%	86.60%	87.80%	87.65%	89.01%	85.05%	73.52%	86.55%	84.19%	72.71%
In-Shell Volume	90.59%	61.41%	52.46%	77.57%	76.31%	77.11%	77.58%	79.29%	78.04%	67.53%	83.49%	83.83%	73.04%
Total Density	93.19%	74.45%	14.68%	87.56%	83.58%	85.04%	84.67%	85.56%	81.03%	70.11%	80.74%	76.97%	66.43%
Nuts/Kg	98.75%	70.84%	31.30%	88.21%	86.40%	87.74%	88.21%	89.17%	86.72%	74.86%	89.84%	87.07%	76.33%
Percent Fill	93.54%	69.41%	15.96%	89.10%	86.00%	88.00%	87.20%	88.05%	84.41%	74.32%	83.33%	78.53%	67.58%
Edible Kernel Mass	92.73%	70.51%	17.42%	89.28%	85.42%	87.04%	85.77%	86.88%	81.87%	72.05%	79.69%	77.05%	62.44%
Shell Mass	91.21%	86.26%	30.04%	75.61%	70.78%	69.75%	71.95%	73.50%	68.42%	54.63%	76.01%	78.45%	71.80%
Packing Material Mass	85.32%	54.80%	27.31%	83.65%	80.29%	83.35%	79.67%	81.10%	77.53%	71.30%	71.55%	68.78%	49.52%
Bad Kernel Mass	64.38%	52.58%	4.90%	67.15%	62.89%	64.07%	61.85%	62.51%	55.98%	49.74%	50.18%	49.51%	33.78%
Weevil Larvae Mass	11.62%	14.37%	2.49%	8.98%	6.67%	7.31%	8.47%	8.99%	7.52%	6.05%	7.30%	6.72%	3.19%
Non-Edible Mass	5.87%	3.33%	7.75%	12.70%	11.71%	12.69%	10.56%	10.33%	7.91%	8.99%	3.18%	2.61%	0.03%
Kernel Mass	98.00%	72.44%	23.96%	91.40%	88.21%	89.89%	89.30%	90.54%	87.03%	76.31%	87.35%	83.84%	72.12%
Non Kernel Mass	94.64%	82.76%	30.96%	81.49%	76.71%	76.54%	77.56%	79.17%	74.14%	61.26%	78.94%	80.22%	69.86%
Shell Water Mass	22.64%	6.62%	75.80%	18.91%	20.28%	19.87%	23.21%	21.05%	23.83%	24.81%	32.15%	35.78%	32.51%
Kernel Water Mass	90.64%	74.92%	12.17%	83.95%	79.90%	82.10%	80.08%	81.06%	75.80%	65.07%	75.39%	72.44%	59.36%
Total Water Mass	73.17%	43.82%	59.81%	65.29%	64.88%	65.52%	68.37%	66.38%	66.80%	62.01%	75.34%	77.23%	66.35%

Table A2.5: Signal phase shift coefficient of determination values for low moisture content Giles cultivar pecans with all measured physical properties at significant frequencies. Highlighted cells have r^2 values that are greater than 80%.

Frequency (GHz)	0.4084	0.4333	0.4582	0.4831	0.508	0.7819	0.8068	0.8317	0.8566	0.8815	0.9064	1.1554
Total In-Shell Mass	78.37%	81.09%	87.41%	92.23%	56.85%	26.19%	30.26%	30.33%	35.56%	31.66%	29.25%	63.35%
In-Shell Volume	66.94%	72.74%	79.61%	76.48%	42.33%	24.19%	28.97%	25.32%	30.64%	27.48%	27.19%	55.65%
Total Density	76.68%	78.14%	83.41%	91.82%	58.04%	24.53%	28.11%	29.51%	34.36%	30.44%	27.56%	60.93%
Nuts/Kg	75.70%	79.23%	83.95%	91.25%	54.34%	24.29%	28.41%	28.07%	33.40%	29.51%	27.74%	59.81%
Percent Fill	75.95%	78.09%	82.37%	92.99%	58.79%	26.28%	29.19%	30.31%	35.20%	32.11%	28.79%	61.68%
Edible Kernel Mass	78.43%	77.65%	85.71%	94.35%	56.07%	30.71%	34.34%	34.96%	39.26%	38.10%	33.21%	67.50%
Shell Mass	64.21%	67.46%	75.86%	65.98%	39.71%	16.16%	21.87%	21.01%	25.53%	19.43%	20.23%	48.33%
Packing Material Mass	58.23%	54.82%	63.30%	80.01%	41.68%	20.63%	23.62%	22.98%	26.63%	28.15%	22.64%	48.28%
Bad Kernel Mass	61.26%	53.96%	65.50%	73.54%	38.14%	30.25%	33.79%	34.76%	36.11%	39.95%	32.03%	59.02%
Weevil Larvae Mass	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Non-Edible Mass	10.12%	5.39%	8.40%	15.72%	5.99%	14.63%	13.33%	14.97%	12.63%	20.89%	12.95%	16.31%
Kernel Mass	77.84%	80.59%	85.80%	93.73%	58.65%	27.57%	30.85%	31.25%	36.37%	33.19%	30.11%	63.94%
Non Kernel Mass	69.99%	72.25%	81.58%	75.66%	44.37%	18.71%	24.56%	23.64%	28.50%	23.05%	22.86%	53.54%
Shell Water Mass	3.73%	1.46%	1.69%	8.32%	4.75%	10.75%	7.50%	10.98%	8.57%	15.06%	8.36%	8.72%
Kernel Water Mass	77.35%	77.21%	89.98%	94.61%	57.36%	30.83%	34.12%	35.13%	38.70%	38.50%	32.85%	70.30%
Total Water Mass	74.16%	78.58%	91.61%	85.63%	52.26%	22.02%	26.97%	25.77%	30.55%	26.69%	25.22%	60.97%

Table A2.6: Signal phase shift coefficient of determination values for low moisture content Kanza cultivar pecans with all measured physical properties at significant frequencies. Highlighted cells have r^2 values that are greater than 80%.

Frequency (GHz)	0.4084	0.4333	0.4582	0.4831	0.508	0.7819	0.8068	0.8317	0.8566	0.8815	0.9064	1.1554
Total In-Shell Mass	97.05%	98.12%	97.75%	98.57%	97.87%	95.87%	95.49%	92.21%	93.01%	89.87%	72.69%	96.36%
In-Shell Volume	72.94%	75.88%	74.63%	75.99%	76.14%	64.26%	75.40%	75.07%	79.39%	66.99%	29.43%	71.02%
Total Density	96.19%	96.84%	96.58%	97.39%	96.35%	96.96%	93.87%	90.54%	89.98%	89.56%	79.05%	95.86%
Nuts/Kg	95.15%	96.25%	95.24%	97.54%	94.35%	95.24%	93.75%	92.14%	89.52%	91.68%	75.59%	94.14%
Percent Fill	94.81%	95.83%	95.29%	96.27%	95.53%	96.25%	92.35%	89.44%	88.67%	88.89%	81.61%	94.89%
Edible Kernel Mass	95.82%	96.93%	96.42%	96.46%	97.30%	95.56%	93.58%	91.29%	92.65%	89.64%	76.18%	94.45%
Shell Mass	43.75%	43.61%	44.65%	44.11%	42.81%	33.42%	47.02%	46.10%	49.80%	36.00%	3.13%	40.72%
Packing Material Mass	61.80%	61.58%	59.78%	61.60%	57.86%	58.90%	63.36%	63.79%	64.05%	66.01%	32.33%	51.46%
Bad Kernel Mass	84.72%	85.41%	85.04%	81.97%	87.56%	82.36%	82.25%	83.16%	88.73%	80.20%	59.91%	79.12%
Weevil Larvae Mass	5.71%	6.23%	4.34%	6.64%	3.92%	3.95%	4.06%	6.25%	7.24%	18.71%	11.77%	2.66%
Non-Edible Mass	58.00%	58.84%	58.03%	55.03%	61.86%	61.60%	53.54%	54.98%	58.86%	57.45%	68.32%	54.86%
Kernel Mass	95.61%	96.81%	96.27%	97.17%	96.67%	95.94%	93.51%	90.44%	90.64%	89.20%	78.12%	95.47%
Non Kernel Mass	56.88%	56.64%	57.45%	57.10%	55.23%	46.06%	60.65%	59.61%	63.22%	49.19%	7.77%	51.82%
Shell Water Mass	33.80%	36.70%	34.67%	37.45%	36.38%	37.62%	31.61%	26.83%	32.19%	38.23%	65.03%	36.63%
Kernel Water Mass	95.60%	96.59%	95.98%	96.16%	96.80%	95.79%	92.52%	91.09%	91.87%	90.28%	77.90%	94.19%
Total Water Mass	97.89%	97.49%	97.86%	96.55%	97.91%	96.01%	95.38%	96.51%	94.24%	89.03%	63.76%	94.60%

Table A2.7: Signal phase shift coefficient of determination values for low moisture content Maramec cultivar pecans with all measured physical properties at significant frequencies. Highlighted cells have r^2 values that are greater than 80%.

Frequency (GHz)	0.4084	0.4333	0.4582	0.4831	0.508	0.7819	0.8068	0.8317	0.8566	0.8815	0.9064	1.1554
Total In-Shell Mass	75.91%	89.61%	91.70%	94.27%	95.67%	91.81%	89.94%	93.68%	90.60%	77.06%	5.81%	83.73%
In-Shell Volume	40.74%	23.56%	18.08%	10.26%	9.09%	12.94%	11.18%	10.90%	6.41%	12.10%	9.81%	10.34%
Total Density	62.05%	78.96%	82.71%	88.58%	90.45%	84.73%	83.94%	87.16%	86.09%	69.79%	9.49%	77.52%
Nuts/Kg	73.17%	86.29%	85.10%	95.88%	91.63%	88.68%	92.45%	88.97%	87.69%	68.24%	5.53%	75.97%
Percent Fill	63.22%	79.58%	82.85%	89.75%	90.87%	84.78%	84.78%	87.18%	86.06%	68.94%	8.63%	76.93%
Edible Kernel Mass	71.46%	85.99%	89.23%	92.85%	94.29%	88.78%	88.17%	91.29%	88.13%	73.42%	7.59%	81.44%
Shell Mass	36.53%	26.00%	24.80%	10.28%	11.92%	15.86%	9.67%	17.56%	12.69%	22.30%	12.02%	16.67%
Packing Material Mass	57.51%	46.21%	35.82%	35.52%	30.23%	41.96%	44.09%	31.17%	27.29%	35.01%	1.72%	36.92%
Bad Kernel Mass	64.52%	74.46%	81.75%	76.25%	80.25%	73.28%	73.25%	76.70%	67.94%	60.87%	14.01%	71.73%
Weevil Larvae Mass	6.87%	2.13%	0.08%	0.48%	0.36%	1.46%	3.44%	0.08%	0.43%	0.62%	1.40%	0.21%
Non-Edible Mass	22.95%	35.62%	42.89%	50.30%	52.76%	41.94%	47.37%	44.55%	41.86%	28.81%	30.73%	40.63%
Kernel Mass	70.67%	85.59%	88.03%	93.18%	94.11%	89.02%	88.33%	91.29%	89.28%	73.57%	6.51%	80.85%
Non Kernel Mass	46.18%	33.56%	30.55%	15.47%	16.46%	22.36%	15.84%	22.54%	17.01%	27.99%	8.44%	22.46%
Shell Water Mass	39.31%	57.32%	63.90%	71.86%	75.88%	67.98%	68.14%	70.08%	70.43%	53.73%	16.78%	63.32%
Kernel Water Mass	73.30%	87.03%	90.44%	93.20%	95.31%	89.92%	89.40%	91.76%	88.04%	75.01%	8.68%	83.69%
Total Water Mass	82.93%	68.78%	61.59%	51.36%	48.19%	52.12%	50.75%	51.82%	43.92%	49.49%	1.31%	48.40%

Table A2.8: Signal phase shift coefficient of determination values for low moisture content Pawnee cultivar pecans with all measured physical properties at significant frequencies. Highlighted cells have r^2 values that are greater than 80%.

Frequency (GHz)	0.4084	0.4333	0.4582	0.4831	0.508	0.7819	0.8068	0.8317	0.8566	0.8815	0.9064	1.1554
Total In-Shell Mass	98.60%	97.51%	93.65%	21.48%	91.64%	93.11%	89.52%	93.37%	89.45%	56.39%	25.29%	16.81%
In-Shell Volume	86.84%	88.76%	92.66%	5.65%	86.54%	89.69%	87.44%	89.57%	89.16%	56.68%	14.09%	10.50%
Total Density	94.35%	92.07%	85.36%	29.52%	85.63%	85.39%	81.78%	85.66%	81.00%	51.55%	28.27%	17.87%
Nuts/Kg	96.41%	96.10%	95.23%	16.25%	92.86%	92.49%	89.96%	92.04%	90.13%	58.66%	21.51%	14.41%
Percent Fill	94.64%	93.58%	86.56%	26.56%	88.03%	87.02%	83.12%	86.13%	83.18%	56.40%	26.74%	16.57%
Edible Kernel Mass	93.31%	92.31%	86.22%	30.22%	84.12%	85.32%	79.22%	86.03%	82.04%	54.60%	27.50%	18.60%
Shell Mass	89.24%	84.91%	86.65%	17.98%	78.94%	83.65%	83.52%	88.17%	79.18%	37.69%	21.16%	14.51%
Packing Material Mass	85.73%	88.77%	82.97%	21.27%	80.90%	82.14%	72.54%	80.25%	81.69%	62.08%	26.89%	22.02%
Bad Kernel Mass	65.14%	63.47%	56.91%	44.26%	52.64%	54.59%	46.47%	57.34%	52.32%	35.31%	26.38%	19.48%
Weevil Larvae Mass	15.22%	14.25%	9.48%	11.25%	18.10%	10.29%	12.48%	9.72%	8.02%	7.87%	60.57%	41.14%
Non-Edible Mass	6.75%	6.71%	3.42%	40.32%	3.14%	3.04%	0.80%	3.47%	2.94%	5.73%	10.02%	7.79%
Kernel Mass	98.39%	97.92%	92.89%	21.73%	92.43%	92.99%	89.05%	92.34%	89.52%	59.28%	25.24%	16.33%
Non Kernel Mass	93.18%	90.37%	90.35%	19.76%	83.68%	87.72%	85.30%	90.92%	83.95%	44.95%	23.83%	17.09%
Shell Water Mass	17.97%	18.57%	34.40%	1.93%	24.95%	23.78%	24.65%	26.56%	33.91%	24.36%	0.75%	0.61%
Kernel Water Mass	91.40%	89.94%	81.10%	36.78%	80.55%	80.15%	76.29%	82.62%	75.87%	46.90%	30.22%	20.08%
Total Water Mass	67.79%	67.84%	80.87%	6.40%	70.56%	69.05%	67.96%	73.45%	77.38%	51.16%	6.52%	4.12%

APPENDIX III

PECAN SAMPLE PROPERTIES

Table A3.1: Pecan sample properties for low moisture content Giles pecan cultivar.

	Low MC Giles Samples											
Sample Property	GL1	GL2	GL3	GL4	GL5	GL6	GL7	GL8	GL9	GL10	GL11	GL12
Total Sample Mass (g)	151.42	159.17	156.28	150.98	150.87	108.12	128.26	150.90	141.39	139.40	153.03	161.32
Total Sample Volume (ml)	249.85	254.50	253.33	249.06	242.72	227.50	240.10	247.67	244.28	248.77	249.41	251.89
Sample Density (g/ml)	0.61	0.63	0.62	0.61	0.62	0.48	0.53	0.61	0.58	0.56	0.61	0.64
Sample Nuts/Kg	184.92	175.91	179.17	185.46	185.59	258.97	218.31	185.55	198.03	200.86	182.97	173.57
Percent Fill (edible ml/total ml)	0.37	0.39	0.40	0.38	0.39	0.23	0.30	0.38	0.36	0.32	0.38	0.41
Edible Kernel Mass (g)	64.61	78.64	80.06	71.25	76.33	27.00	43.47	68.56	64.74	59.06	73.25	83.23
Shell Mass (g)	69.29	70.47	67.84	67.23	65.90	60.12	62.31	67.26	63.23	67.40	68.20	69.35
Packing Material Mass (g)	7.15	7.98	8.01	7.71	8.27	6.03	7.06	7.59	7.81	7.31	7.89	8.40
Non-Edible Kernel Mass (g)	10.03	1.76	0.00	4.37	0.00	14.48	14.93	7.00	5.12	5.19	3.26	0.00
Weevil Larvae Mass (g)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Non-Edible Mass (g)	86.47	80.21	75.85	79.31	74.17	80.63	84.30	81.85	76.16	79.90	79.35	77.75
Total Kernel Mass (g)	74.64	80.40	80.06	75.62	76.33	41.48	58.40	75.56	69.86	64.25	76.51	83.23
Total Non-Kernel Mass (g)	76.44	78.45	75.85	74.94	74.17	66.15	69.37	74.85	71.04	74.71	76.09	77.75
Non-Edible Water Mass (g)	5.52	5.39	5.08	5.22	4.98	5.22	5.41	5.27	5.06	5.41	5.21	5.17
Edible Portion Water Mass (g)	2.10	2.53	2.63	2.22	2.45	1.01	1.46	2.10	2.09	1.84	2.32	2.53
Total Water Mass (g)	7.62	7.92	7.71	7.44	7.43	6.23	6.87	7.37	7.15	7.25	7.53	7.70

Table A3.2: Pecan sample properties for low moisture content Kanza pecan cultivar.

	Low MC Kanza Samples											
Sample Property	KL1	KL2	KL3	KL4	KL5	KL6	KL7	KL8	KL9	KL10	KL11	KL12
Total Sample Mass (g)	195.81	186.93	186.38	198.52	190.38	102.69	121.76	130.03	149.21	155.93	170.12	175.88
Total Sample Volume (ml)	296.82	285.46	289.01	295.84	290.67	271.16	271.79	280.85	283.84	273.26	283.22	282.02
Sample Density (g/ml)	0.66	0.65	0.64	0.67	0.65	0.38	0.45	0.46	0.53	0.57	0.60	0.62
Sample Nuts/Kg	102.14	106.99	107.31	100.75	105.05	194.76	164.26	153.81	134.04	128.26	117.56	113.71
Percent Fill (edible ml/total ml)	0.39	0.40	0.38	0.40	0.39	0.08	0.15	0.18	0.23	0.29	0.33	0.35
Edible Kernel Mass (g)	102.62	96.80	92.75	100.10	94.49	0.00	14.54	21.15	45.79	57.89	67.36	80.87
Shell Mass (g)	80.76	75.00	77.72	81.76	78.87	73.27	76.44	75.45	79.25	73.10	76.70	76.57
Packing Material Mass (g)	11.42	11.57	10.11	11.22	10.76	9.23	9.70	10.15	11.55	10.88	10.96	10.89
Non-Edible Kernel Mass (g)	0.00	2.47	4.80	3.77	5.23	18.86	20.23	22.46	12.61	13.04	13.83	6.33
Weevil Larvae Mass (g)	0.00	0.00	0.00	0.00	0.26	0.23	0.00	0.00	0.00	0.00	0.00	0.00
Total Non-Edible Mass (g)	92.18	89.04	92.63	96.75	95.12	101.59	106.37	108.06	103.41	97.02	101.49	93.79
Total Kernel Mass (g)	102.62	99.27	97.55	103.87	99.72	18.86	34.77	43.61	58.40	70.93	81.19	87.20
Total Non-Kernel Mass (g)	92.18	86.57	87.83	92.98	89.89	82.73	86.14	85.60	90.80	83.98	87.66	87.46
Non-Edible Water Mass (g)	8.17	7.81	8.00	8.17	8.18	8.76	8.40	8.49	8.95	8.16	8.46	8.34
Edible Portion Water Mass (g)	3.29	3.02	3.03	3.08	3.00	0.00	0.60	0.69	1.49	1.89	2.20	2.66
Total Water Mass (g)	11.46	10.83	11.03	11.25	11.18	8.76	9.00	9.18	10.44	10.05	10.66	11.00

Table A3.3: Pecan sample properties for low moisture content Maramec pecan cultivar.

	Low MC Maramec Samples											
Sample Property	ML1	ML2	ML3	ML4	ML5	ML6	ML7	ML8	ML9	ML10	ML11	ML12
Total Sample Mass (g)	176.26	181.80	187.37	185.90	180.11	98.92	111.62	120.97	131.20	142.01	150.08	159.24
Total Sample Volume (ml)	254.45	263.61	266.49	272.81	264.73	264.16	254.50	267.00	266.38	252.13	249.76	277.34
Sample Density (g/ml)	0.69	0.69	0.70	0.68	0.68	0.37	0.44	0.45	0.49	0.56	0.60	0.57
Sample Nuts/Kg	113.47	110.01	106.74	107.58	111.04	202.18	179.18	165.33	152.44	140.84	133.26	125.60
Percent Fill (edible ml/total ml)	0.46	0.46	0.48	0.45	0.45	0.09	0.17	0.20	0.24	0.32	0.36	0.33
Edible Kernel Mass (g)	101.51	104.87	110.46	102.89	102.31	9.25	24.31	38.11	44.66	60.33	71.72	75.61
Shell Mass (g)	62.42	66.65	66.95	67.75	66.19	66.98	63.01	64.88	63.56	62.87	60.91	67.82
Packing Material Mass (g)	10.34	10.34	10.10	10.55	10.23	9.65	9.97	9.78	10.52	9.49	9.69	11.08
Non-Edible Kernel Mass (g)	0.00	0.00	0.00	4.72	1.41	12.37	13.74	7.93	12.07	9.06	7.36	4.48
Weevil Larvae Mass (g)	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.12
Total Non-Edible Mass (g)	72.76	76.99	77.05	83.02	77.83	89.00	86.76	82.59	86.15	81.42	77.96	83.50
Total Kernel Mass (g)	101.51	104.87	110.46	107.61	103.72	21.62	38.05	46.04	56.73	69.39	79.08	80.09
Total Non-Kernel Mass (g)	72.76	76.99	77.05	78.30	76.42	76.63	73.02	74.66	74.08	72.36	70.60	79.02
Non-Edible Water Mass (g)	5.18	5.59	5.43	5.72	5.38	7.47	6.94	6.87	6.58	6.14	5.80	6.58
Edible Portion Water Mass (g)	2.79	2.83	2.93	2.77	2.75	0.38	0.82	1.16	1.28	1.57	1.96	2.13
Total Water Mass (g)	7.97	8.42	8.36	8.49	8.13	7.85	7.76	8.03	7.86	7.71	7.76	8.71

Table A3.4: Pecan sample properties for low moisture content Pawnee pecan cultivar.

	Low MC Pawnee Samples											
Sample Property	PL1	PL2	PL3	PL4	PL5	PL6	PL7	PL8	PL9	PL10	PL11	PL12
Total Sample Mass (g)	202.40	194.31	211.09	197.10	209.45	118.90	124.23	144.61	150.92	188.55	182.98	202.16
Total Sample Volume (ml)	294.15	284.69	302.04	278.94	296.67	243.63	252.28	265.83	265.30	299.45	297.22	295.96
Sample Density (g/ml)	0.69	0.68	0.70	0.71	0.71	0.49	0.49	0.54	0.57	0.63	0.62	0.68
Sample Nuts/Kg	118.58	123.51	113.70	121.77	114.59	201.85	193.19	165.96	159.02	127.29	131.16	118.72
Percent Fill (edible ml/total ml)	0.46	0.47	0.48	0.50	0.49	0.28	0.28	0.33	0.36	0.43	0.41	0.47
Edible Kernel Mass (g)	115.33	118.09	123.88	122.35	127.63	28.52	39.70	56.57	56.20	88.97	99.47	117.20
Shell Mass (g)	68.88	61.91	67.62	61.41	67.36	48.22	51.26	56.41	56.99	60.75	62.31	66.63
Packing Material Mass (g)	12.74	13.53	14.38	12.68	13.68	9.12	10.08	9.83	9.35	13.21	13.42	13.19
Non-Edible Kernel Mass (g)	4.66	0.00	4.32	0.00	0.00	32.05	22.55	21.01	27.35	24.85	7.10	4.42
Weevil Larvae Mass (g)	0.00	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Non-Edible Mass (g)	86.28	75.44	86.44	74.09	81.04	89.39	83.89	87.25	93.69	98.81	82.83	84.24
Total Kernel Mass (g)	119.99	118.09	128.20	122.35	127.63	60.57	62.25	77.58	83.55	113.82	106.57	121.62
Total Non-Kernel Mass (g)	81.62	75.44	82.12	74.09	81.04	57.34	61.34	66.24	66.34	73.96	75.73	79.82
Non-Edible Water Mass (g)	5.64	5.29	5.92	5.20	5.74	2.17	5.85	6.25	6.39	7.09	6.92	6.93
Edible Portion Water Mass (g)	3.74	3.62	3.78	3.83	3.99	0.89	1.20	1.77	1.68	2.73	2.87	3.29
Total Water Mass (g)	9.38	8.91	9.70	9.03	9.73	3.06	7.05	8.02	8.07	9.82	9.79	10.22

Table A3.5: Pecan sample properties for both medium and high moisture content Giles pecan cultivar samples.

	Medium MC Giles (GM) and High MC Giles (GH) Samples						
Sample Property	GM1	GM2	GM3	GM4	GH1	GH2	GH3
Total Sample Mass (g)	159.85	161.31	161.29	162.50	171.41	182.86	173.20
Total Sample Volume (ml)	256.97	253.95	256.21	257.50	269.80	279.70	279.90
Sample Density (g/ml)	0.62	0.64	0.63	0.63	0.64	0.65	0.62
Sample Nuts/Kg	175.16	173.58	173.60	172.31	163.35	153.12	161.66
Percent Fill (edible ml/total ml)	0.39	0.41	0.40	0.40	0.39	0.41	0.38
Edible Kernel Mass (g)	79.54	82.45	81.54	82.52	82.29	90.68	76.62
Shell Mass (g)	70.00	69.08	69.76	69.78	74.62	78.86	77.23
Packing Material Mass (g)	9.05	8.52	8.60	8.94	8.55	9.48	8.83
Non-Edible Kernel Mass (g)	0.00	0.00	0.00	0.00	2.27	1.06	7.39
Weevil Larvae Mass (g)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Non-Edible Mass (g)	79.05	77.60	78.36	78.72	85.44	89.40	93.45
Total Kernel Mass (g)	79.54	82.45	81.54	82.52	84.56	91.74	84.01
Total Non-Kernel Mass (g)	79.05	77.60	78.36	78.72	83.17	88.34	86.06
Non-Edible Water Mass (g)	7.11	6.99	7.00	7.10	12.64	14.02	14.36
Edible Portion Water Mass (g)	3.10	3.07	2.86	3.01	5.70	6.51	5.81
Total Water Mass (g)	10.21	10.06	9.86	10.11	18.34	20.53	20.17

Table A3.6: Pecan sample properties for medium moisture content Kanza pecan cultivar.

	Medium MC Kanza Samples		
Sample Property	KM1	KM2	KM3
Total Sample Mass (g)	194.87	181.29	182.54
Total Sample Volume (ml)	0.00	301.18	294.83
Sample Density (g/ml)	0.66	0.60	0.62
Sample Nuts/Kg	102.63	110.32	109.57
Percent Fill (edible ml/total ml)	0.38	0.37	0.39
Edible Kernel Mass (g)	89.38	93.03	94.26
Shell Mass (g)	78.27	79.95	80.47
Packing Material Mass (g)	11.26	11.95	11.35
Non-Edible Kernel Mass (g)	8.94	4.91	6.35
Weevil Larvae Mass (g)	0.00	0.00	0.07
Total Non-Edible Mass (g)	98.47	96.81	98.24
Total Kernel Mass (g)	98.32	97.94	100.61
Total Non-Kernel Mass (g)	89.53	91.90	91.89
Non-Edible Water Mass (g)	9.24	9.31	9.37
Edible Portion Water Mass (g)	3.28	3.41	3.35
Total Water Mass (g)	12.52	12.72	12.72

Table A3.7: Pecan sample properties for both medium and high moisture content Maramec pecan cultivar samples.

	Medium MC Maramec (MM) and High MC Maramec (MH) Samples						
Sample Property	MM1	MM2	MM3	MM4	MH1	MH2	MH3
Total Sample Mass (g)	194.87	181.29	182.54	195.79	205.37	213.41	218.38
Total Sample Volume (ml)	274.48	269.86	272.68	272.19	304.50	305.00	315.20
Sample Density (g/ml)	0.71	0.67	0.67	0.72	0.67	0.70	0.69
Sample Nuts/Kg	102.63	110.32	109.57	102.15	97.39	93.72	91.58
Percent Fill (edible ml/total ml)	0.48	0.44	0.44	0.49	0.43	0.46	0.45
Edible Kernel Mass (g)	115.31	101.47	101.44	115.77	110.97	117.90	120.79
Shell Mass (g)	68.25	67.20	66.37	68.38	76.24	75.95	78.94
Packing Material Mass (g)	10.47	10.52	10.80	10.79	12.57	12.96	13.01
Non-Edible Kernel Mass (g)	0.00	0.81	3.04	0.00	2.01	3.06	2.06
Weevil Larvae Mass (g)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Non-Edible Mass (g)	78.72	78.53	80.21	79.17	90.82	91.97	94.01
Total Kernel Mass (g)	115.31	102.28	104.48	115.77	112.98	120.96	122.85
Total Non-Kernel Mass (g)	78.72	77.72	77.17	79.17	88.81	88.91	91.95
Non-Edible Water Mass (g)	7.78	7.70	7.81	7.92	17.93	17.66	18.48
Edible Portion Water Mass (g)	3.70	3.28	3.40	3.91	11.45	12.37	13.43
Total Water Mass (g)	11.48	10.98	11.21	11.83	29.38	30.03	31.91

Table A3.8: Pecan sample properties for both medium and high moisture content Pawnee pecan cultivar samples.

	Medium MC Pawnee (PM) and High MC Pawnee (PH) Samples					
Sample Property	PM1	PM2	PM3	PH1	PH2	PH3
Total Sample Mass (g)	216.68	221.70	221.25	239.95	236.37	238.33
Total Sample Volume (ml)	327.52	324.58	323.14	336.30	331.90	345.00
Sample Density (g/ml)	0.66	0.68	0.68	0.71	0.71	0.69
Sample Nuts/Kg	110.76	108.25	108.47	100.02	101.54	100.70
Percent Fill (edible ml/total ml)	0.44	0.47	0.46	0.49	0.48	0.45
Edible Kernel Mass (g)	124.38	132.97	124.38	138.36	141.43	131.12
Shell Mass (g)	70.66	71.35	72.48	76.16	74.83	79.86
Packing Material Mass (g)	15.44	15.21	15.64	16.01	16.22	16.93
Non-Edible Kernel Mass (g)	3.87	0.00	6.49	5.37	0.00	6.14
Weevil Larvae Mass (g)	0.00	0.00	0.00	0.00	0.00	0.00
Total Non-Edible Mass (g)	89.97	86.56	94.61	97.54	91.05	102.93
Total Kernel Mass (g)	128.25	132.97	130.87	143.73	141.43	137.26
Total Non-Kernel Mass (g)	86.10	86.56	88.12	92.17	91.05	96.79
Non-Edible Water Mass (g)	13.38	11.91	12.49	19.75	19.10	20.53
Edible Portion Water Mass (g)	5.15	5.32	5.03	14.55	17.08	15.41
Total Water Mass (g)	18.53	17.23	17.52	34.30	36.18	35.94

APPENDIX IV

DIELECTRIC MEASUREMENT DATA

Table A4.1: Signal attenuation and phase measurements for low moisture content Giles (GL), Kanza (KL), Maramec (ML) and Pawnee (PL) pecan cultivar samples at frequencies selected for presentation in Chapter IV.

Frequency (GHz)	0.4084	1.0309	0.4333	0.4582
Sample	Signal Attenuation (dB)		Signal Phase Shift (neg. degrees)	
GL1	0.33311	0.48485	4.6095	3.4273
GL2	0.3454	0.512	4.6917	3.5636
GL3	0.3468	0.50451	4.7814	3.6493
GL4	0.32879	0.48267	4.9524	3.2976
GL5	0.33004	0.49359	4.497	3.3992
GL6	0.26825	0.38491	3.7366	2.7989
GL7	0.28565	0.41615	4.0031	2.9924
GL8	0.32186	0.47595	4.475	3.3261
GL9	0.30744	0.43864	4.2933	3.1894
GL10	0.31039	0.42793	4.2571	3.204
GL11	0.32489	0.49803	4.5011	3.3332
GL12	0.32771	0.51393	4.6119	3.4305
KL1	0.40991	0.83612	6.1246	4.2465
KL2	0.40519	0.77902	5.9814	4.1523
KL3	0.39615	0.79314	5.888	4.1036
KL4	0.41866	0.83395	6.1676	4.3493
KL5	0.39639	0.78943	5.9314	4.201
KL6	0.28904	0.46749	4.311	3.0739
KL7	0.3124	0.53047	4.6462	3.2814
KL8	0.32639	0.56693	4.7996	3.3373
KL9	0.35995	0.66347	5.4507	3.8259
KL10	0.35314	0.68443	5.2712	3.7072
KL11	0.3746	0.73792	5.6525	3.9732
KL12	0.39099	0.76058	5.7974	4.0774
ML1	0.37249	0.63937	5.2003	3.7754
ML2	0.40137	0.72242	5.4874	4.0609
ML3	0.40137	0.72242	5.4874	4.0609
ML4	0.39205	0.7281	5.5204	4.0062
ML5	0.39176	0.70997	5.3206	3.9125
ML6	0.29313	0.47553	4.358	2.993
ML7	0.30779	0.52494	4.552	3.1668
ML8	0.33003	0.47834	4.7197	3.3246
ML9	0.33878	0.54104	4.855	3.3557
ML10	0.34011	0.52816	4.8048	3.3034
ML11	0.33703	0.54046	4.7641	3.3335
ML12	0.37516	0.63382	5.3947	3.7638
PL1	0.4132	0.70281	5.8911	4.2914
PL2	0.40072	0.84034	5.9782	4.2716
PL3	0.43082	0.87414	6.4725	4.624
PL4	0.39945	0.83618	6.014	4.2904
PL5	0.41241	0.90133	6.3048	4.4932
PL6	0.28123	0.51105	4.4639	3.0484
PL7	0.28475	0.52912	4.409	3.2297
PL8	0.32963	0.63621	4.9602	3.6982
PL9	0.33811	0.6703	5.0607	3.7382
PL10	0.40084	0.81027	6.0332	4.4737
PL11	0.3866	0.78043	5.7905	4.2643
PL12	0.41436	0.88603	6.0941	4.7115

Table A4.2: Signal attenuation and phase measurements for Giles, Kanza, Maramec, and Pawnee (G, K, M, and P respectively) pecan cultivar samples with low, medium, and high (L, M, and H respectively) moisture content at frequencies selected for presentation in Chapter IV.

Frequency (GHz)	0.4084	1.0309	0.4333	0.4582
Sample	Signal Attenuation (dB)		Signal Phase Shift (neg. degrees)	
GL1	0.33311	0.48485	4.6095	3.4273
GL2	0.3454	0.512	4.6917	3.5636
GL3	0.3468	0.50451	4.7814	3.6493
GL4	0.32879	0.48267	4.9524	3.2976
GL5	0.33004	0.49359	4.497	3.3992
GM1	0.35267	0.54202	5.2941	3.928
GM2	0.35408	0.52733	5.3291	3.9104
GM3	0.35948	0.5238	5.1255	3.8891
GM4	0.3434	0.54115	5.1964	3.753
GH1	0.49657	0.82438	8.477	6.7132
GH2	0.54414	0.8985	9.1937	6.9636
GH3	0.53697	0.86084	9.2207	6.8475
KL1	0.40991	0.83612	6.1246	4.2465
KL2	0.40519	0.77902	5.9814	4.1523
KL3	0.39615	0.79314	5.888	4.1036
KL4	0.41866	0.83395	6.1676	4.3493
KL5	0.39639	0.78943	5.9314	4.201
KM1	0.41485	0.61042	6.1562	4.5166
KM2	0.40744	0.6067	6.1209	4.4652
KM3	0.41159	0.62932	6.2072	4.5909
ML1	0.37249	0.63937	5.2003	3.7754
ML2	0.40137	0.72242	5.4874	4.0609
ML3	0.40137	0.72242	5.4874	4.0609
ML4	0.39205	0.7281	5.5204	4.0062
ML5	0.39176	0.70997	5.3206	3.9125
MM1	0.41857	0.69602	6.2263	4.4867
MM2	0.39615	0.65622	6.0098	4.4517
MM3	0.39651	0.64598	5.979	4.3913
MM4	0.4183	0.68008	6.2628	4.6025
MH1	0.77808	1.2059	12.294	9.0967
MH2	0.78617	1.2264	12.344	9.1455
MH3	0.80398	1.2692	12.791	9.4935
PL1	0.4132	0.70281	5.8911	4.2914
PL2	0.40072	0.84034	5.9782	4.2716
PL3	0.43082	0.87414	6.4725	4.624
PL4	0.39945	0.83618	6.014	4.2904
PL5	0.41241	0.90133	6.3048	4.4932
PM1	0.50838	0.8279	8.035	5.8352
PM2	0.51648	0.81817	7.2541	4.7828
PM3	0.51949	0.83943	8.1568	5.922
PH1	0.8502	1.3788	13.647	10.208
PH2	0.84667	1.4296	13.722	10.356
PH3	0.84905	1.4149	13.668	10.273

VITA

Joshua D. Grundmann

Candidate for the Degree of

Master of Science

Thesis: NON-DESTRUCTIVE QUALITY ANALYSIS OF IN-SHELL PECANS USING MICROWAVE DIELECTRIC SPECTROSCOPY

Major Field: Biosystems and Agricultural Engineering

Biographical:

Personal Data: Born in 1984 in Shawnee, Oklahoma to John and Janice Grundmann.

Education: Graduated from Shawnee High School, Shawnee, Oklahoma in May, 2003. Received Bachelor of Science in Biosystems and Agricultural Engineering at Oklahoma State University, Stillwater, Oklahoma in May, 2007. Completed the requirements for the Master of Science in Biosystems and Agricultural Engineering at Oklahoma State University, Stillwater, Oklahoma in May, 2009.

Experience: Graduate Research Assistant at Oklahoma State University from August, 2007 through May, 2009.

Name: Joshua D. Grundmann Date of Degree: May, 2009

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: NON-DESTRUCTIVE QUALITY ANALYSIS OF IN-SHELL PECANS USING MICROWAVE DIELECTRIC SPECTROSCOPY

Pages in Study: 69 Candidate for the Degree of Master of Science

Major Field: Biosystems and Agricultural Engineering

Scope and Method of Study: The application of non-destructive pecan quality assessment is important to both pecan growers and pecan buyers and would allow quick, easy, and reliable quality checks of pecan batches before transactions occur. This research analyzed pecan samples using electromagnetic waves in the radio/microwave range from 100 MHz to 2.5 GHz with an open air transmission-type measurement device. Fifteen to 20 new-crop samples each of the Maramec, Kanza, Pawnee, and Giles cultivars ranging from 20 to 28 nuts per sample depending on the size of the cultivar were analyzed for the signal attenuation and phase shift caused by the sample of pecans using a network analyzer. Samples of each cultivar varied in both overall quality and moisture content. Physical quality parameters of each sample were also measured, such as in-shell density, edible kernel mass, non-edible kernel mass, volume percent fill, packing material mass, shell mass, kernel water content, and shell water content. Each measure of quality was correlated with the signal attenuation and phase shift caused by the sample at each of the 101 measured frequencies, with the best matches reported.

Findings and Conclusions: Results suggest there is a linear correlation between both total kernel mass and edible kernel mass with both signal attenuation and phase shift measurements in the 400 to 500 MHz and 1.00 to 1.10 GHz ranges, while there is very little correlation between shell mass and signal attenuation and phase shift at any frequency. At these same frequencies the mass of water in the kernel can be correlated with both signal attenuation and phase shift measurements. Results can be applied to design a non-destructive and automatic pecan grading machine to further the market technologically.

ADVISER'S APPROVAL: Dr. Carol L. Jones