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JAMES COOK UNIVERSITY

Ground Detection Sensor for Cane Harvester Base-Cutter Height Control

Thesis submitted by

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Abstract

The harvesting of sugar cane is the first stage in the commercial milling of sugar cane to produce sugar and plays a major role in determining the overall efficiency of the sugar production process. In Australia, where virtually all sugar cane is harvested using mechanical harvesters, efficient operation of the harvester is essential to reduce operating costs. One area of harvesting that has, on numerous occasions, been identified as an impediment to improved harvester efficiency is the adjustment of the base cutter height. Improper setting during harvesting has a number of serious consequences for sugar production including reduced production, crop damage, additional harvester running costs and inefficient transportation and milling of the sugar cane due to the introduction of dirt.

The overall aim of this thesis was to develop a ground detection sensor based on microwave radar technology that could sense ground level in front of a working sugar cane harvester. The eventual purpose of such a device would be to automatically control the cutting height to the optimum level and thus improving the efficiency of the harvesting, farming and milling processes.

The measurement technique investigated is based upon the use of a radio transmitter and receiver positioned on either side of the row of sugar cane. The principle of this design is that a receiver close to ground level would experience more attenuation from the soil than a receiver positioned well above ground

level. Thus, it was suggested that changes in the received signal strength with respect to the height above ground level could be used to detect changes in the height of the ground.

The project evolved in two main stages. Initially, work concentrated on verifying the sensing principle in the laboratory and later in the field. Testing verified the proposed measurement procedure with the following major conclusions. Firstly, for best results a radio signal of 2-3GHz polarised horizontal to the ground was most suitable. This signal provided the best compromise between being insensitive to the presence of the sugar cane while still allowing practical sized antennas to be employed. Secondly, field-testing showed that the sugar cane stalks do affect the ideal sensor response with the orientation and condition (density, leaf matter, etc) of the sugar cane having a noticeable influence on the measurements. These results suggested that a practical sensor would need to incorporate automatic compensation for the variations in the sugar cane and that some averaging or signal processing would have to be applied to remove the underlying trends.

The second stage of the project involved building a prototype sensor and testing it on a working sugar cane harvester. The prototype worked by measuring the received amplitude of a 2.4GHz, horizontally polarised microwave radio signal that was transmitted from one side of the sugar cane row to the other. For this application, multiple receivers are stacked vertically to measure the full height profile instantaneously. The idea of using multiple receivers with some positioned well above the ground level, was to compensate for the changing density of the sugar cane. The transmitter and receiver antennas were based on rectangular microstrip patch antenna arrays. The low profile of these patch antennas meant that they were ideal for flush mounting on the harvesters' crop divider walls. Dedicated transmitter and receiver electronics was also needed to generate and detect the microwave radio signals used by this system. A full control system and data logger was developed for this application.

The prototype sensor that was developed was trialled on an Austoft harvester over a one week period in the Burnett region. Theses tests were used to confirm that the sensor would work and that it could survive the harsh conditions experienced during harvesting.

Overall, the aim of this thesis was to test the potential of the microwave ground height detection sensor for automated control of the base cutter height on sugar cane harvester and to develop a plan to use this technology in a commercial base cutter height control system.

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3. WOODS, G.S. and PAGE, R.L. "Automated base cutter height control" JCU Sugar Technology 2000, Conference 8th November 2000.

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Chapter 1: Background

1.1 Introduction

Sugar cane is the main agricultural crop grown in Queensland producing almost ninety-five percent of all the raw sugar produced in Australia. In 2000-2001, 4.14 million tons of raw sugar was produced from around thirty million tons of harvested sugar cane [1]. Sugar is the second largest export crop for Australia and is estimated to be worth in excess of A$1 billion to the Australian economy[1]. Australia produces four percent of the world's raw sugar but exports the majority of this, which totals twelve percent of the world's raw sugar trade each year. Ninety-nine percent of the sugar exported by Australia is supplied directly by the Queensland sugar industry.

Sugar is grown in Australia in the following three regions, Queensland, New South Wales and Western Australia, with each respectively producing approximately 94.2 percent, 5.1 percent and 0.7 percent of Australia's harvested sugar each year. After the harvesting process the sugar cane is refined into raw sugar at one of Australia's thirty sugar mills; there are twenty-six raw sugar mills located in Queensland, three in New South Wales and one in Western Australia

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[1] This figure is based upon the 1999/2000 Australian season.

[2]. Australia also produces refined sugar from four sugar refineries; two are located in Queensland, one in New South Wales and one in Victoria. Queensland directly exports eighty-five percent of the raw sugar produced and refines the other fifteen percent. New South Wales refines all raw sugar produced, while all of the raw sugar produced in Western Australia is directly exported.

The deregulated world sugar market is perceived as a volatile market and it is essential for the Australian sugar industry to remain competitive by optimising the efficiency and profits of all aspects of the production process. The high labour costs for the Australian workforce, when compared to other countries, directly affects the profitability of the industry and as such, automated processes are often required to achieve high efficiency and produce higher quality product to increase these profits.

The harvesting and transport of sugar cane has been identified as having a major influence on the efficiency of the whole industry [3]. In particular, inaccurate setting of the base cutter height and the subsequent collection of particulate contamination with the harvested sugar cane is known to be one of the factors contributing to the inefficiencies in the production of sugar. Previous studies have indicated that increased cutting accuracy will lead to reduced costs for the sugar refining mills as well as increased sugar quality for farmers [4]. By achieving precision control over this single parameter, farmers, millers and harvesting contractors could expect to obtain greater returns due to the reduced operating costs and higher production rates. It is therefore not surprising that the automatic control of the harvester base cutter depending on the ground height has been a long-time goal of the Australian sugar industry.

1.2 Growing Sugar Cane

All of the raw sugar produced in Australia is refined from sugar cane. Sugar beet is the only other commercial source for sugar, but is generally only used in the temperate parts of the world [17]. Seventy percent of the world's sugar is produced form sugar cane, while the remaining thirty percent is produced from the sugar beet.

Growing sugar cane usually involves planting three hundred millimetre long sections of the cane stalk, called billets, in long furrows and burying them. Figure 1.1 shows a sugar cane paddock before the billets have been planted. The billets are placed in bottom of the furrow and then covered with soil to form a row of sugar cane along the length of the paddock. The root system of the sugar cane plant emanates from the billet that was planted, which has been covered by two hundred millimetres of soil.

Figure 1.1: Sugar cane paddock before planting of sugar cane.

On average a sugar cane paddock is only replanted with new billets every four years; the crop regrowth during the second and consecutive years is called ratoon sugar cane. Ratoon crops result in slightly lower crop yields and quality, but eliminate the requirement of replanting a sugar cane paddock every year, saving farmers both time and money. The planted billets are cultivated for a period of up to sixteen months before being harvested. During this time the sugar cane commonly grows to a height of between two and four meters with the diameter of the individual stalks ranging between thirty to fifty millimetres.

Sugar cane is harvested in Australia using mechanical harvesters that try to cut the stalks of the sugar cane at ground level, strip the trash from the stalks, if the sugar cane is harvested green, and finally cuts the stalks into short lengths to optimise the volume of the harvested sugar cane during transport to the raw sugar mills. The harvested sugar cane is either placed directly into sugar cane train bins that are loaded onto tractor trailers and then transported to the mills or more commonly nowadays the tractors use custom trailers that hold large quantities of harvested sugar cane that is then tipped into the sugar cane train bins. This increases productivity by minimising the required number of tractors and drivers.

After the harvesting process, the cut sugar cane is transported by either rail or road to a sugar mill for processing into raw sugar. Raw sugar is pale brown in colour and must be further refined, at a sugar refinery, before the pure white substance that most people are familiar with is produced. Just over eighty percent of the raw sugar produced by Australian mills is exported and sold on the world sugar market [1].

1.3 Problems with Inefficient Base cutter Height Control

Inefficient harvesting methods affect all three major sectors of the Australian sugar industry. The three sectors are: -

- The farming sector, which produce the sugar cane,
- The harvesting sector, which harvest the sugar cane and
- The milling sector, which transport and process the sugar cane.

The effects of inefficient height control upon these sectors, including estimates of additional expenses from dirt in the sugar cane supply, are described below. It should be noted however, that the costs estimates provided here are based on the extrapolation of old data and assume reductions in dirt levels will provide proportional decreases in operating costs. Obviously, these assumptions will not be completely valid but certainly the figures quoted do give some indication to the magnitude of the problem.

1.3.1 Benefits to the Farming Sector

The process of mechanical harvesting can cause problems if the sugar cane is cut either too high or too low with respect to the ground level during the harvesting process. When the sugar cane stalks are cut too high, they may shatter introducing diseases into the plant causing a loss of production in subsequent years. On the other hand, if the sugar cane stalks are cut too low, the stool, or the root system may be damaged leading to similar results. In either case, instead of being able to achieve four seasons' growth from the same plant, earlier replanting may be required. It has been shown that during the raw sugar refining process, the Commercial Cane Sugar (CCS) level is degraded in proportion to the percentage of dirt in the harvested sugar cane [4]. The lowered CCS level signifies that a reduced quantity of raw sugar is produced per ton of cane. The reduction of the CCS level affects the farmers directly as the price paid to the producer is directly related to the CCS level of the sugar cane sold to the mill.

The current extraneous matter content of sugar cane that has been mechanically harvested is, on average, 1.7 percent per tonne. The Bureau of Sugar Experimental Stations (BSES) has calculated that the CCS level of sugar cane is reduced by 0.18 for each percent of extraneous matter present in the harvested sugar cane [5]. It has also been shown by Hankel that optimal harvesting results in less that 0.5 percent extraneous matter per tonne of cane harvested. As such, it can be calculated that by optimising the harvesting process through base cutter height control the CCS level would be increased by approximately 0.22. This increase in the CCS level would in turn increase the return per tonne of sugar cane by A$0.45[II]; equivalent to a total increase in revenue exceeding A$15 million per year for the farming sector[III].

Ultimately the use of automatic base cutter height control would optimise the return per tonne by maximising the CCS levels. Correct base cutter control will also result in less damage to ratoon cane and therefore increased ratoon yield in subsequent years. Less disruption to the row profile would most probably also lead to a reduction of soil erosion.

[II] Based upon a CCS level of 11.00.

[III] Assuming 35 million tonnes of sugar cane is harvested per year. The costs were calculated based upon prices paid to farmers in the year 2000 season.

1.3.2 Benefits to the Harvesting Sector

Over the years, sugar cane harvesting has changed dramatically. One of the biggest changes has been the introduction of the mechanical harvester. The first mechanised harvester was invented and patented just over one hundred years ago, but only became popular in Australia during the 1940's and 1950's. A photograph of a modern sugar cane harvester is shown in Figure 1.2 with detailed photographs of the base cutter blades shown in Figure 1.3 and Figure 1.4. It can be seen that the base cutter position on the harvester is located directly below the harvester cabin, out of the view of the operator. Automatic control of the base cutter would mean that the base cutter height would be adjusted to track the changes in height of the ground level. Height adjustment of the base cutter is currently crudely achieved by the operator manually adjusting the cutting height up or down using hydraulic controls based upon their experience and "gut feeling".

Figure 1.2: Photograph of the front of a sugar cane harvester.

Figure 1.3: Photograph of the row dividers and base cutter of a harvester.

Figure 1.4: Close-up photograph of the base cutter of a harvester.

Since the introduction of the mechanical harvester there has been a steady increase in the level of extraneous matter in the harvested sugar cane that is transported to the mills [6]. Figure 1.5 was obtained from Anon (1953-1991) Annual synopsis of chemical control figures, (Bureau of Sugar Experimental Stations) and shows the trend that extraneous matter has increased over time as has the horsepower of the sugar cane harvesters.

Figure 1.5: Trend of extraneous matter at mill over time.

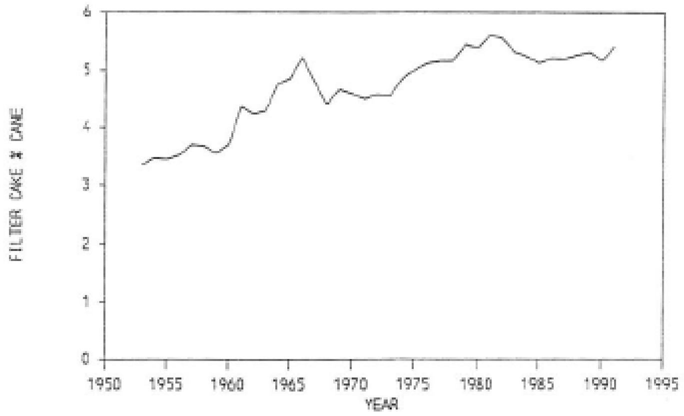

Figure 1.1 **Historical Trend of Filter Cake % Cane in Queensland Factories (from Anon., 1953-1988, Anon., 1989, 1990 and 1991)**

The power of modern harvesters makes it possible to cut well below ground level with no noticeable effect on the speed, or other indicators on the harvester. Again however, there is a down side to cutting too low due to the increased wear and tear on the machinery, particularly the base-cutter blades. Unnecessarily loading the machine also increases operating costs through extra fuel and oil usage. Despite this, anecdotal evidence suggests most sugar cane farmers request that the contactors cut their sugar cane below ground level to presumably give them the best return on their crops.

The cost savings estimated by Neves et al for the reduced wear on the base-cutter blades was US$4400.00 per season[IV]. This figure assumes that the harvester operates for twenty-four hours per day. Amending this figure to eight hours per day over a two hundred day season, provides an estimate that Australian harvester operators could expect cost savings of the order of US$1400.00 per season by using a moderately effective base-cutter height control system.

Automatic control of the base-cutter height should lead to reduced wear for the cutting blades and less maintenance and running costs for the harvester. However, the full improvement will only be possible if farmers and harvester operators can be convinced of the benefits of proper height settings.

1.3.3 Benefits to the Refining Sector

With up to 40 million tonnes of sugar cane being processed each year in Australia, even a small reduction in milling costs will translate into significant savings to the sugar industry. In 1986, Mason and Garson performed an investigation into the extra costs associated with the milling of sugar cane contaminated with extraneous matter [7]. It was concluded that the cost to the sugar industry was A$0.62 per tonne of sugar cane to

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[IV] IV Based upon a two hundred day harvesting season.

maintain the milling facilities due to the extraneous matter. Assuming that inflation has increased at a rate of three percent each year over the past fifteen years, the cost today should be approximately A$1.06 per tonne for maintenance of the mill.

Assuming the current average amount of soil in harvested sugar cane is around 1.7 percent [6], it can be estimated that by reducing this level to around 0.5 percent by optimising the cutting height, a total saving of approximately A$0.74 per tonne to the sugar milling community could be expected. This figure corresponds to an estimated reduction in running costs to the milling sector of up to A$29 million each year.

These figures are based solely on the maintenance costs to the milling sector. In practice, in addition to these costs, there is extra expenditure associated with the transportation of the extra material to and from the mill, reduced sugar quality and quantity, and extra wear on milling facilities. These factors mean that the actual costs to the milling sector are much greater than those estimated above.

The microwave ground level detection sensor investigated in this application was primarily designed for base-cutter height control. However, there are a number of different systems on board a harvester where ground height measurements may be usefully employed to better control the harvesters operation. Some of these other applications include the row divider height control as well as positioning the harvester centrally in respect to the sugar cane row. Although the described sensor might be useful in these situations, these applications were not explicitly examined in this project.

1.4 Background

Ever since the introduction of the mechanical harvester, there has been a steady increase in the level of dirt in the harvested sugar cane that is transported to the mills [6]. One factor that has contributed to this rise is the increased power of modern harvesters. With a more powerful machine, it becomes easier to cut at a lower level because the operator does not experience any adverse side effects such as reduced speed of operation when cutting below ground level. Harvester operators are therefore more inclined to err towards cutting on the low side to satisfy the farmers desire to maximise their crop yield. Another reason for increased dirt levels seems to be the common perception amongst the farming community that cutting lower improves profits through a greater mass of material being harvested. This view remains common despite recent studies showing that the trade off in adding more dirt to the harvested sugar cane will often result in reduced profits due to a lowering of the CCS levels [8].

The current opinion on the introduction of automatic base-cutter height control to the harvester is that this system will probably be similar to a car's cruise control system. That is, the operator will be free to set the base-cutter height to the level that he (or the farmer) desires and the control system will simply try to maintain the set position of the base-cutter height from the ground. Obviously then, improvements in the reduction of dirt in harvested sugar cane will depend largely on the proper use of this technology and thus whether operators and farmers can be convinced of the benefits of trying to reduce soil levels in harvested sugar cane. However, these concerns were not the focus of this project. One immediate benefit of an automatic base-cutter height control system though will be that the problem of continuously adjusting the base-cutter height to track small changes in ground height can be overcome. An automatic system will make it possible for the operator to use a "set and forget" approach confident in the knowledge that the base-cutter height will be adjusted to follow the contour of the sugar cane row at the specified cutting height.

1.5 Sensing Techniques

Currently, Australian sugar cane harvesters use no form of automatic base-cutter height adjustment. The harvester operator is required to manually adjust the base-cutter level from within the cabin. However, due to the positioning of the base cutters directly below the harvester cabin, the operator is unable to directly observe the cutting height. It seems that most operators therefore adjust the base-cutter based on “experience”, though some claim they make adjustments using a combination of a visual inspection of the row profile behind the harvester and/or by observing the pressure reading of the base cutter's hydraulic motor. In any case, it is

clearly very difficult to accurately determine the base-cutter height setting from inside the harvester cabin, and thus the setting is rarely optimal. The typical view that a harvester operator has of the row profile can be seen in both Figure 1.6 and Figure 1.7. Moreover, it would be physically impossible to make the many small adjustments manually that would be required to track the row profile over the length of the sugar cane paddock even if the operator could accurately judge the current base cutter setting relative to the ground level due to the many other controls that must be operated.

Figure 1.6: The typical view of from the cabin of a harvester during operation.

Figure 1.7: Close-up photograph of the operator's view to the ground below.

There have been a number of proposals over the past twenty years or so of methods to control the base-cutter height on mechanical harvesters. It appears that most of these approaches have had limited success due to the difficult measurement environment involved. From a control point of view it is highly desirable to measure the ground height in front of the base-cutter so that the base-cutter height can be adjusted to suit the required ground height profile. However, when sensing the ground height in front of the base-cutter, a sensor has to contend with the presence of the sugar cane. The sugar cane stalk and leaf can obscure a sensors "view" of the soil or may cause fouling and even damage to the sensor. Measuring ground height behind the base-cutter has the advantage that most of the sugar cane has been removed and the sensor will have a clearer view of the soil. On the other hand, when measuring behind the base-cutter, the passing of the base-cutter nearly always disturbs the soil making it near impossible to get an accurate reading of the ground level. Furthermore, the lag between cutting the sugar cane and measuring the actual ground height, means the control system is continuously playing "catch up" and hence will not perform as well as a forward looking system.

There are two distinct classes of devices that have been tested for base-cutter height control. One style of device that has been tried in many different forms can be broadly termed a "mechanical contact sensor". This type of sensor might use a skid or wheel to gauge the ground height [9]. Generally, this type of sensor suffers from fouling by the sugar cane, leaf matter and mud that can be found around the base cutter region on the harvester. Figure 1.8 shows the amount of sugar cane trash that gets caught in behind the harvester's row dividers.

Figure 1.8: Photograph of trash caught behind the row divider of the Austoft R & D harvester after harvesting.

The other style of ground level detection sensor can be broadly labelled as a "non-contact sensor". This type of sensor attempts to determine the position of the soil by detecting changes in a field or a travelling wave that interacts with the surroundings. Some sensors of this type include ultrasonic sensors that measure delays of a sound wave or radar sensors that detect variations in a travelling electromagnetic (EM) wave. The main advantages of the non-contact type sensors is that the measurement device does not disturb the ground level and there is less chance of fouling, as the sensor does not physically contact the soil or the sugar cane. For similar reasons, non-contact sensors also tend to require less maintenance to ensure reliable operation.

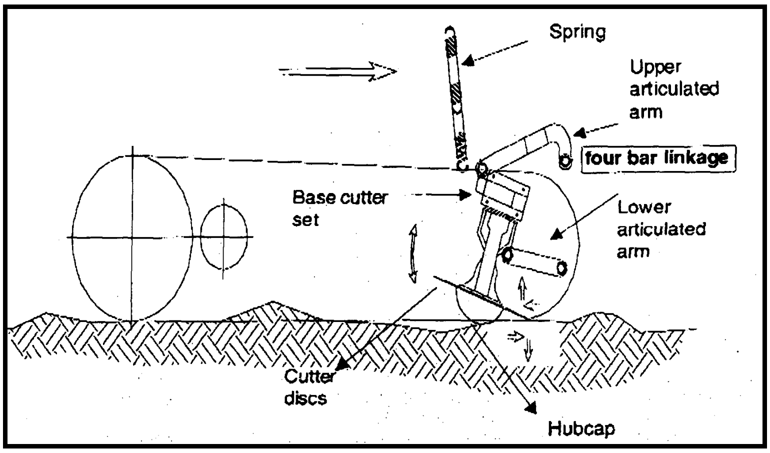
1.5.1 Mechanical Contact Sensors

Simplicity is quite often the best approach to practical problems, and measuring the ground height using a skid or wheel at first seems the most practical and logical concept of all. These systems use angle sensors and other techniques to measure a distance or angle created by the mechanical sensing device to calculate the location of the ground.

However, to date most of these types of sensors have had little success. Mechanical sensors in front of the base-cutters are usually unsuitable due to interference from trash, mud, and even the sugar cane itself [10]. Trash and debris is often caught in the device causing jamming of the mechanical movement rendering the sensor useless. In some devices the skid or wheel uses a spring to maintain contact with the soil, but when operating in soft or muddy paddock conditions, the spring drives the sensing device into the soil, breaking or damaging it in the process. This problem is worse in areas where flood irrigation creates soft or muddy paddocks. Sugar cane can also grow along the ground, stopping the sensor from making contact with the ground and hence giving an inaccurate reading.

Recently, a base-cutter height control system being trialled on Brazilian sugar cane harvesters has been publicised [11]. This system uses a "floating" base-cutter arrangement with a raised dome "hubcap" below the base-cutters to raise the base-cutter height when the ground level increases, refer to Figure 1.9. This type of system measures directly behind the base-cutter, which is less desirable from a control point of view. Furthermore, there is no information available on how this device might operate in soft or muddy conditions. Never the less, this is an interesting idea and it would be worth investigating this approach further.

Figure 1.9: Brazilian floating base cutter design for sugar cane harvesters



When the variation in row height is less than one hundred millimetres the hub cap can maintain contact with the surface of the ground due to the suspension system that is used to adjust the base-cutter to follow the contour of the row, thus reducing the extraneous matter content of the harvested sugar cane by approximately half [11]. It should be noted that these tests were conducted during a period where very little rain occurred biasing the results towards dry soil conditions. It is probable that as with past mechanical measurement devices that this device would not be suitable for the entirety of a typical Australian harvesting season and in particular might not be useful in the very wet regions.

The Brazilian test results have proven that the benefits of using an automated control system would improve the efficiency of the harvesting process. If the base-cutter height is maintained at close to the top of the row, then extraneous matter included in the harvested sugar cane could be halved resulting in significant cost savings for harvester operators.

1.5.2 Hydraulic Pressure Sensors

This technique involves monitoring the pressure across the hydraulically driven base-cutter motor. In theory, the pressure should vary as the base-cutter starts to cut more deeply through the more dense soil [10]. The base-cutter essentially becomes the mechanical contact sensor in this approach. Unfortunately, more recent studies [4] have shown that the base-cutter pressure does not vary in a predictable manner. In particular, the base-cutter pressure was found to vary non-linearly with both the cutting height and the harvester's travel speed, making it difficult to use this method with any confidence. At best, it seems this technique will only be useful as a crude indication of when the base-cutter is working well below the ground level.

1.5.3 Ultrasonic Sensors

In this approach, an ultrasonic signal is transmitted and subsequently reflected by the ground. The time difference between sending a signal and receiving the reflection is measured and used to determine the distance that the signal travelled. The Sugar Research Institute (SRI) has been investigating the use of ultrasonic detection for base-cutter height control for a number of years [6]. Their investigations have shown that if the sugar cane is cut green or only partially burnt, then the trash surrounding the stool often blocks the ultrasonic signal. Since most sugar cane is now harvested green, there seems little possibility of using an ultrasonic sensor in front of the base-cutter. Investigators at SRI have had better success using ultrasonic technology when installed in a position not prone to blockage from sugar cane trash. Using ultrasonic sensors for base-cutter control would only be a feasible option if the sensors were located behind the base-cutter, which is not the optimal solution.

1.5.4 Microwave Sensors

Microwaves, being an electromagnetic wave, will penetrate most materials (except conductors) to differing degrees. A microwave ground height detection sensor for use on board a sugar cane harvester is therefore an attractive concept as such a device may be suitable for positioning in front of the harvester base-cutter. There have been previous investigations into the feasibility of utilising microwave radar technology for ground height measurement applications [12]. Shin, Dodd and Han examined the potential for using a dual-frequency radar measurement technique at a frequency of around 1GHz. However, this work was all conducted in the laboratory and no conclusive results were obtained.

More recently, Ruxton conducted preliminary studies as to whether a microwave detection system could be used to measure the ground height for the base-cutter control application [13]. Ruxton's laboratory experiments showed that a microwave radar system that measured reflections from the ground using the radar ranging technique was not suitable due to the strong interference from reflections off of the sugar cane. However, it was shown that a "transmission style" sensor might be appropriate for this measurement application. A microwave sensing technique was proposed where the attenuation of a signal transmitted just above the ground was measured. In this configuration, it was found that the signals were reasonably insensitive to the presence of the sugar cane and that the attenuation of the signal increased significantly as the height of the antennas approached ground level. Further investigations into this sensing approach were conducted in 1999 by Page to determine the optimum transmission frequency and antenna characteristics for the newly developed microwave sensing technique [14]. This work led to the operational specifications of transmission frequency, antenna beamwidth, polarisation and equipment configuration for the microwave detection system that has been further developed in this thesis.

The development of the transmission style microwave sensing technique has been well documented [15],[16]. SRDC funded a research grant between July 1999 and July 2002 for the purpose of developing this sensing technique towards the goal of developing a commercially viable sensor.

1.5.5 Other sensors

There are undoubtedly other sensor types that could be considered for this application. Obviously though it is most feasible to investigate the simplest, cheapest and safest approaches first.

Another approach that possibly has not been tried as yet for this application is a nuclear sensor. The radioactive decay of a nuclear material can be measured through virtually any material, including metals. By measuring the energy of the radioactive particles that escape from a source in different directions, it is possible to judge the density of the medium through which the particles have travelled. It should therefore be possible to determine when the particles pass through only sugar cane and when the transmission path includes a proportion of denser material such as the soil. In this way, the distance to the ground could be measured in front of the base-cutter. The main advantage (and disadvantage too) of a nuclear sensor is that the radioactive particles will penetrate virtually any material, making this type of sensor suitable in even the most difficult measurement applications. Obviously, when using a radioactive material there are always some health and safety concerns that would make this sensing technique a last resort.

1.6 Aim

The aims of this study were to:

1) To determine the optimum operating frequency range and polarization state of a microwave sensor to measure ground level through sugar cane.

2) To test various sensor configurations for this application in order to find the optimum arrangement.

3) Build a prototype microwave ground level detection system, which could operate in the harvesting environment, and was suitable for

future development towards control of the base-cutter height and other sugar cane harvester operations.

To achieve these objectives the first step taken was to verify that the microwave transmission sensor approach was suitable for the base-cutter height control application. This was to be conducted through a series of laboratory and field tests. These preliminary investigations were also used to determine the best configuration of the sensor for use on a sugar cane harvester.

The second stage was concerned with the building of a prototype sensor and testing on an operational sugar cane harvester. While it would have been nice to have produced a functional sensing system for commercial use on board a sugar cane harvester to control the base-cutter height, this would have been an unachievable task, and was not an aim of this study. What was to be achieved was to ensure the suitability of a microwave ground level detection sensor for this application. The control of the base-cutter height based upon an output from the new sensor and testing the effectiveness of the control system is a topic for future work.

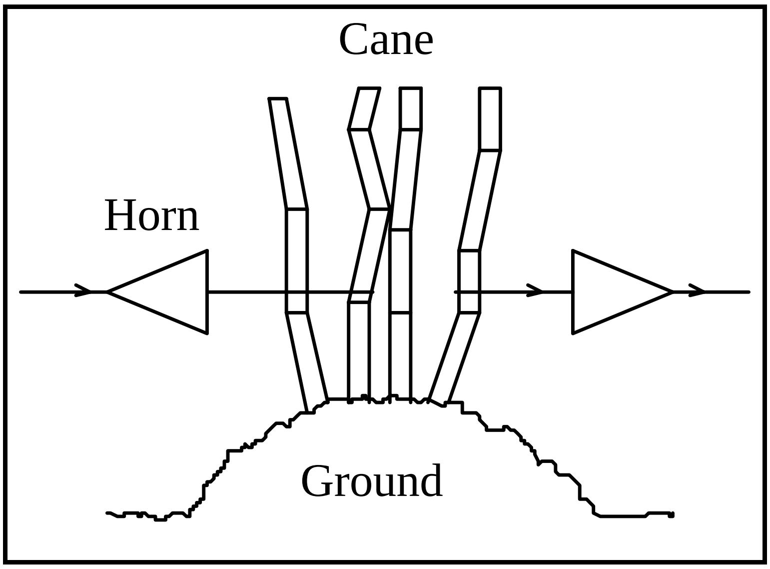
Chapter 2: Laboratory Testing

2.1 Introduction

The first stage of this project was concerned with testing the sensing technique in the laboratory. The work conducted by Ruxton [13] and Page [14], had shown that the only viable measurement approach was a transmission style configuration, refer to Figure 2.1. This project therefore started with this configuration and worked towards determining the optimal transmission frequency, signal polarisation and antenna specifications for the application of sugar cane harvester base-cutter height control. The development of the sensor was primarily focused upon finding the best system specifications so that the sensor would optimally respond to the presence of the soil while being insensitive to the presence of the sugar cane. Previous work was relevant to this objective and some earlier results are recapped.

Before the results of these tests are reported though, this section includes a description of a computer simulation of the proposed measurement system. Although not a stated aim of this project, this work was considered useful to give a better understanding of the measurement principle and what system parameters would effect the operation of the sensor.

Figure 2.1: Transmission configuration of the microwave ground detection sensor



2.2 Simulation Results

2.2.1 Knife Edge Diffraction Model

Before experimental measurements were conducted, a simple theoretical model for of the sensing technique was examined. This model was based on the theory of "knife-edge diffraction" of electromagnetic waves [18]. This model totally neglected the effects that the sugar cane would have upon the results as the model was based upon a simple thin conductive sheet, which can be seen in Figure 2.2. The crude assumptions made by this model meant that very accurate results were not expected but it was hoped that it would provide a qualitative insight into the operational characteristics of the proposed technique.

The equation describing signal loss between the transmitter and receiver for this model is given as [18]:

$$L_d(dB) = \begin{cases} 0 \\ 6.02 + 9.0v + 1.65v^2 \\ 6.02 + 9.11v - 1.27v^2 \\ 13 + 20\log(v) \end{cases} \text{for} \begin{cases} \text{-0.8>v} \\ \text{-0.8} \le \text{v} \le 0 \\ 0 \ge \text{v} \ge 2.4 \\ \text{v>2.4} \end{cases} \tag{2.1}$$

where $v = h\sqrt{\frac{2}{\lambda_0}\frac{d_1 + d_2}{d_1 d_2}}$ and λ_0 is the free space wavelength of the transmitted frequency and h is the distance between the top of the knife-edge obstacle and the direct path between the transmitter and the receiver. Distance is defined as being negative if the line of a direct ray travelling between the transmitter and receiver passes above the top of the knife-edge obstruction. d_1 is the horizontal distance between the transmitter and the obstruction and d_2 is the distance between the obstruction and the receiver.

Figure 2.2: Knife-edge diffraction model of the sugar cane row

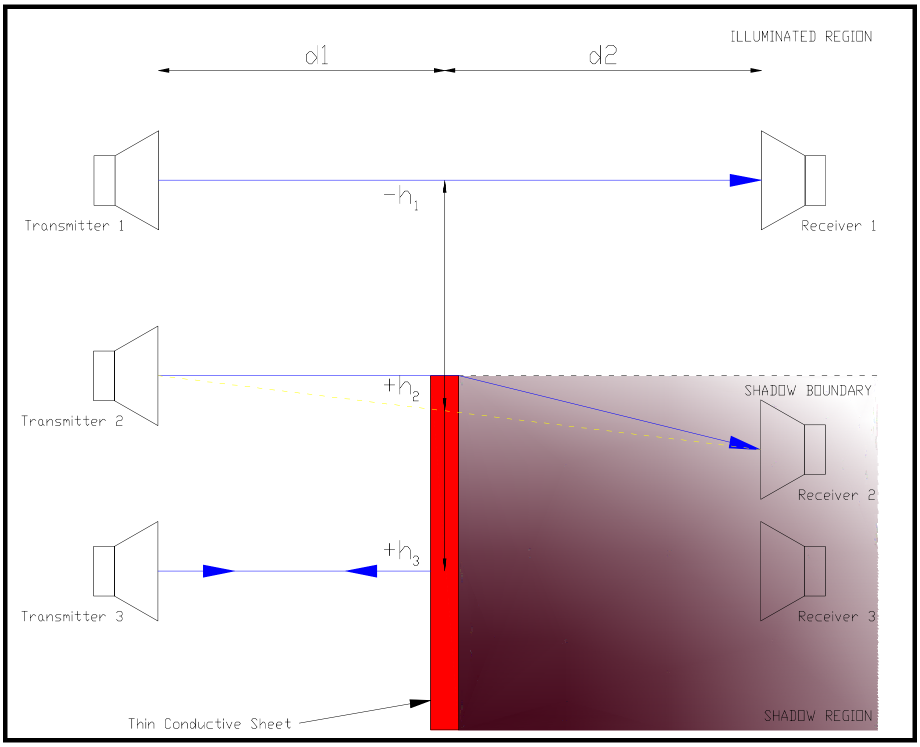
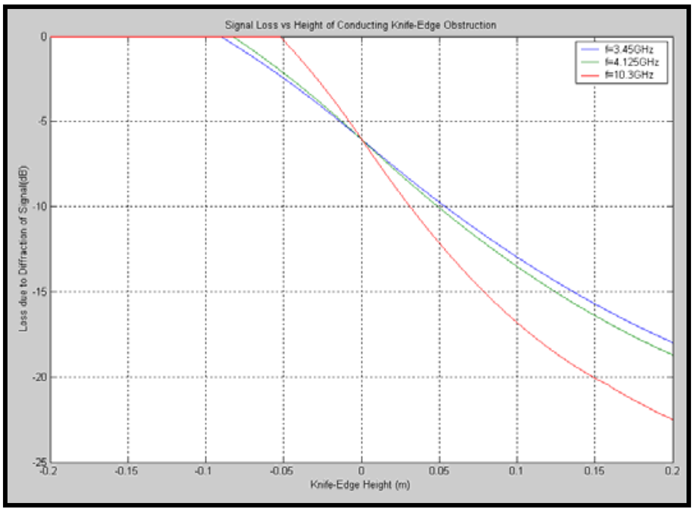


Figure 2.3 shows the results of signal attenuation versus height at frequencies of 10.3GHz, 4.125GHz and 3.45GHz. These three transmission frequencies were simulated, as they would be later used for the laboratory experiments.

Figure 2.3: Predicted signal loss around ground level for a "conducting knife-edge" obstruction.



Observing the results obtained in Figure 2.3 it is clear that this sensing technique should be able to detect height of the sugar cane row profile. All three of the simulated frequencies show that the amplitude of the received signal decreases as the transmission height approaches and then goes below the knife-edge obstruction. Above the obstruction the transmitted signal strength is only slightly attenuation, while below the obstruction the strength decreases almost linearly.

This theoretical model was useful to provide an insight into the typical operating characteristics that should be expected for this type of sensor. For example, Figure 2.3 shows that lower transmission frequency sensors will provide a greater measurement range, while higher frequency signals will be more sensitive to change in the height of the obstruction.

The microwave transmission properties can thus be used to select the optimal operating frequency of the sensor providing the following features for the sensor:

a) The physical characteristics of the sensor hardware can be influenced by the selected frequency as there are size constraints for the mounting of the sensor on a sugar cane harvester, and

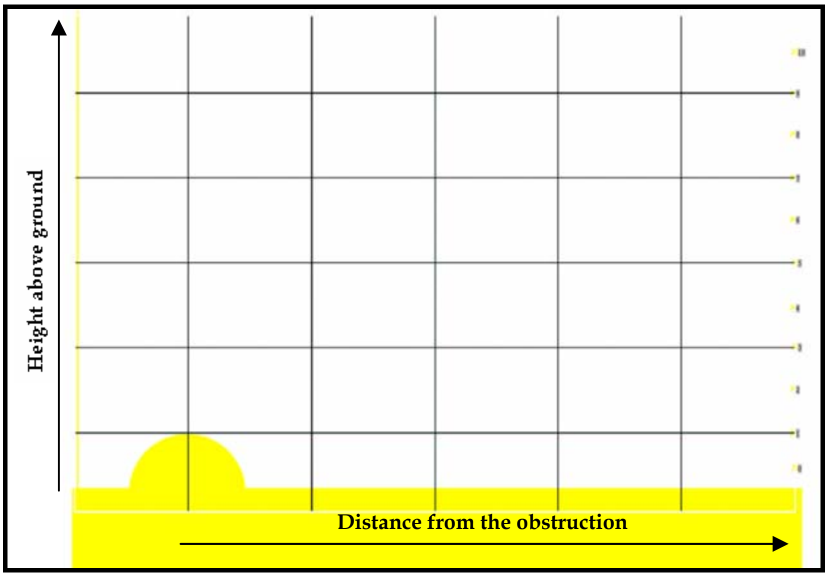
b) The developed sensor must ensure that a useful output is provided for the automated control of the base-cutter height of, a sugar cane harvester.

2.2.2 Electromagnetic Field Simulation

The knife-edge diffraction theory that was simulated above assumes that the obstruction is a thin, highly conductive material. In this particular application the obstruction is a combination of the sugar cane root mound and the row of soil. Neither the root mound nor the soil are “thin” or have the properties of a highly conductive material. There may therefore be some question about the validity of this model for this situation. To give a better appreciation of how the ground height detection sensor might respond in the actual measurement conditions to be encountered in a sugar cane paddock, an electromagnetic field simulation was also performed. An electromagnetic field was modelled using a full-wave, two-dimensional, electromagnetic simulator program called “Real Time” [19]. This simulation program is based on the Finite-Difference Time-Domain (FDTD) technique and illustrates the propagation of electromagnetic waves including reflection and diffraction effects.

The first test performed with the field simulation software was a repeat of the diffraction test mentioned above but assuming a “real” row profile and characteristics. The configuration of the model that was simulated is shown in Figure 2.4.

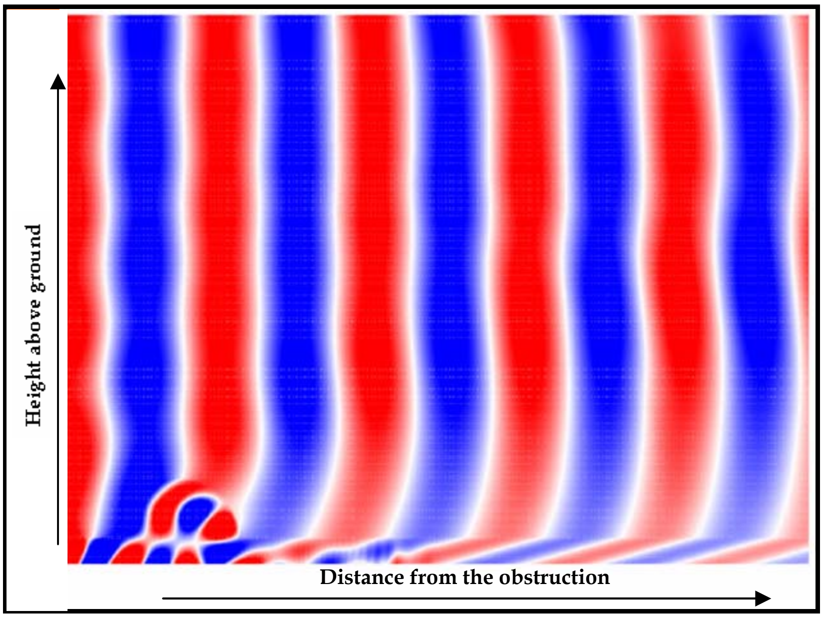
Figure 2.4: Configuration of the Real Time FDTD model used to simulate the effect of the sugar cane row profile.



The model assumes that a plane wave field at 2.5GHz is propagating from the left to right hand side of Figure 2.4. The field is polarised so as to be out of the page or horizontal to the ground as recommended by Page’s previous results. The position of the ground and the sugar cane root mound are shown in yellow in this figure. The soil was assumed to have a dielectric constant of 8.00 and a conductivity of 0.0011 [22]. These values were chosen to represent what might be classified as “moist soil”. The grid lines shown in Figure 2.4 are 100mm apart and thus the row height was assumed to be fairly low, less than 100mm high, however in practice it can often be twice this height. The effect of the ground on the propagating electromagnetic field was measured at the extreme right of the model using test probes located at different heights. The probes were positioned 500mm from the centre of the row to replicate the spacing of the sensors when mounted on a sugar cane harvester. The measurement probes where positioned 50mm apart with the first probe 20mm above the ground level. This placed the top probe just over 500mm above the ground level.

The field intensity at the end of the simulation period for the model is shown in Figure 2.5. The regions of dark red and blue show areas where the electromagnetic field is the strongest while the colour white represents where the field strength is zero. The red and blue colours show the different polarity of the field being either positive or negative. The cyclic intensity of the field as it propagates from the left to right hand side is thus clearly seen as the alternating of the red and blue bands. During the simulation, these bands can be seen to progress from left to right hand side as the electromagnetic field travels in that direction. Towards the top of Figure 2.5, well away from ground level, it can be seen that the electromagnetic field is not affected or attenuated by the presence of the row profile. However, closer to ground level, the intensity of the colours is lighter indicating that the field strength here is weaker than the region at the top of the model.

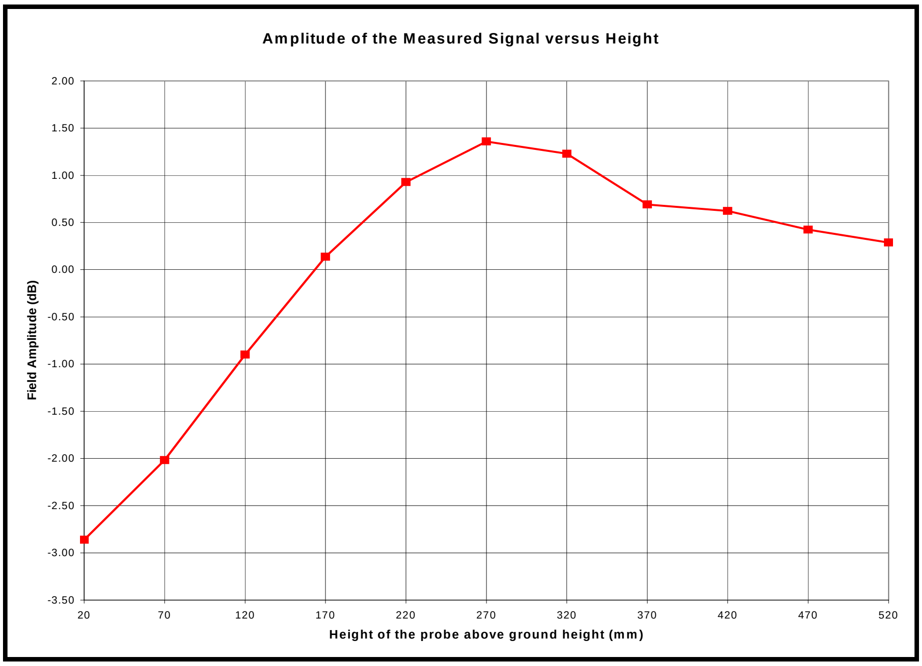
Figure 2.5: Results of the Real Time FDTD model that was used to simulate the effect of the sugar cane row profile.



Essentially, this is what was seen in the knife-edge diffraction model. As the height of transmission of the measured signal approaches the top of the row profile and goes below the obstruction, the field amplitude decreases.

Plotting the measurements recorded by the probes located on the right hand vertical of the model versus their distance above ground level gives a better visual indication of the effect that height has upon the electromagnetic field strength. The peak dB amplitudes of the measurements have been plotted in Figure 2.6

Figure 2.6: Real Time model of field amplitude in dB vs height.

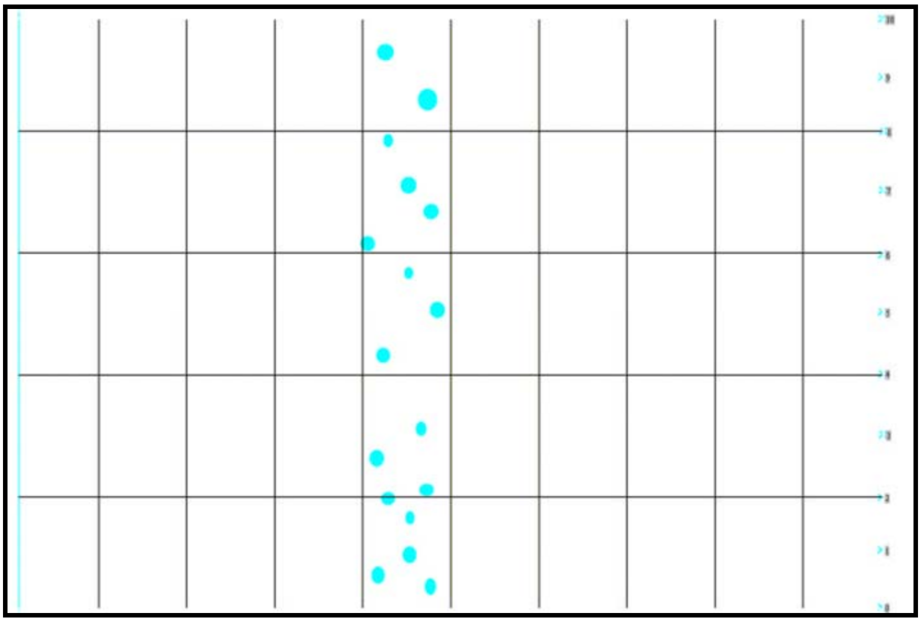


The trend shown in Figure 2.6 is very similar to the response predicted by the simple knife-edge diffraction simulation, Figure 2.3, and provided additional confidence that the microwave ground height detection sensor was a viable measurement technique.

In both of the two simulations, the presence of the sugar cane was neglected when predicting the amplitudes of the electromagnetic fields that would be measured around ground height in this application. In practice though, the sugar cane will have an effect on the measured field strength. Unfortunately, the orientation, size and density of the sugar cane plant will vary significantly throughout a sugar cane paddock and hence a typical model would be difficult to simulate. Furthermore, the electromagnetic field simulation software that was available for this project, only allowed for 2-dimensional structures to be modelled, and therefore could not take into account both affects of the ground and the sugar cane at the same time.

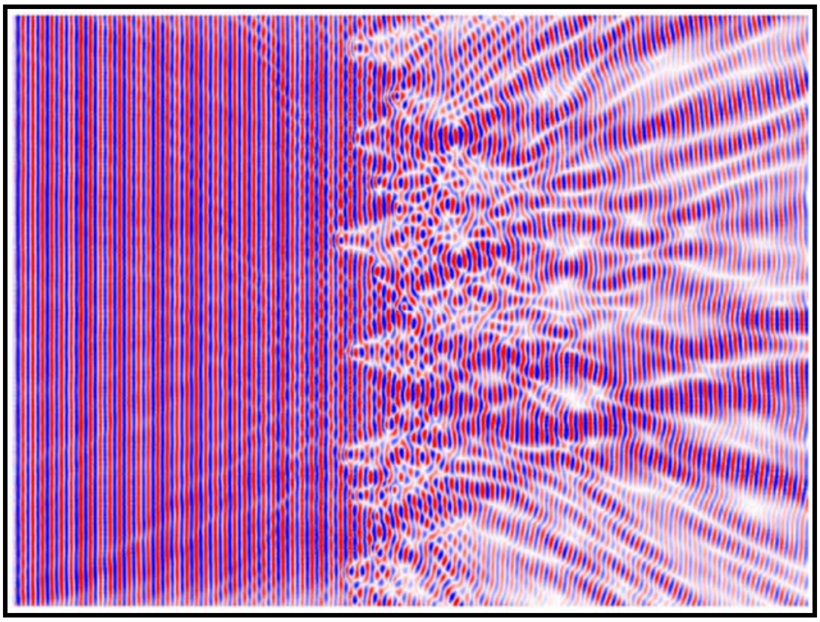
In order to get an idea of the effect of the sugar cane, it was decided to run a simulation of the model in the horizontal plane rather than the vertical plane; this was modelled and is shown in Figure 2.7. Thus, rather than simulating the field amplitude variation due to the height that the signal was positioned above ground level, the variation of the electromagnetic field at a set height along the length of a row of sugar cane was modelled.

Figure 2.7: Configuration of the Real Time FDTD model that was used to simulate the effect of the sugar cane.



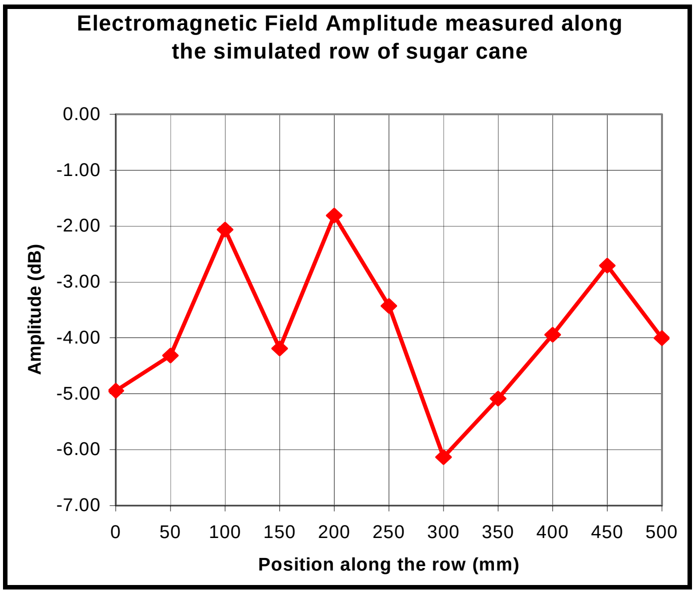
This simulation is similar to the previous one and involves the propagation of a 2.5GHz electromagnetic plane wave, from the left to the right hand side of the model. However, the vertical axis of this model is now the position along the row of sugar cane, rather than the height above the ground. The grid spacing is again 100mm per division. The light blue dots along the centre of the model simulate the cross section of the sugar cane stalks placed randomly along the length of the simulated sugar cane row. The electrical characteristics of the sugar cane were modelled to have a dielectric constant of 2.00 and conductivity of 0.03 [20]. The electromagnetic field is polarised to be in the plane of the diagram, but because of the change of orientation, this again implies that the field is polarised horizontally with respect to the ground. The field at the right of the model was measured at different points using probes. The 2-dimensional colour plot of the field intensity at the end of a simulation period is shown in Figure 2.8.

Figure 2.8: Results of the Real Time FDTD model that was used to simulate the effect of the sugar cane.



Note that in the left hand half of the model the pattern displayed the alternating blue and red bands that are characteristic of a travelling wave propagating from the left to right hand side without interference. As the propagating electromagnetic field interacts with the sugar cane at the centre of the model, the field amplitude is affected which is depicted by the lighter colouring of the field intensity on the right hand side of the model. There is also a distinct streaking pattern of the field intensity in the right hand half of the model as the field strength is affected by the multi-path propagation of the transmitted electromagnetic waveform through the sugar cane. The multi-path signals are combined on the right hand side of the model either in or out of phase producing constructive or destructive interference. The significance of these results is that the simulation shows that the sugar cane will attenuate the transmitted electromagnetic field, however, this attenuation level will not be constant along the length of the row. This is clearly shown by plotting the dB values of the field amplitude that is measured by the probes in the model. The results can be seen in Figure 2.9.

Figure 2.9: Electromagnetic field strength measured along a model of a sugar cane row using the Real Time FDTD software – Probe measurements in dB.



As expected, the results shown in Figure 2.8 demonstrate that the electromagnetic field strength will vary due to the changing characteristics of the sugar cane along the length of the row. These results imply that the commercial application of the microwave technique for detecting the ground level will require some form of digital signal processing to filter the measurements and detect the underlying trends that are caused by the signal attenuation due to the height above ground.

It was tempting to further investigate the simulation results of this model to further establish the required averaging ranges and the accuracy level that could be expected of the technique as well. However, the focus of this project was a practical study and as such no further investigation was undertaken.

2.3 Laboratory Measurements

Having theoretically established a principle by which the ground height might be measured, it was necessary to test this idea in practice. This was a very important stage of this project where measurements of the proposed technique were performed under laboratory conditions.

A system for testing the propagation of the microwave signals through sugar cane and around the root system of the plant was designed and built at James Cook University. This system comprised of a rectangular plastic tray onto which a stool of sugar cane could be positioned. The tray was braced and supported by ropes so that the tray and the stool of sugar cane could be manually raised and lowered using a block and tackle pulley arrangement. To measure the attenuation of the microwave test signal with respect to ground height, two microwave horn antennas were statically mounted on either side of the sugar cane stool while it was raised and lowered. A vector network analyser (Hewlett Packard model 8722A) was connected via radio frequency cables to the horn antennas. With each set of antennas connected the transmitted signal was referenced with no obstruction between the transmitter and the receiver to eliminate the effect of the different gains of the three antennas. The amplitude of the signal transmitted was then measured through the sugar cane at various heights above the row sample. Measurements were logged and were analysed at a later date.

Using the test system described above, the amplitude of the received signal was measured as it was transmitted at different heights above ground level. Tests were performed on three different sugar cane samples using three different frequency band signals; S-Band (2.6-3.95GHz), C-Band (3.3-4.9GHz) and X-Band (8.2-12.4GHz). In all cases the transmitted signal was polarised horizontally to the ground[V].

[V] Ruxton established in a preliminary study that this was the preferred polarisation state to minimise interference from vertical cane stalks.

The three sugar cane samples that were tested originated from two different areas; one sample was from the Burdekin region and two samples from the Herbert region. The sample from the Burdekin (Sample #1) was striped of trash to simulate burnt sugar cane. The Burdekin samples were quite thick (the diameter of the stalks was between 25mm and 30mm) but the sample was also quite old and was almost dead. The two Herbert stools were both alive but were somewhat different; one sample (Sample #2) possessed reasonably thick stalks (diameters between 20mm and 25mm) and had a lot of trash while the second sample (Sample #3) was thinner (diameters between 15mm and 20mm) and also had noticeably less trash.

The results from the measurements obtained using these samples are shown graphically in Figure 2.10 to Figure 2.21. Figure 2.10 to Figure 2.12 show the results of transmission through the “burnt” sugar cane, which has been referred to as Sample#1, and shows the response for the three frequency bands respectively. Figure 2.13 to Figure 2.15 shows the results for the thicker diameter sugar cane stalks, or Sample#2. Figure 2.16 to Figure 2.18 shows the results for the thinner sugar cane sample, Sample#3. Figure 2.19 to Figure 2.21 show 2-dimensional plots of the average frequency response for signal amplitude versus height of transmission in the three frequency bands respectively.

Figure 2.10: 3D S-Band Plot for Sample #1

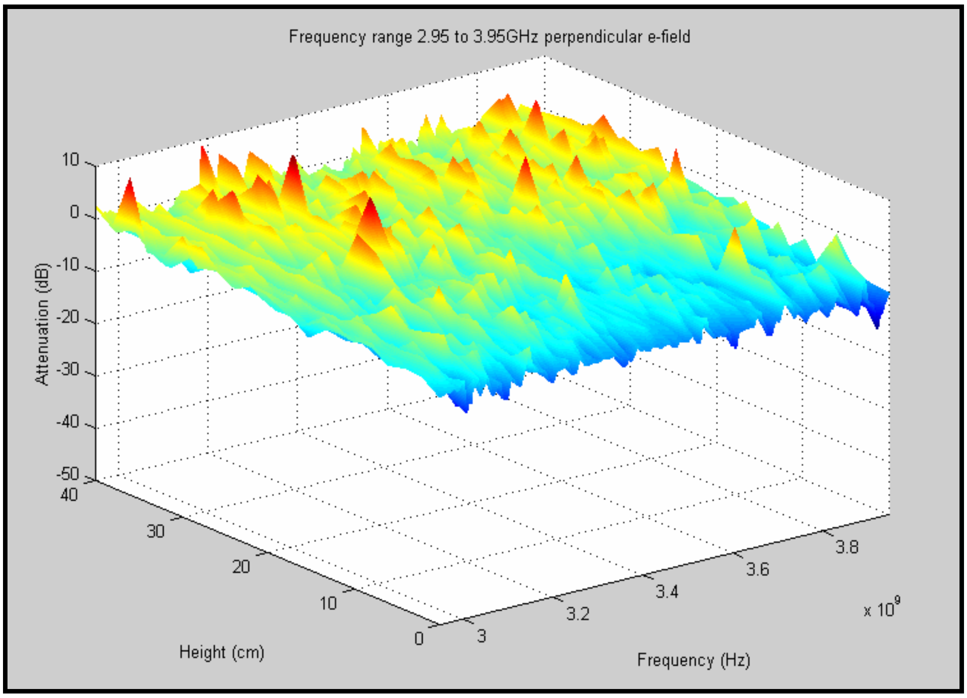


Figure 2.11: 3D C-Band Plot for Sample #1

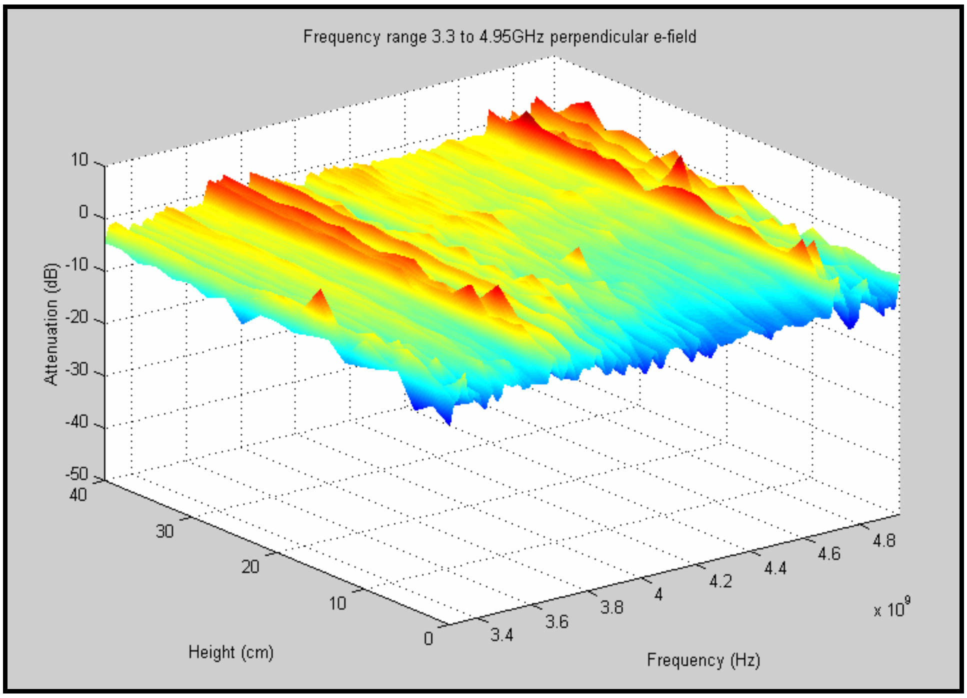


Figure 2.12: 3D X-Band Plot for Sample #1

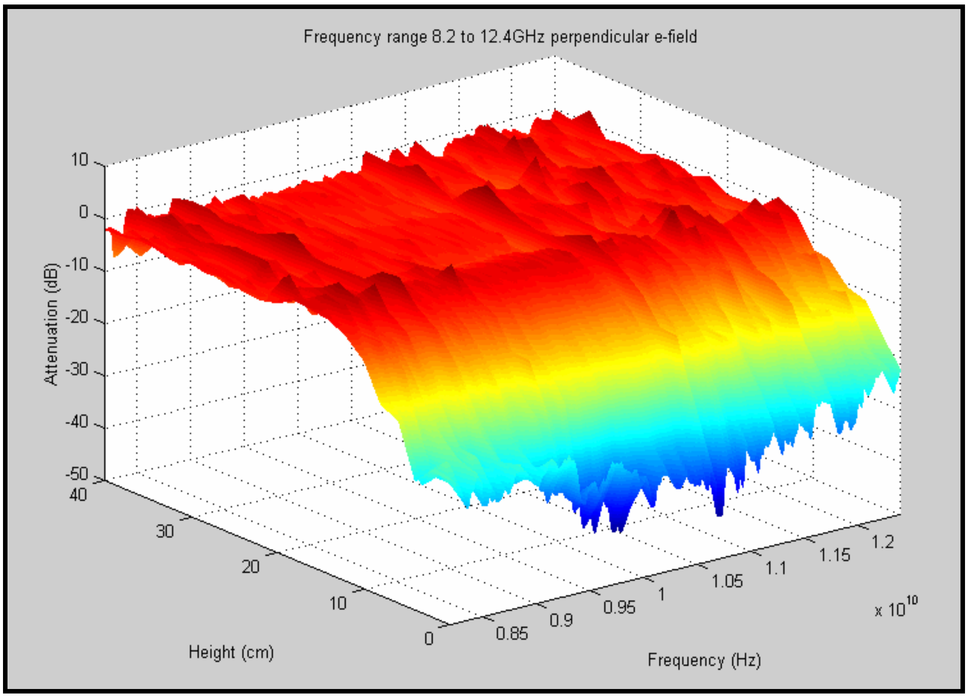


Figure 2.13: 3D S-Band Plot for Sample #2

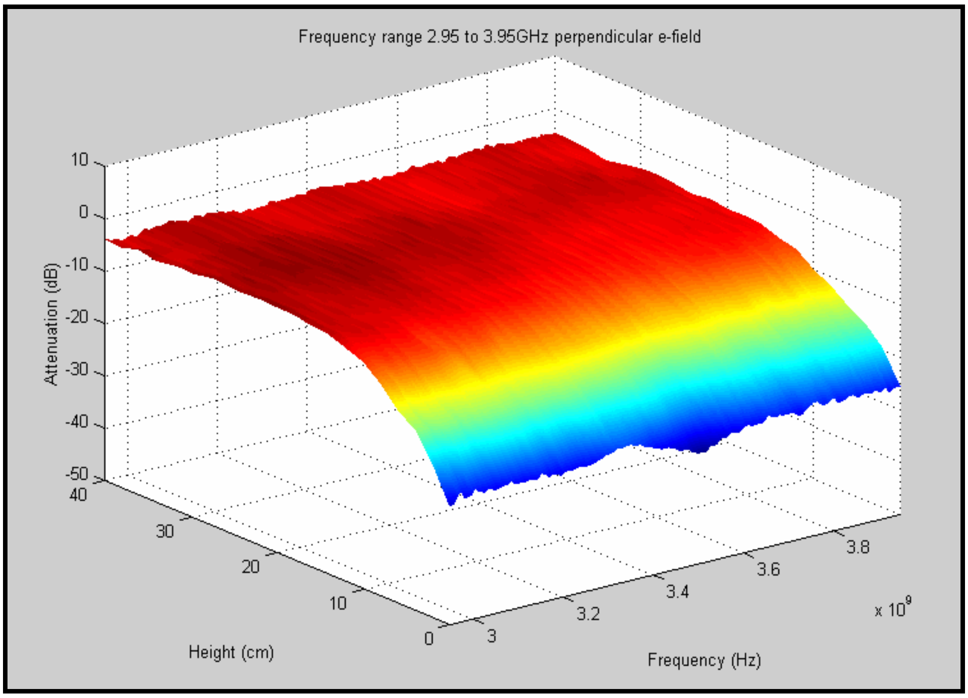


Figure 2.14: 3D C-Band Plot for Sample #2

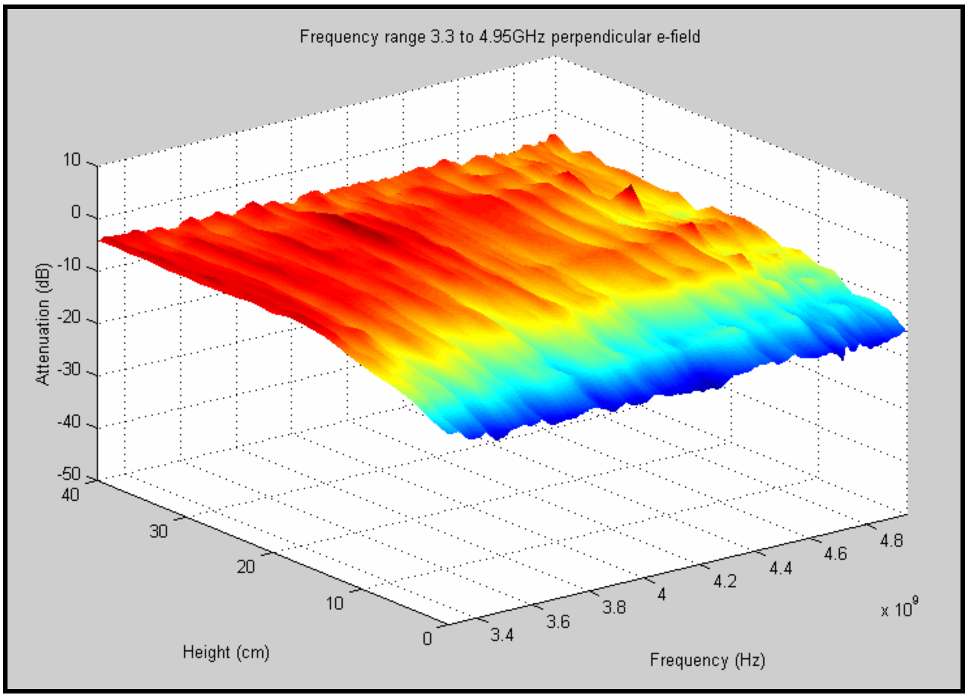


Figure 2.15: 3D X-Band Plot for Sample #2

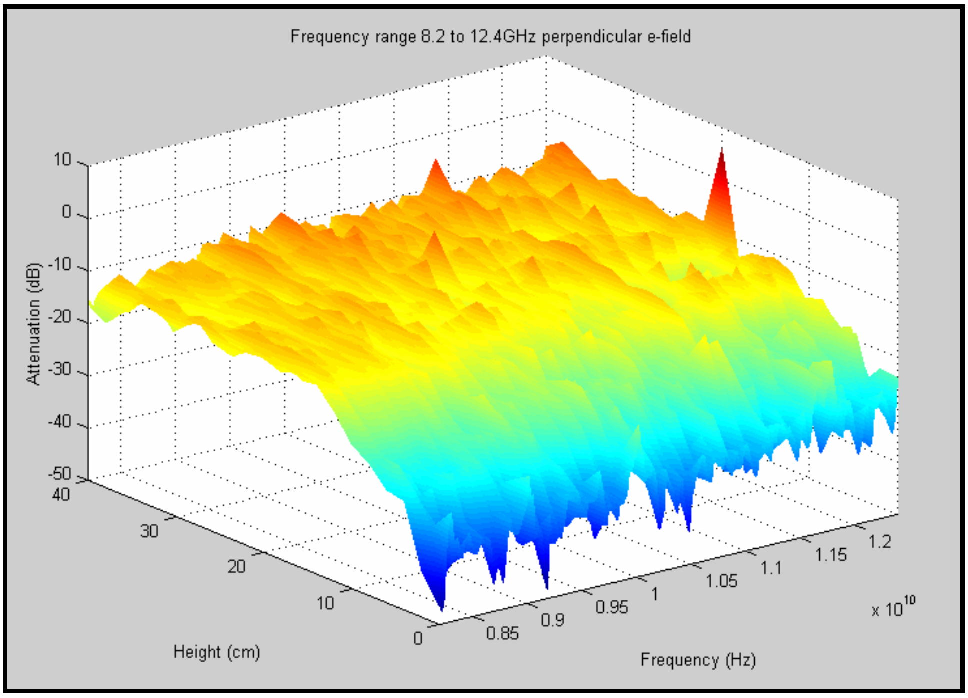


Figure 2.16: 3D S-Band Plot for Sample #3

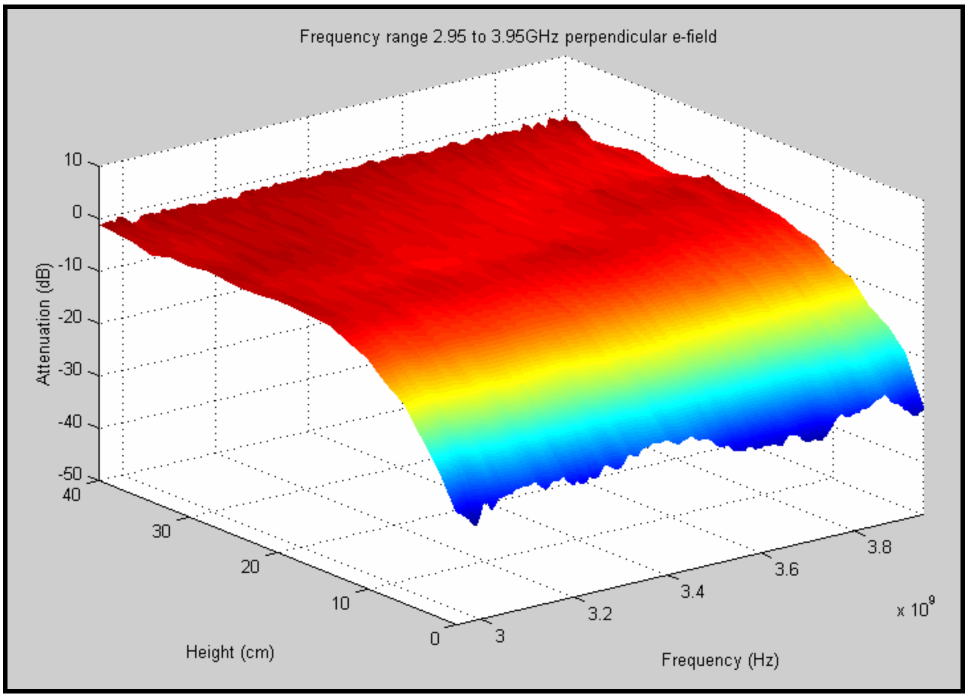


Figure 2.17: 3D C-Band Plot for Sample #3

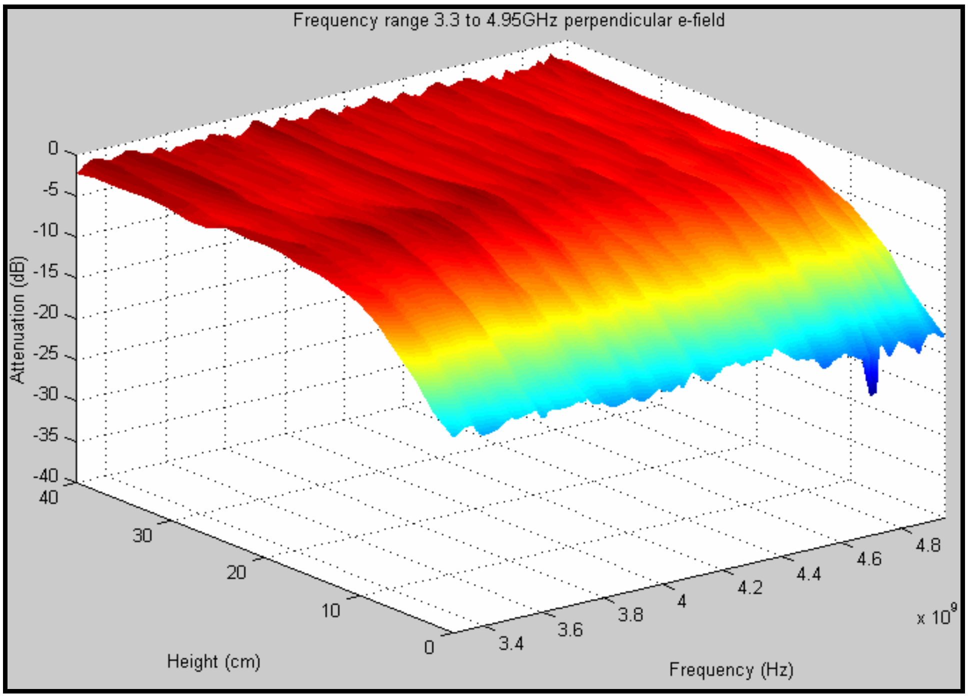


Figure 2.18: 3D X-Band Plot for Sample #3

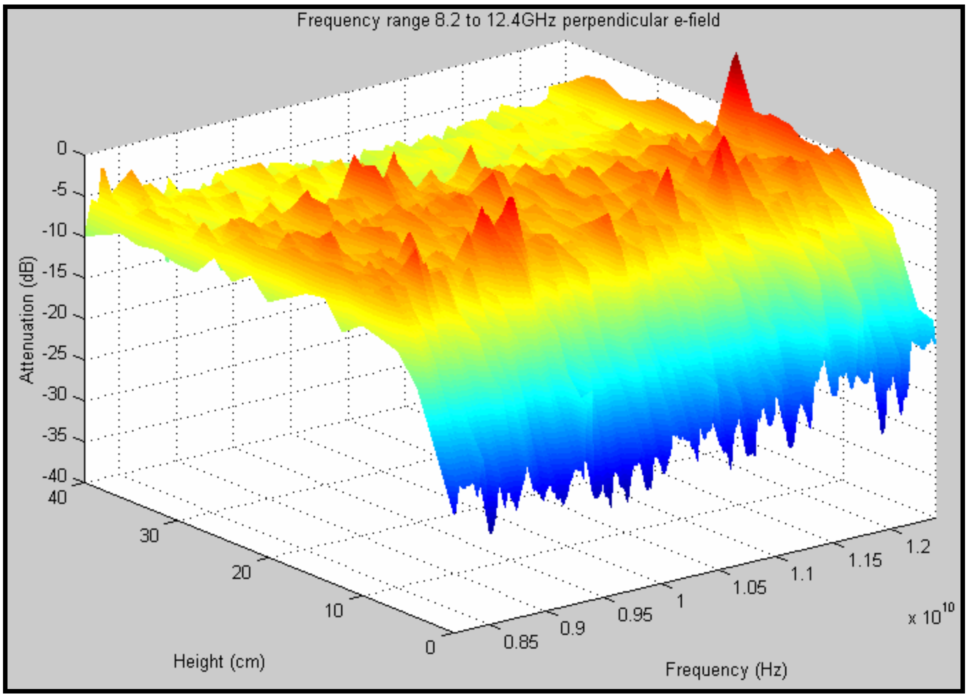


Figure 2.19: 2D S-Band Plot for all Samples

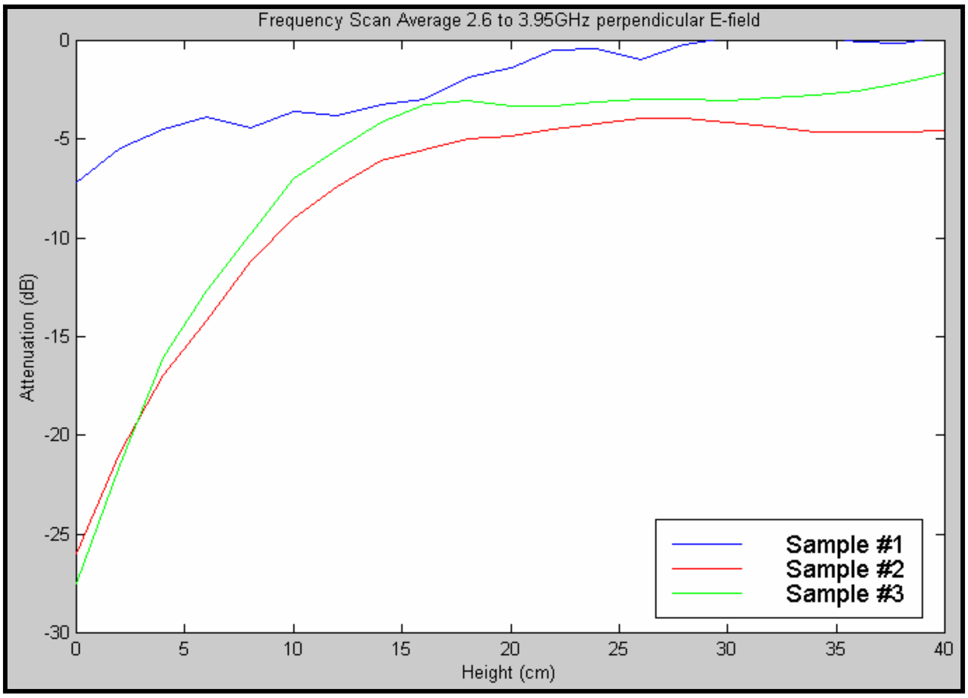


Figure 2.20: 2D C-Band Plot for all Samples

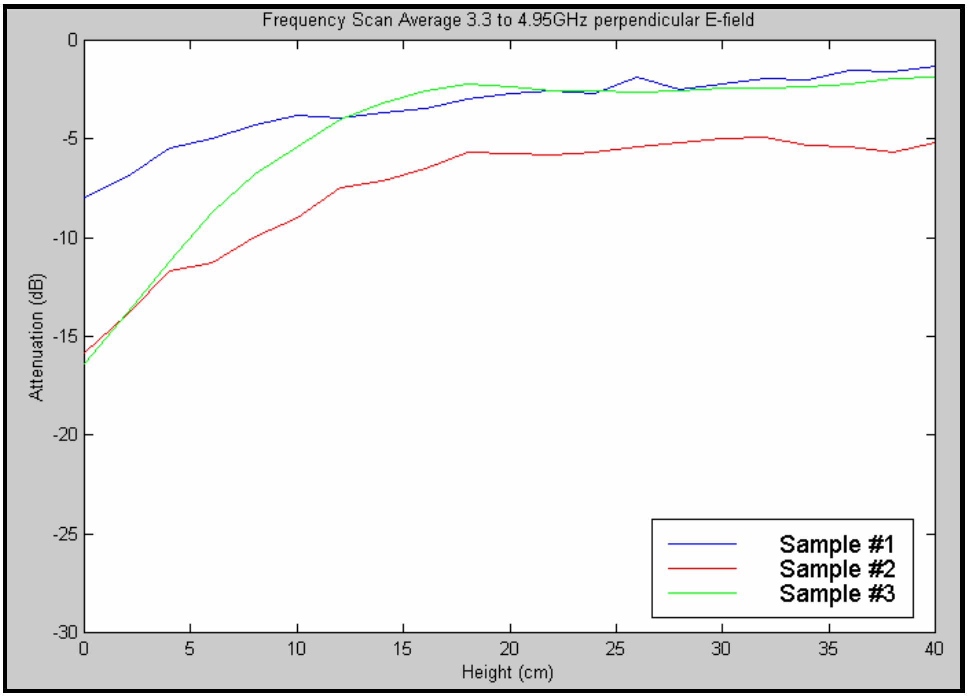
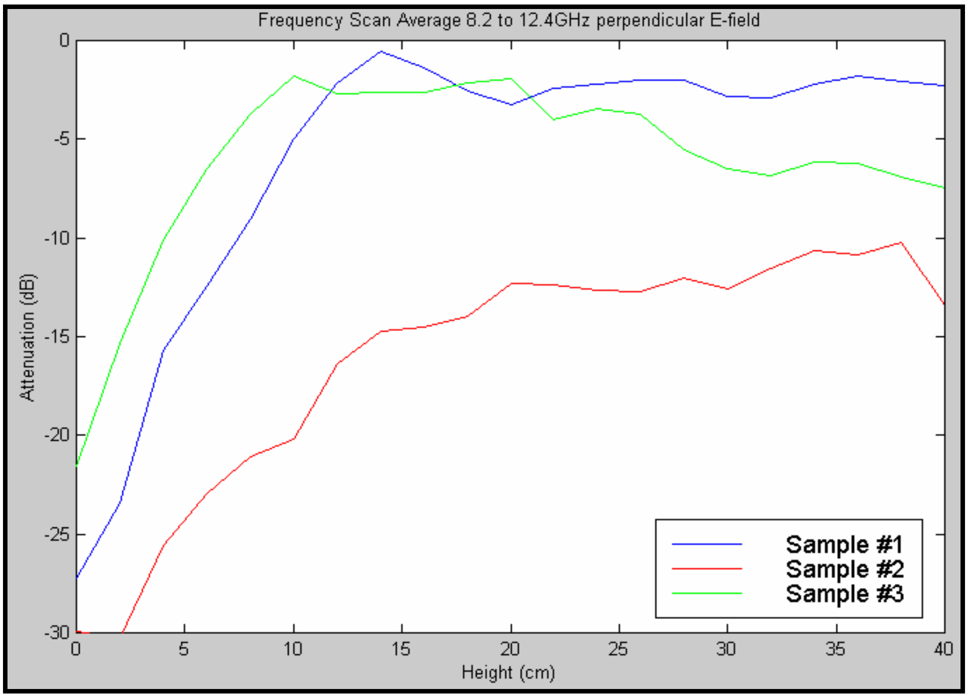


Figure 2.21: 2D X-Band Plot for all Samples



These last three graphs show that sugar cane diameter and trash levels effect the attenuation of the transmitted signal. It should also be noted that the antenna used for the C-Band measurements (Operating frequency of 3.3-4.9GHz in Figure 2.11, Figure 2.14 and Figure 2.17) was significantly more directive compared to those employed in the other two bands. The gain for the C-Band antenna was 18dB whereas the S-Band antenna had a gain of 10dB and the gain of the X-Band antenna was 16.4dB[VI].

The main conclusions drawn from both the experimental measurements and the theoretically predicted results are:

- The lower the frequency of the measurement signal, the “smoother” the measured amplitude variations are. The most probable reason for this observation is that lower frequency signals are less sensitive to multi-path interference caused by reflections as the measurement signal is transmitted through the sugar cane. From this point of view, lower frequency measurement signals would be advantageous.
- When comparing the results in Figure 2.12, Figure 2.15 and Figure 2.18, it can be clearly seen that sugar cane attenuates higher

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[VI] The sharp peaks visible in the measured results of Figure 2.10 to Figure 2.18 were later discovered to be bad data points due to an intermittent fault in a cable assembly.

> frequency signals more than lower frequency signals. This is most clearly seen when comparing the measured attenuation at the maximum height above ground level, especially when comparing the measured results for the green sugar cane where the higher frequency signal measurements exhibit attenuation of between 10 to 15dB, where in comparison, the lower frequency measurement signal exhibit less than 5dB attenuation at the same height. The sugar cane therefore affects the lower frequency signal much less, again indicating that this frequency range would be the preferred choice for a microwave based ground level sensor.

Another characteristic that was noticed at this stage was the effect that the directivity of the antenna had upon the response of the sensor. This effect is easily identified when comparing the experimental results of the C-Band and S-Band measurements. The frequencies of the transmitted signals for these measurements overlapped slightly but were measured using two antennas with quite different antenna gains. The antenna used for the measurements in the S-Band had a gain value of 10.1dB, while the antenna used in the C-Band was much more directional with a gain value of 18dB. Comparing these results leads to the conclusion that the highly directional antenna is less sensitive to the ground level. This result is understandable when it is noted that both of the antennas were always used with the centre of the transmitted signal positioned above ground level during these tests. Under such conditions, only a small area of the Fresnel zone of the signal will be obstructed by the row profile and thus less attenuation would be expected when comparing a high gain antenna to one with a much lower gain. This observation indicates that a lower gain antenna would be better suited to the proposed measurement application.

It can be summarised that the laboratory results indicate that the microwave ground level detection technique should be further investigated with the design optimised to operate at a low, horizontally polarised transmission frequency signal with reasonably low gain antennas.

2.4 Conclusion

By performing simulations and laboratory results of the proposed measurement technique it was determined that further development of the technique was required to be able to eventually produce a commercially available ground level measurement system suitable for use on a sugar cane harvesters. Both the theoretical and laboratory results indicated that the technique was fundamentally sound and the sensor would respond to changes in the height of the ground and that it was also fairly insensitive to the affects of signal attenuation due to the sugar cane. The following chapters of this report describe the practical measurements made with prototype sensors both in the field using portable test equipment and on-board a sugar cane harvester during operation.

Chapter 3: Field Testing

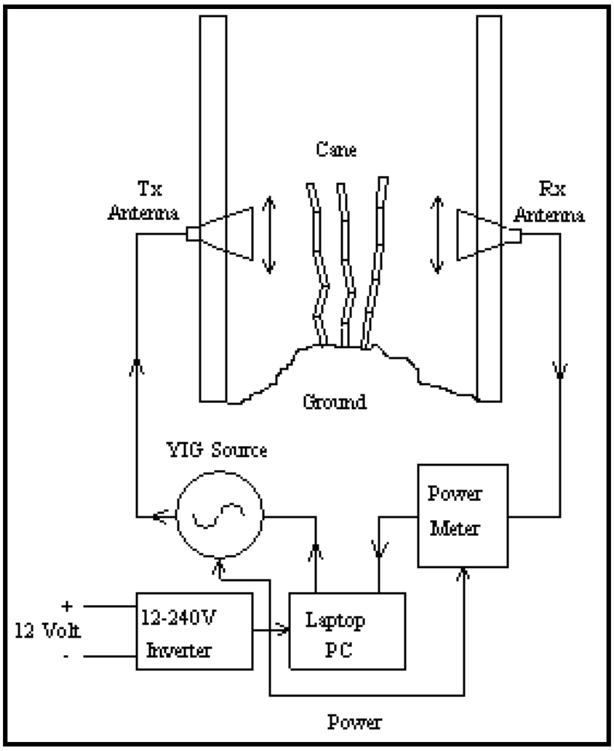
3.1 Introduction

The laboratory results, outlined in the previous chapter, verified the fundamental principle of the proposed microwave ground level sensing technique and helped to define the main configuration parameters of a device that was expected to be able to be used on a sugar cane harvester. However, it was evident that the operational environment where the sensors would be positioned on a real sugar cane harvester could be significantly different to the simulated test conditions that were established in the laboratory. For this reason it was decided to perform some tests in the field using an experimental set-up. The purpose of these tests were to establish what effect real sugar cane and any other obstructions would have on the operation of the ground level sensor.

3.2 Field Test System

To test the proposed measurement technique in the field a portable testing unit was built. The block diagram schematic of the system that was developed for these field tests is shown in Figure 3.1.

Figure 3.1: Schematic of the portable field testing unit



It can be seen in the schematic shown in Figure 3.1 that the portable testing unit again uses the two horn antennas from the laboratory tests positioned on either side of the row of sugar cane. These S-Band antennas had gain values of 10.1dB. During testing the height of the antennas was adjusted either up or down using motorized worm drives. This arrangement allowed the amplitude of the measurement signal to be measured at set heights above ground level. The unit was constructed so that it was easily transportable to allow multiple measurements to be made along the length of sugar cane paddock row.

The measurement equipment comprised of a microwave transmitter, a YIG microwave frequency source that produces a 2.6-3.4GHz transmission signal that is transmitted through the sugar cane by the transmitting antenna. The second horn antenna received the signal that had been attenuated as it was transmitted across the sugar cane row and the amplitude was measured using an Anritsu microwave power meter.

A laptop PC was used to control the operating frequency of the YIG microwave frequency source and to read the measured amplitude of the signal that was received by the power meter. A Visual Basic program was developed to control both the measurement system and to log the measured data. As the system was to be used in the field, it was designed to be powered by a 12 volt battery system that could be recharged by connecting it to a conventional motor vehicle alternator. A 12 volt DC to 240 volt AC inverter was used to power the Anritsu power meter and the laptop PC.

The YIG microwave frequency source, the Anritsu power meter, the power inverter and the 12 volt car battery were all housed in a metal enclosure for protection during testing. Some photographs of the equipment set up outside the Electrical Engineering building at James Cook University, are shown in Figure 3.2 and Figure 3.3.

Figure 3.2: Portable testing unit showing the worm drive mounts used to vary the transmission height of the horn antennas.

Figure 3.3: Photograph of the control box showing the YIG microwave source, Anritsu power meter, power inverter and 12 volt battery

The measurements recorded using the portable test equipment were later analysed using Matlab™ scripts. The measured responses were plotted to produce a visualise display of the field test data, some of these 3-dimensional plots are shown in Figure 3.4 to Figure 3.23. These plots show the typical variety of results that were measured using the portable field testing equipment. The 3-D graphs show the signal attenuation versus the height of transmission above ground level versus the frequency of transmission for the frequencies of 2.6-3.4GHz (the height measurement of zero is defined as the top of the root mound of the sugar cane plant and is theoretically the optimum cutting height of the base-cutters). The 2-D graphs show the average frequency response of the signal attenuation versus height of transmission above ground level, for height measurements less than 500mm.

The received signal strength was measured as the height from the ground level to the centre of the transmitted signal was varied in two centimetre increments from 0 to 70 centimetres. The graphs shown in Figure 3.4 through to Figure 3.23 show some of the measurements from a series of tests that were conducted on a farm at Trebone in the Herbert District over 3 separate days. Data for Figure 3.8 to Figure 3.23 was collected on the 13th and 14th November, 2000 while the data displayed in Figure 3.4 to Figure 3.7 was obtained on the 17th November, 2000. The weather during this period was "terrible" and significant rain fell while undertaking these experiments. During the tests on the 17th November, Figure 3.4 to Figure 3.7, the sugar cane was clumped together and pushed over to simulate the orientation of sugar cane immediately in front of the base-cutter on a harvester. Some comments concerning these results are provided below;

1) Most graphs show the same "general shape" as those obtained in the laboratory tests and in the electromagnetic field simulations. Well above ground level the attenuation is reasonably constant, giving a "flat" look to the surface. As the antennas approach ground level though, the attenuation increases rapidly. Figure 3.4 and Figure 3.6 show good examples of this.

2) Occasionally responses are almost flat (Figure 3.10) while others show a cyclic variation (Figure 3.22). It is possible that these responses are just bad readings as some equipment calibration problems were experienced during these tests. However, these results could also be caused by the random orientation of the sugar cane during this "real world" test. Such results indicated that some averaging or filtering of these random measurements may be required in the final implementation.

3) The laboratory measurements suggested that the "knee" in the averaged response curve could be used as a reference point in establishing the ground height with respect to the antenna array. However, the field measurements shown here indicate that there is likely to be some variation in this point and again some averaging may be required to ensure consistency of the results.

4) The knee point in Figure 3.10 to Figure 3.22 occur at a height of between twenty and thirty centimetres above ground level, while in Figure 3.4 and Figure 3.7 this knee occurs at thirty-two to thirty-five centimetres. The higher than average knee heights in Figure 3.4 and Figure 3.7 is probably due to the measurement conditions as these two tests configured the sugar cane as it would be deep inside the throat of the harvester, just before the base cutter. As might be expected, it appears that the sensor cannot distinguish between the

row profile and a tightly packed bundle of sugar cane that would have similar properties to that of a solid mass. Therefore, due to the configuration of the sugar cane the knee point appears higher with respect to the real ground level as it has been artificially raised. Based upon these findings the following observations and recommendations were made:

a) Tightly packed sugar cane produces the same measurements as the row profile and therefore the positioning of the sensor on the harvester will need to be considered carefully so as to best measure the required parameter.

b) To measure the full height profile instantaneously, an array of antennas set at different heights that can be individually switched to a common receiver, will need to be developed..

c) Some filtering or averaging of results will need to be implemented in the commercial product to reject random fluctuations due to the random orientation of the sugar cane.

d) The current field test system is slow to use and does not provide a continuous set of results along the full length of the sugar cane row. Further tests should be made with an antenna array mounted on a sugar cane harvester.

Figure 3.4: Portable FTU 3-D Results, location #1, Trebone

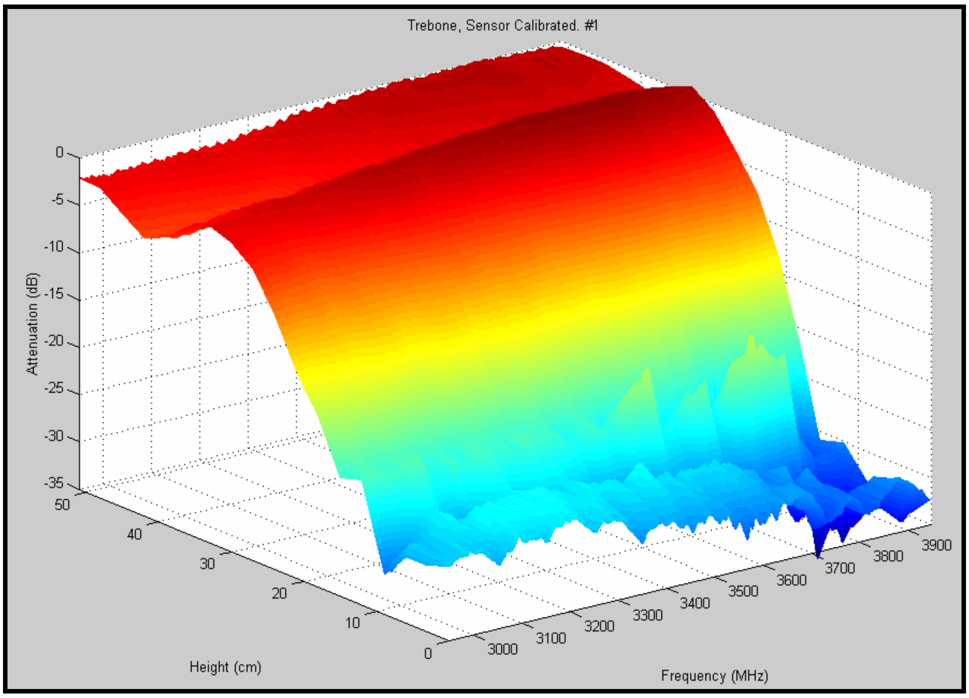


Figure 3.5: Portable FTU 2-D Results, location #1, Trebone

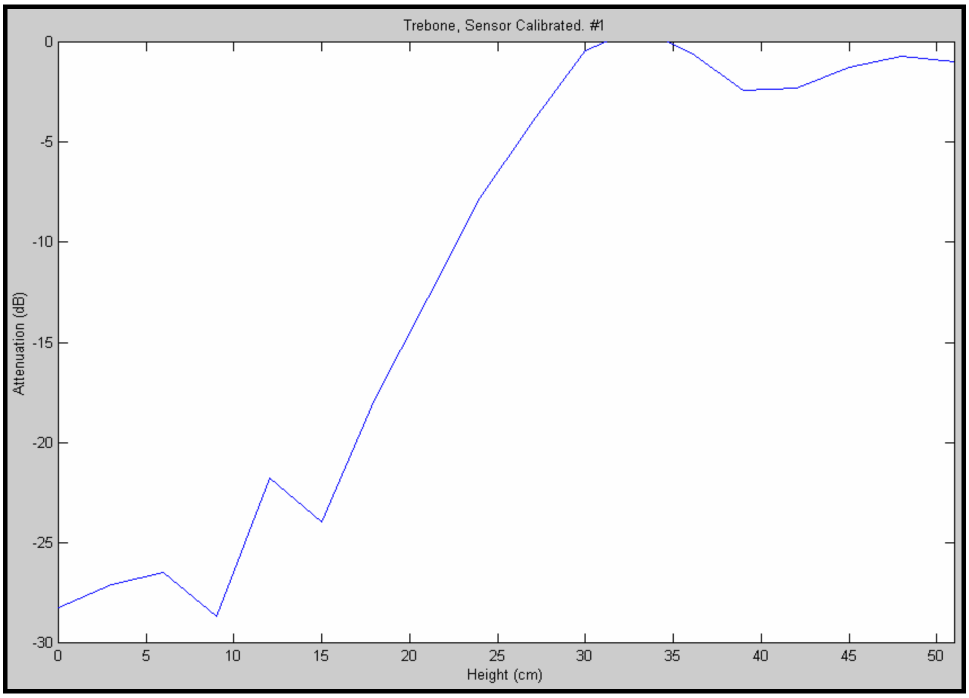


Figure 3.6: Portable FTU 3-D Results, location #2, Trebone

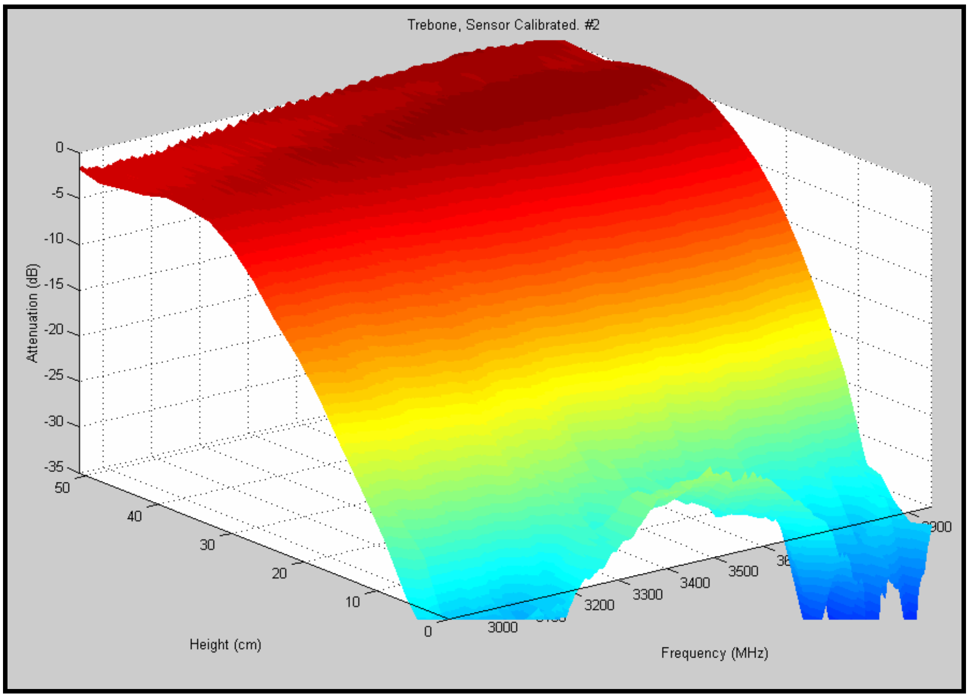


Figure 3.7: Portable FTU 2-D Results, location #2, Trebone

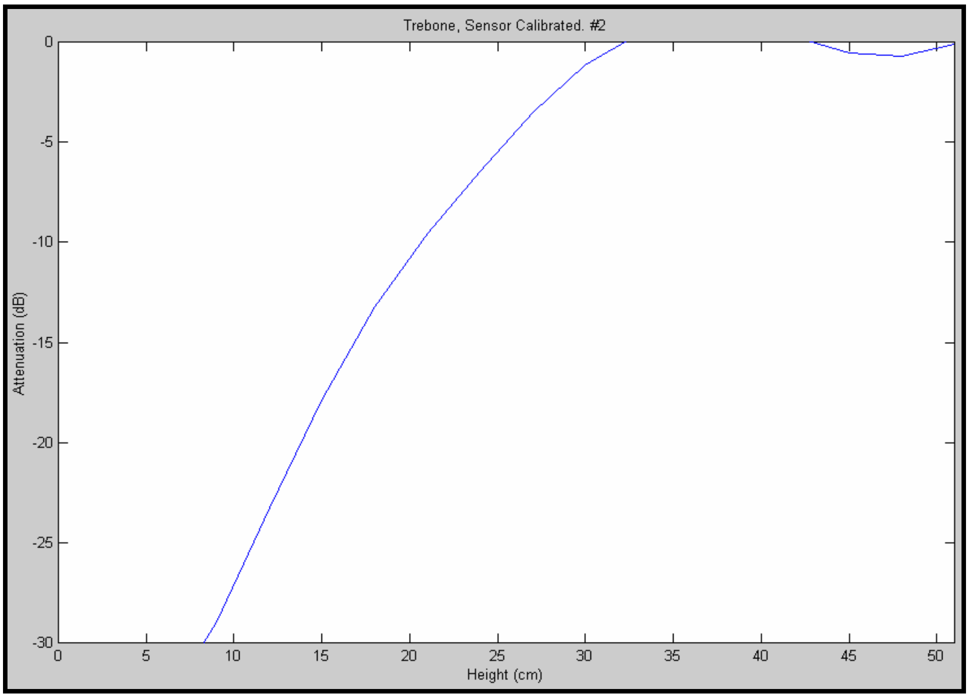


Figure 3.8: Portable FTU 3-D Results, location #4, Trebone

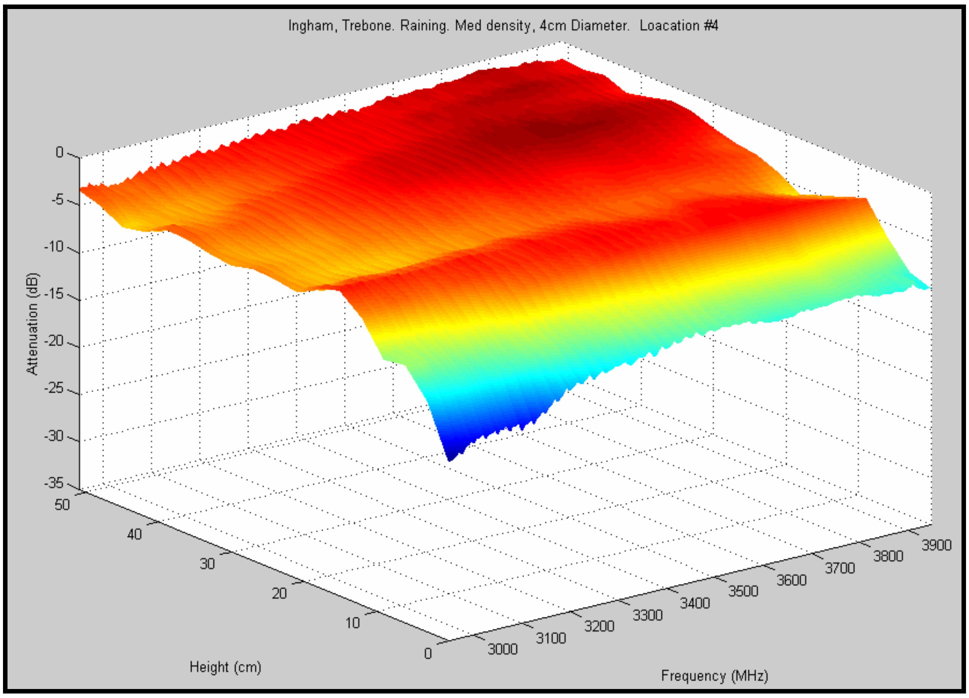


Figure 3.9: Portable FTU 2-D Results, location #4, Trebone

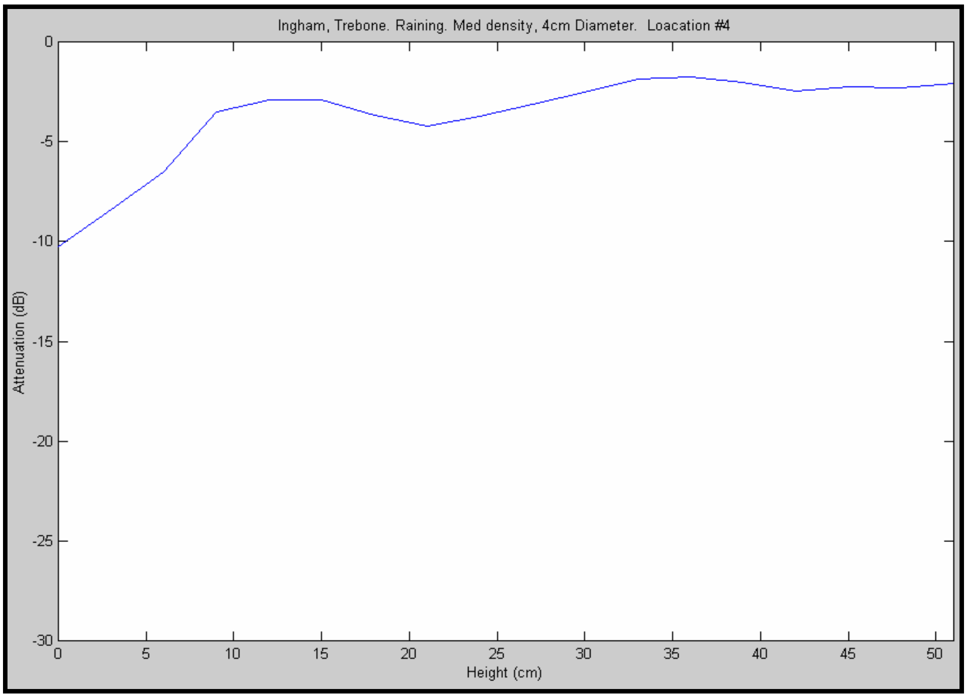


Figure 3.10: Portable FTU 3-D Results, location #5, Trebone

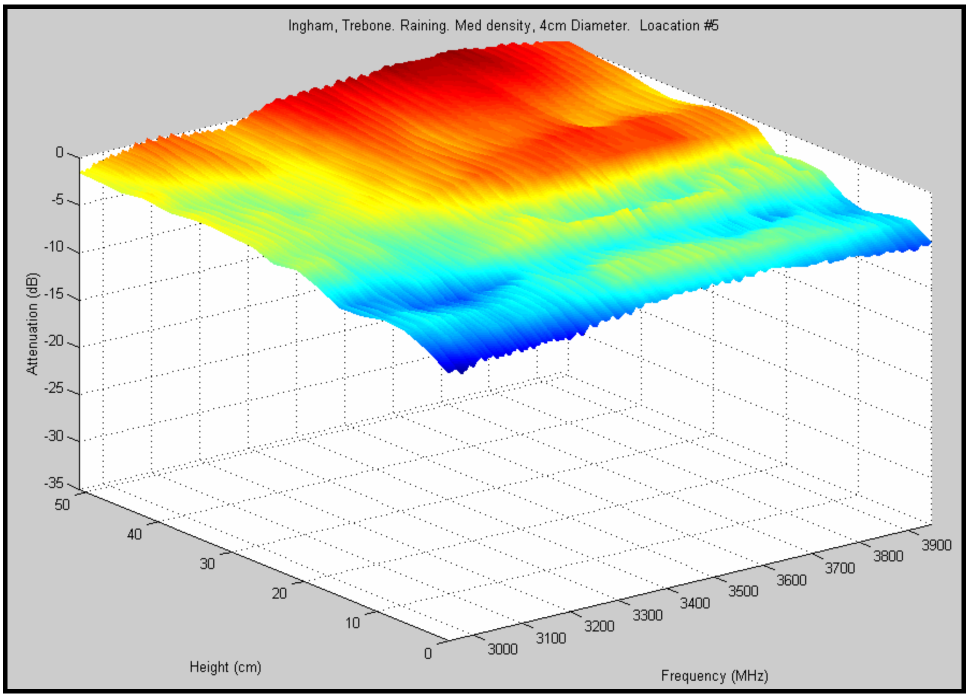


Figure 3.11: Portable FTU 2-D Results, location #5, Trebone

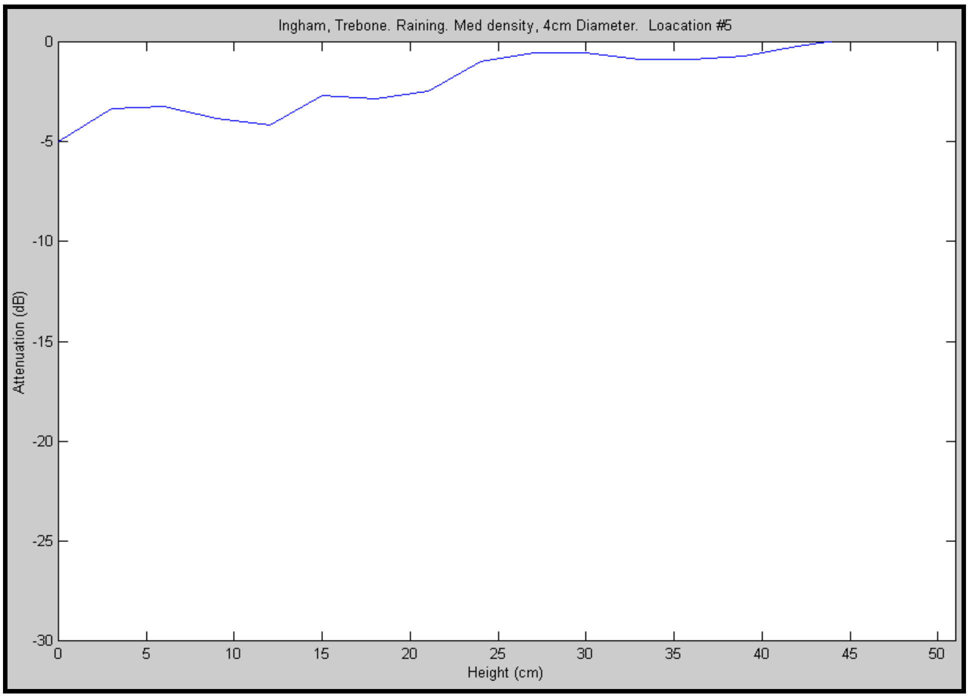


Figure 3.12: Portable FTU 3-D Results, location #8, Trebone

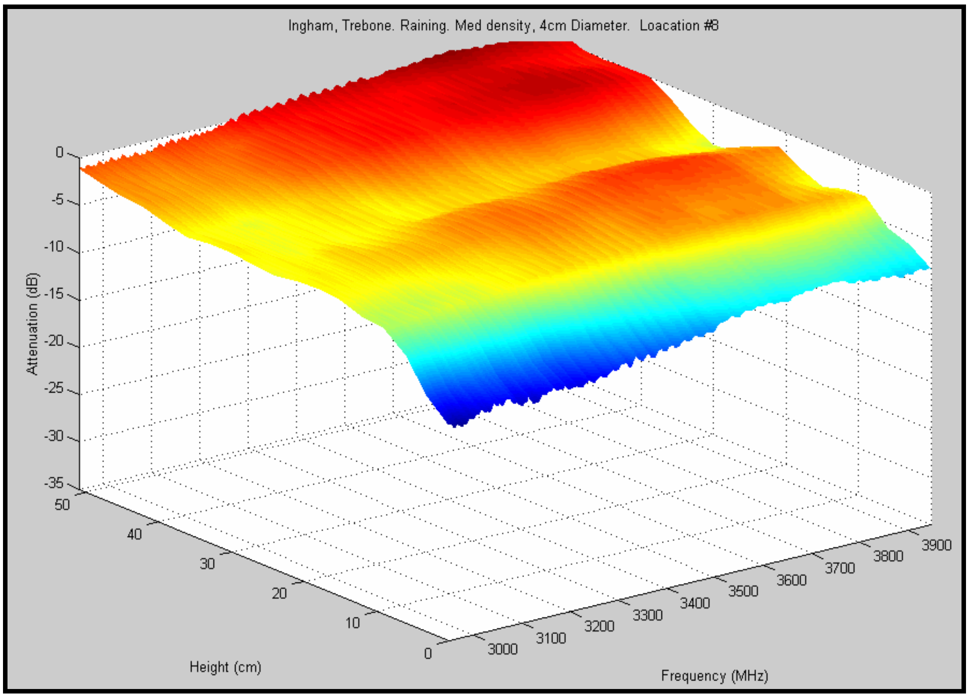


Figure 3.13: Portable FTU 2-D Results, location #8, Trebone

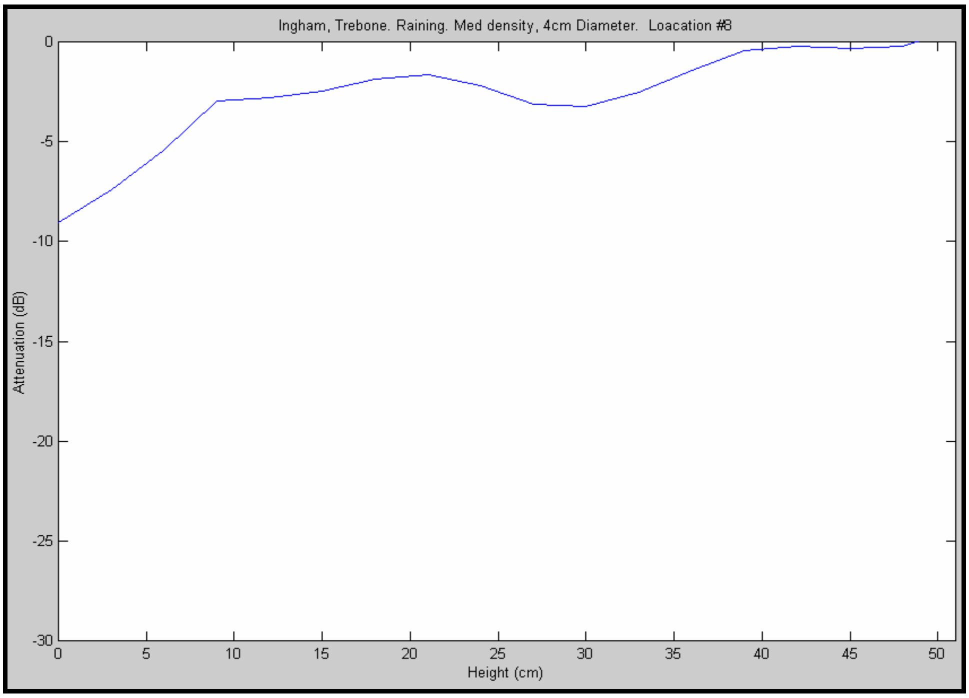


Figure 3.14: Portable FTU 3-D Results, location #9, Trebone

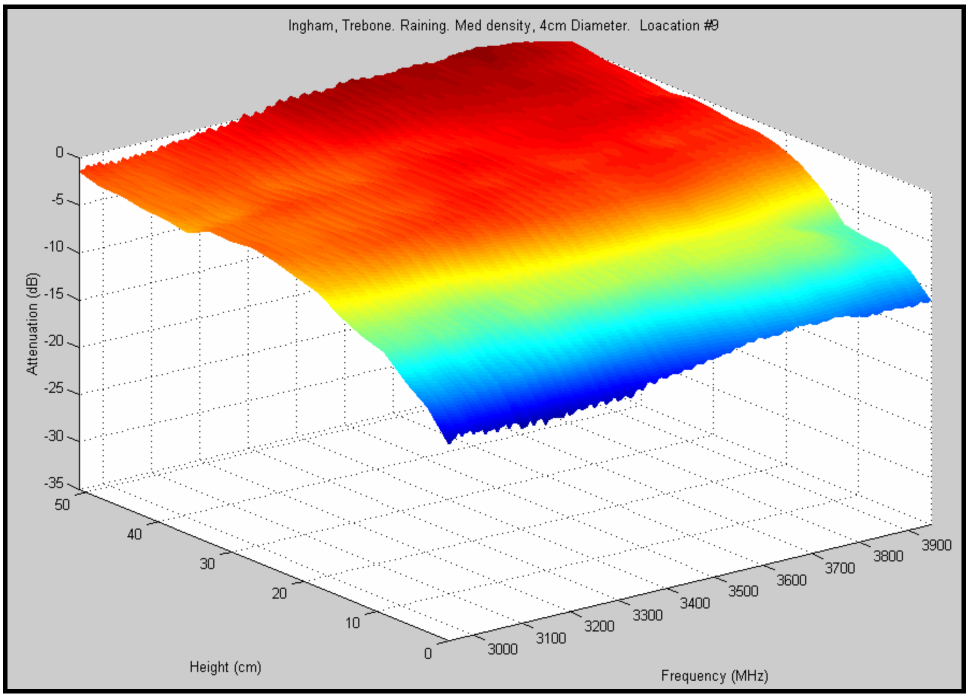


Figure 3.15: Portable FTU 2-D Results, location #9, Trebone

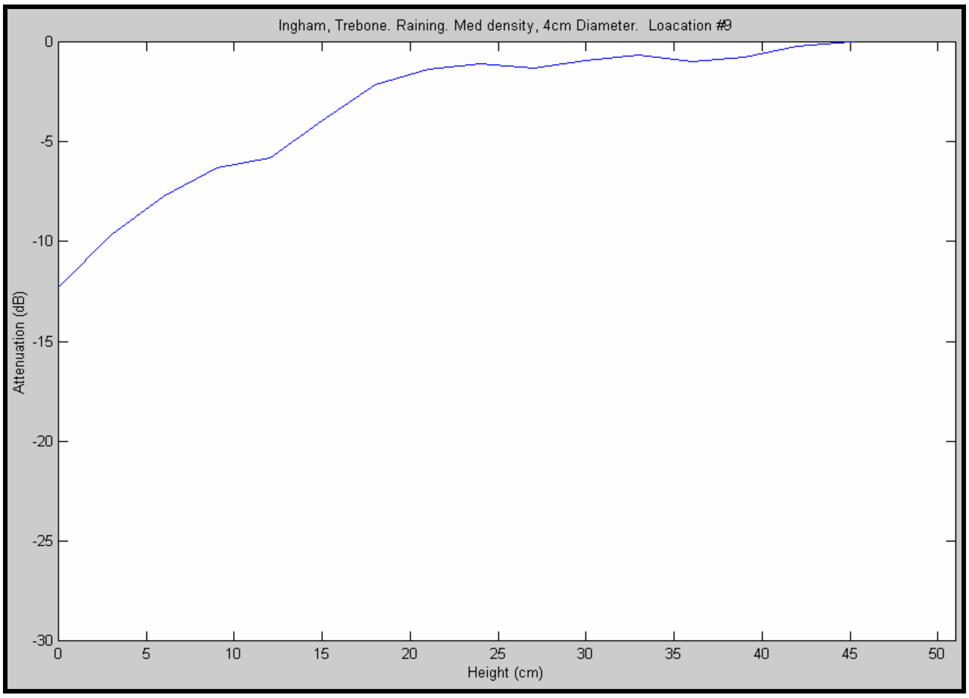


Figure 3.16: Portable FTU 3-D Results, location #11, Trebone

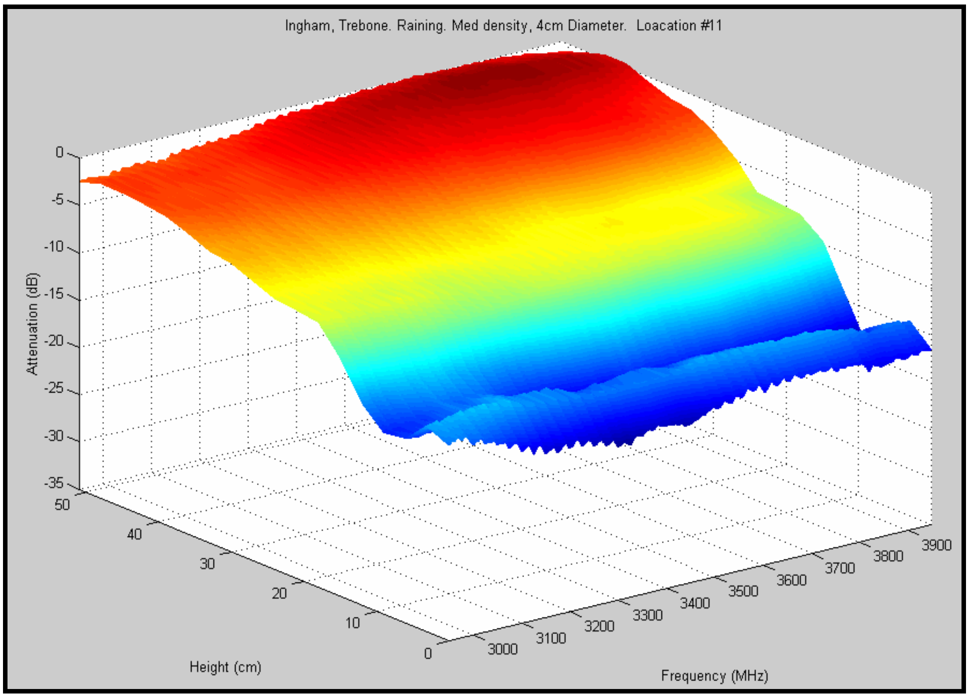


Figure 3.17: Portable FTU 2-D Results, location #11, Trebone

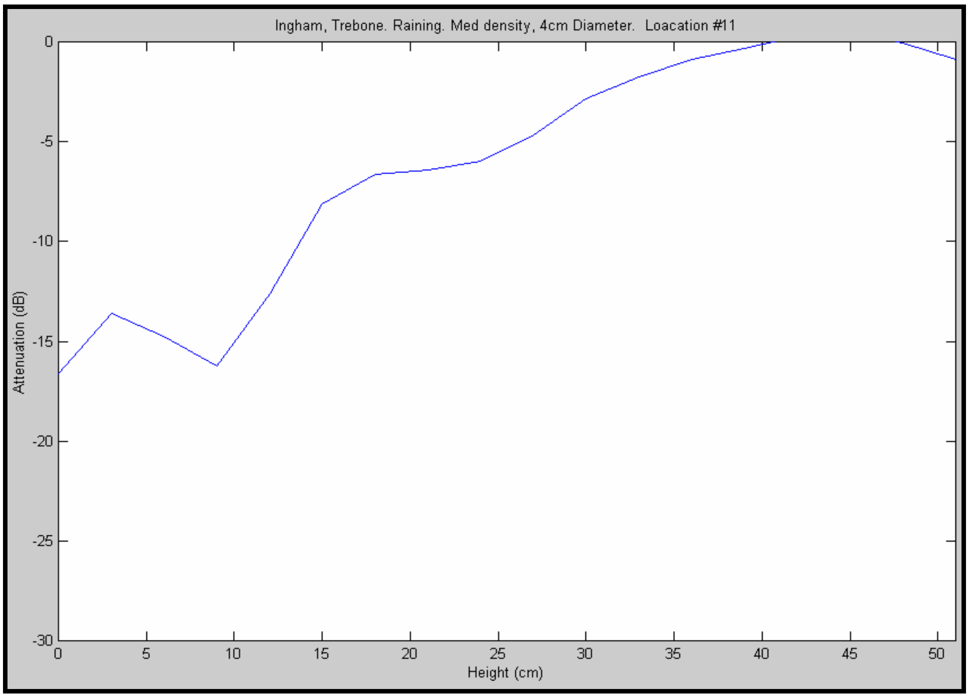


Figure 3.18: Portable FTU 3-D Results, location #12, Trebone

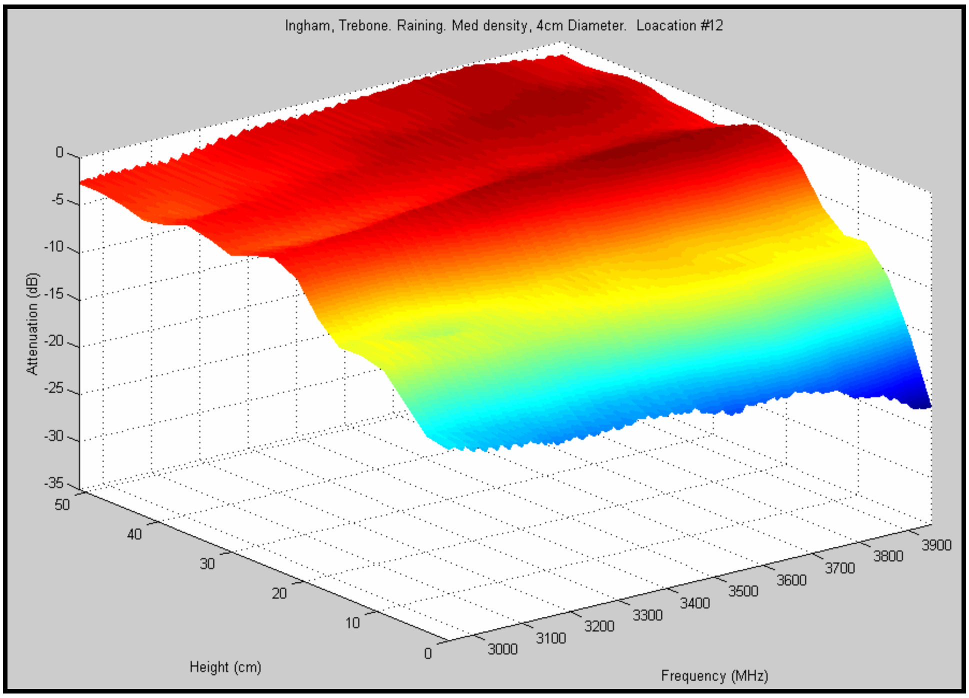


Figure 3.19: Portable FTU 2-D Results, location #12, Trebone

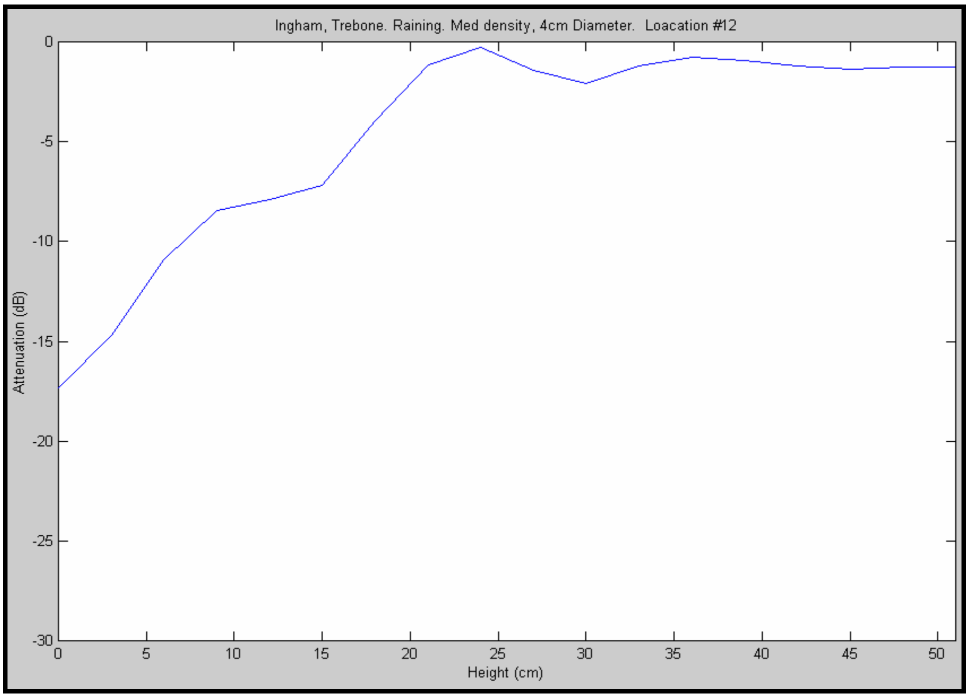


Figure 3.20: Portable FTU 3-D Results, location #15, Trebone

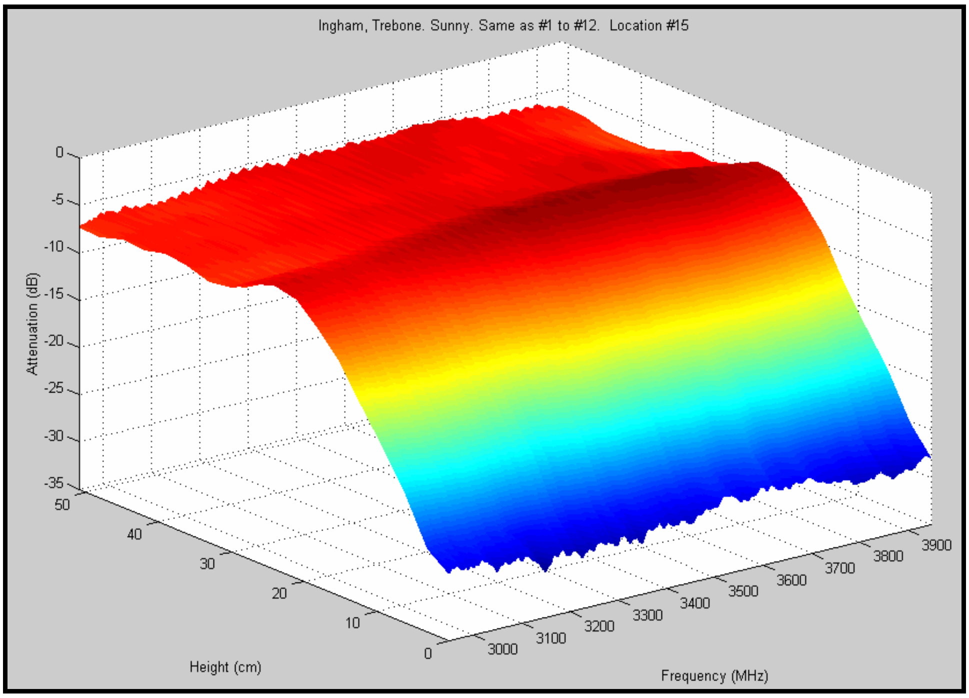


Figure 3.21: Portable FTU 2-D Results, location #15, Trebone

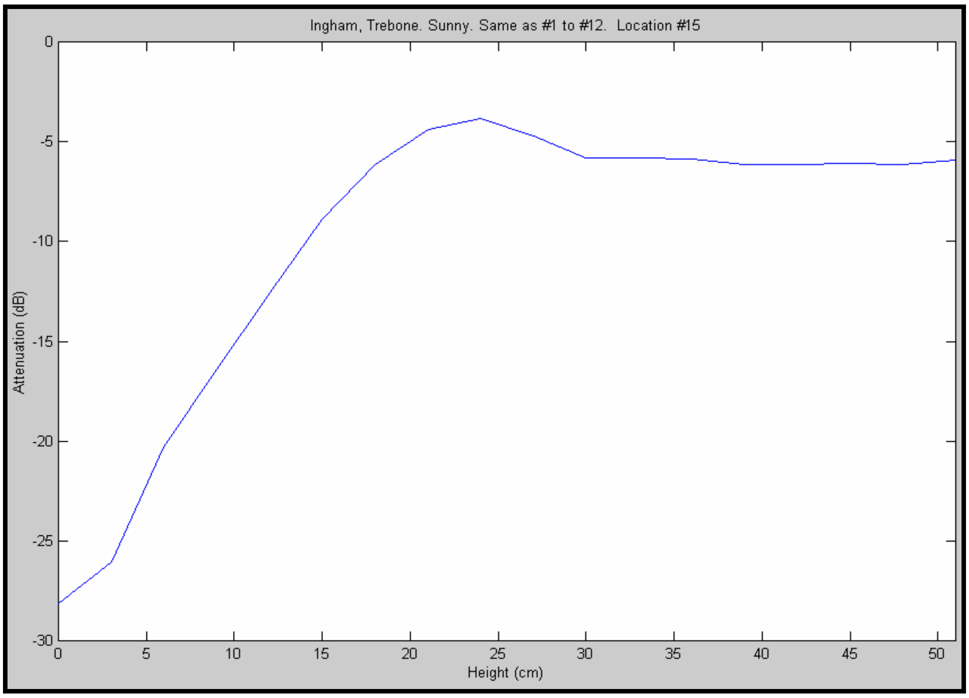


Figure 3.22: Portable FTU 3-D Results, location #16, Trebone

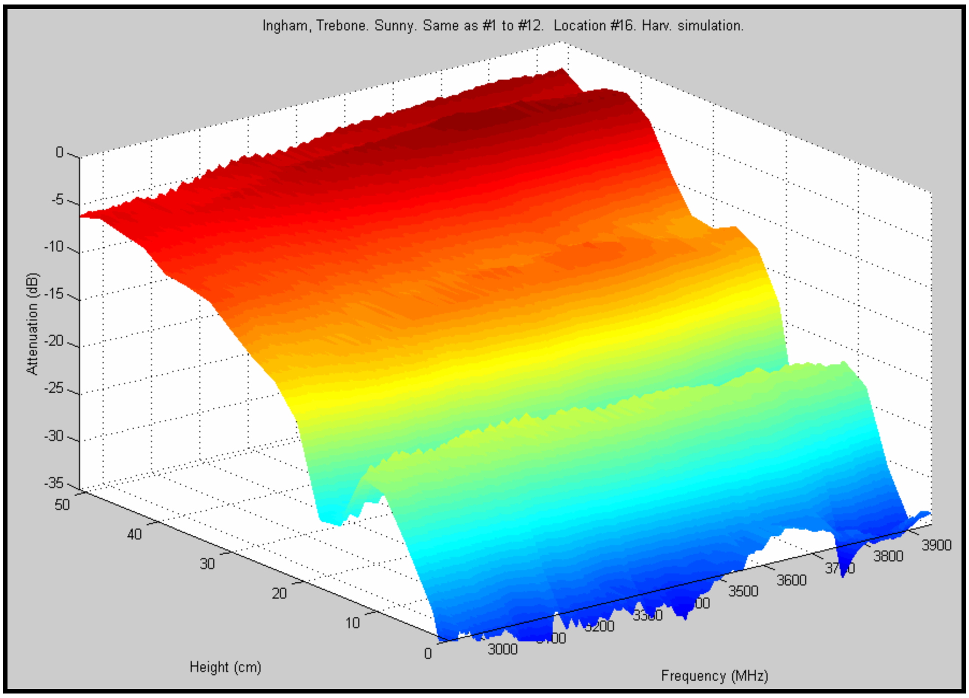
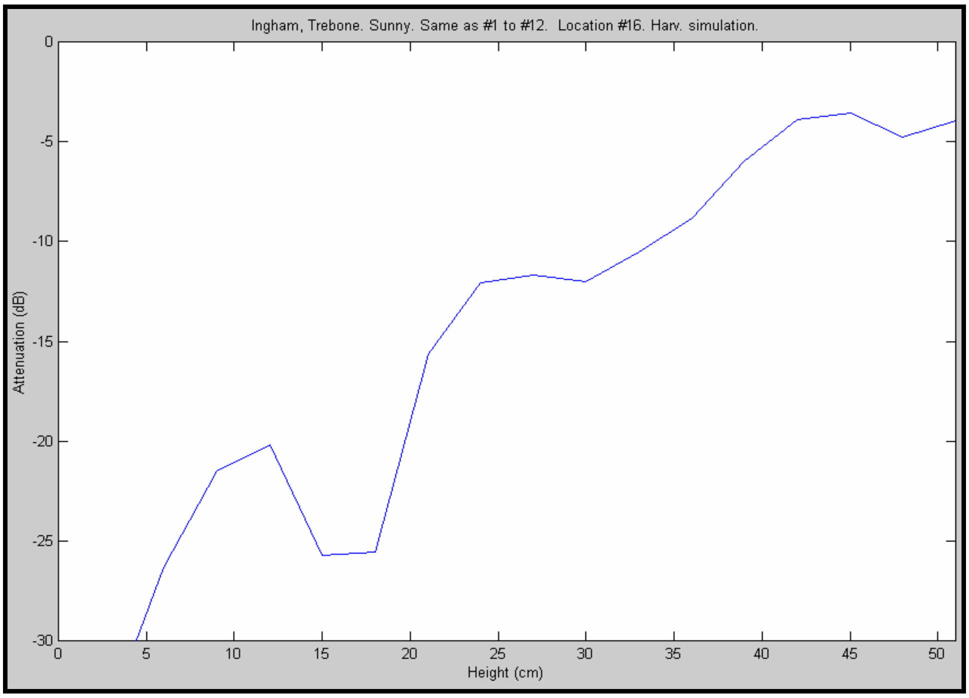


Figure 3.23: Portable FTU 2-D Results, location #16, Trebone



3.3 Summary

The field measurements described in this chapter were interesting due to the fact that they showed the sugar cane does have a significant effect on the proposed ground detection sensor. As might be expected in a “real world” situation where the sugar cane stalks are randomly orientated between the transmitter and receiver, the attenuation profile will not always follow a smooth well-defined shape. However, it could also be argued that if the effect of the sugar cane is random, then averaging of the data measurements should remove these variations leaving the desired trend. Fortunately, in the sugar cane harvester application, averaging should be possible as many measurements can be taken along the length of a sugar cane row due to the slow travelling speed of the harvester.

Another conclusion was that the “fixed” receiver antenna position due to the construction of the mounting device and the operation of the measurement equipment was not suitable for taking multiple measurements along the length of a sugar cane row to record the required number of data points to enable the data averaging described above. To overcome this problem, it was suggested that the test system be mounted on a movable platform and be equipped with a high speed data acquisition module. Some preliminary work was undertaken to mount the prototype sensor[VII] on a high clearance tractor to enable such measurements. Figure 3.24 shows the proposed mounting position on a high clearance tractor where the antennas could be positioned on a bracket to permit trials to be conducted in the field. Unfortunately, this additional investigation could not be completed within the time frame of the main project and no tests results are therefore available.

Figure 3.24: Photograph of the back of a high clearance tractor showing the height adjustable mount

Hydraulically operated height adjustable mounting bracket. It is normally used for herbicide, pesticide or fertiliser spraying attachments

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[VII] This is described in Chapter 4:

Chapter 4: Prototype Ground Detection Sensor

4.1 Introduction

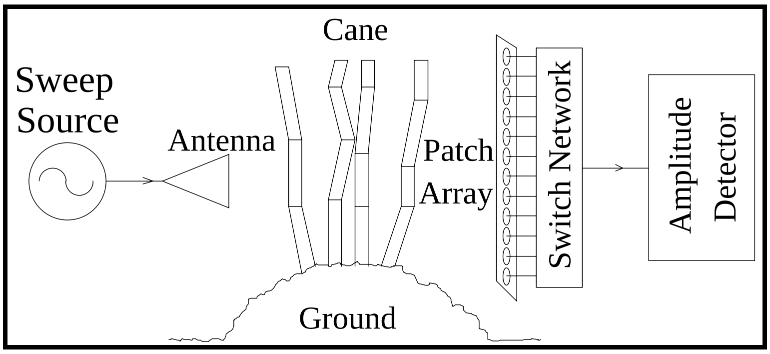
Based upon the success of both the laboratory experiments and the field trials the construction of a prototype ground detection sensor for testing on board a sugar cane harvester was developed. The preliminary work had identified the main specifications and features that were required to ensure the successful development of a suitable sensor. This chapter details the design, calibration and laboratory testing that was conducted while building the prototype ground detection sensor that was later trialled on an operation sugar cane harvester.

4.2 Prototype Ground Detection Sensor Design

The findings of the tests and simulations that had been previously undertaken concluded that the optimal method for detecting ground level, if a microwave sensor was used, is to instantaneously measure the signal attenuation versus height profile and identify any changes of the "knee point" in this response.

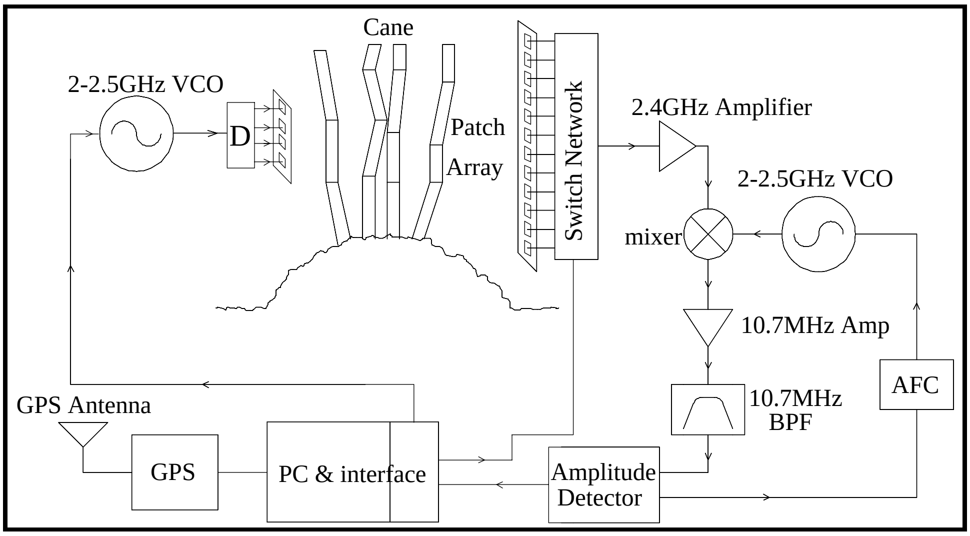
The concept diagram of a transmitter/receiver system to achieve this measurement is shown in Figure 4.1. This design consists of a single antenna being used to transmit the signal on one side of the sugar cane row and a multi-element receiver array on the other side. The elements of the receiver array would be individually switched at high speed to the amplitude detector circuitry to measure the field amplitude at different heights almost instantaneously.

Figure 4.1: Ground Detection Sensor configuration using a receiver array



From the proposed schematic diagram, the system configuration shown in Figure 4.2, was designed and constructed.

Figure 4.2: Prototype ground detection sensor configuration schematic



This arrangement of equipment for the ground detection sensor transmits a signal at 2.5GHz from the transmitter. The transmitter is a four element array of rectangular patch antennas that are driven “in-phase” using a four way power divider. The transmitter array provides a broadside radiation pattern with a gain of close to the recommended 10dB. This particular radiation pattern was specifically chosen to provide close to equal power distribution over the receiver array positioned on the opposite side of the sugar cane row.

Twelve rectangular patch antennas that are spaced over a length of six hundred millimetres are used for the receiver array. A similar design was used to that of the transmitter array, with the dimensions modified to suit the microwave substrate properties. On the receiving side of the sensor, only one patch antenna is used at a time to simulate repositioning of the antenna to measure the signal strength level at that particular height. An antenna at a particular height is selected using a digitally controlled switching network that is connected to the twelve receiving antennas. This configuration enabled the amplitude profile to be measured over the entire height span of the array in around one millisecond.

The rectangular patch antennas that were designed for the ground detection prototype sensor were configured to use a conventional edge fed arrangement [21] that was matched to 50 Ohms. The receiver antennae were manufactured on a thick substrate with a low dielectric constant[VIII] in order to provide a usable frequency bandwidth of 120MHz. This is considered to be a wide bandwidth for a patch antenna design which is usually only 1-2% of the operational frequency. The wide frequency band was designed to provide tolerance to frequency inaccuracies and drift in the rest of the electronic circuitry as well as providing the option of allowing a small amount of frequency scanning, if this was found to be necessary. The low profile patch antenna configuration was also identified as being an ideal design to allow the antenna to be mounted flush along the inside walls of the sugar cane harvester row dividers.

The remainder of the ground detection sensor consists of specific electronic circuits to both generate the 2.5GHz test signal and to measure the amplitude of the received signal including the automatic frequency control (AFC) used to mix the received signal down to 10.7MHz. The transmitter used a Minicircuits voltage controlled oscillator integrated circuit, while the amplitude detector is based upon a conventional heterodyne radio receiver circuit. The amplitude detection is achieved using a Motorola MC13055 FM demodulator integrated circuit. This

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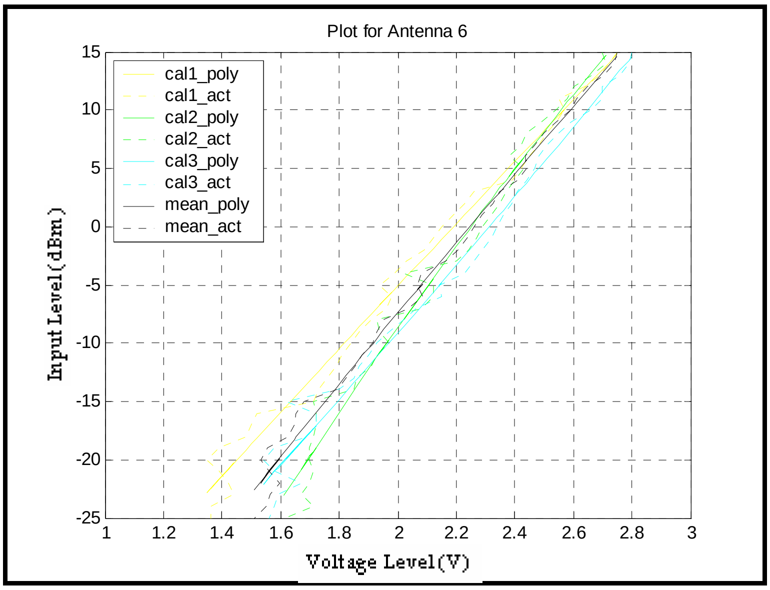
[VIII] $\varepsilon_r = 4.5$ and $h = 6.4$mm device features an analogue voltage output that is proportional to the input signal power level and the associated interface circuitry allows the receiving antenna to be frequency locked to the incoming measurement signal.

Calibration of this device for signal level measurement showed that the receiver had a dynamic range of 30 to 40dB with a typical accuracy of ±2dB. Before operation of the prototype sensor, each channel of the receiver was individually calibrated to normalise the received signal to compensate for the different levels of signal losses in the antennas, switching network and cables.

Three measurements were taken at each power level injected into the system and 5^{th} order polynomials were used to create an operating equation between voltage level received and the actual power level. A typical calibration curve for one of the twelve channels of the prototype sensor is shown in Figure 4.3. It can be seen that by taking the mean of the three measurements and calculating a 5^{th} order polynomial to fit the data points clearly gives the best line of best fit.

Figure 4.3: Receiver calibration for Antenna #6



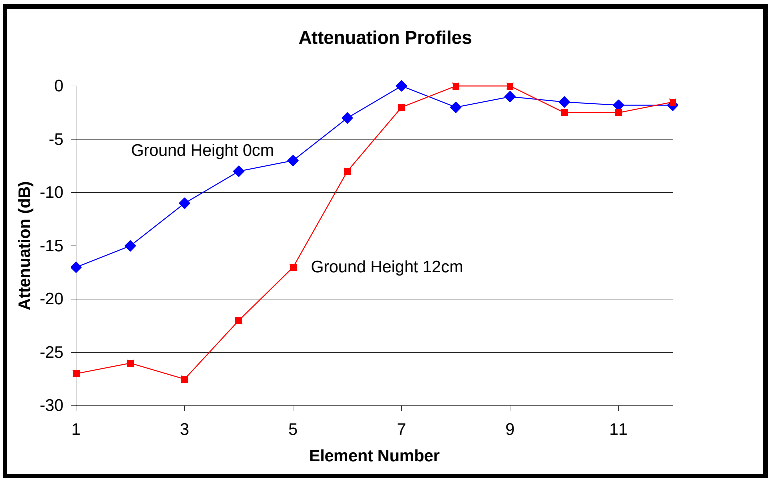
A laptop was used to control the operation of the sensor by automatically setting the transmission frequency, selecting the desired receiving antenna and logging the measured received signal level. During the testing that was performed, the received signal power levels were stored to hard disk for analysis at a later point in time, these calculations would need to be conducted in real time for a commercial product. Likewise the calibration process was only conducted once before field testing, this may also need to be automated to allow operators to calibrate the system daily or it may only be required on a quarterly, bi-annual or annual period, this determination was not part of these works. During testing the laptop was also connected to a Global Positioning System (GPS) receiver to allow the position and speed of the harvester to also be recorded and time stamped to the data log. The GPS equipment was directly powered from the harvester's 24V DC electrical supply.

Most of the electronics and equipment that was used in the design of this system was relatively low cost. The most expensive components of the design are the four microwave switches that were used to select the individual receiver array antennae, which were valued at $800. However, these components would be replaced with much lower cost alternatives for the commercial product and would be much smaller in physical size as well. Even including the high cost of the switches the total cost of the components for the sensor was estimated to be less than $1000. The total anticipated cost for a commercial product to be fully installed on a sugar cane harvester including additional equipment such as a micro-controller, cabling etc, is still expected to be less than $2000. It should be noted that this is the hardware cost only and does not include any mounting costs that would be associated with installing the system on a real harvester.

4.3 Detector Testing Results

Initially the sensor system described in Chapter 4.2 was verified under controlled conditions to measure its performance. During these tests, bags of soil were placed between the transmitter and receiver arrays to simulate the signal obstruction that would be present for different row profile heights. One result from these tests is shown in Figure 4.4. The two responses shown were measured with a simulated row profile height obstruction of 0 and 12 centimetres, which was measured from the centre of the lowest receiver array element. The results shown in Figure 4.4 are very similar to the predicted response plotted in Figure 2.3. The measured amplitude profiles do show small amounts of variation but the general trend is that the signal levels on the antenna elements closest to the row profile are proportionately less than the higher positioned antenna. It can also be concluded that the change in the height of the row profile moved the “knee” of the measure response and changed the rate of signal attenuation for the antenna positioned closer to the ground.

Figure 4.4: Measurement system response under controlled conditions



4.4 Installation on Harvester

To test the prototype design on a harvester, the transmitter and receiver antennas were mounted flush against the inside of the row dividers walls.

The surface of the patch antennas were left unprotected with only a slightly raised metal deflector welded in front of the patches to try to stop the sugar cane from damaging the antennas. Although the antennas did not sustain any significant damage during the course of the testing procedure of this project, (refer to Figure 4.5), a commercial product would required that the antenna was covered with a fibreglass skin or similar product to prevent mechanical damage caused by the sugar cane impacting the surface of the antenna to ensure long term operation.

A photograph of both the transmitter and the receiving antenna arrays mounted on the Austoft research and development harvester is shown in Figure 4.6. This figure shows three photographs of the sensor viewed from the front of the harvester as well as the two antenna arrays shown separately.

Figure 4.5: Photograph of the surface of the receiver antenna after one week of operation on a sugar cane harvester

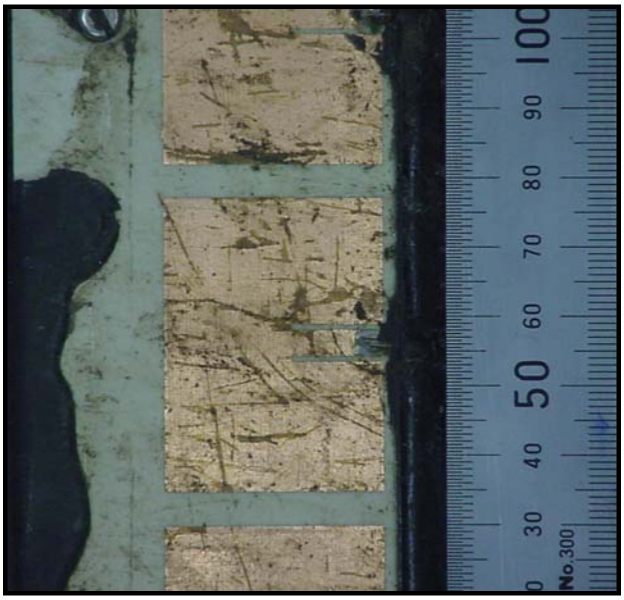
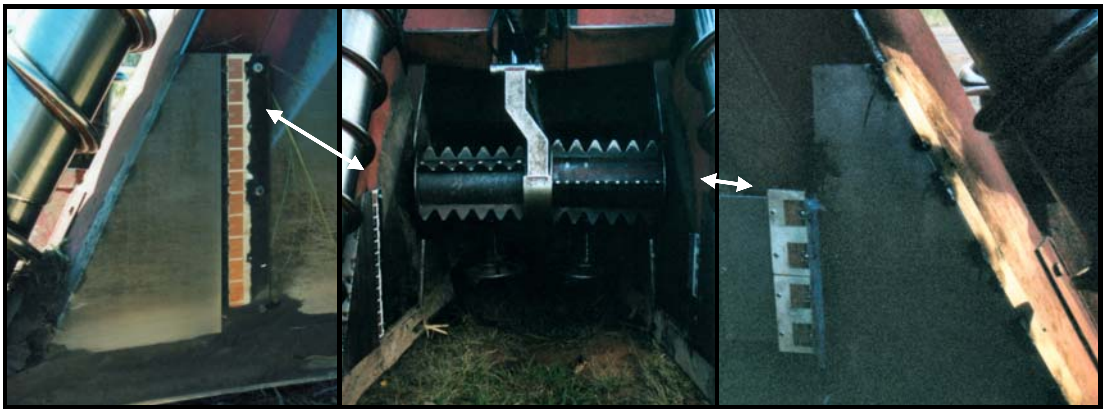


Figure 4.6: Installation of the antenna on a sugar cane harvester



There was some concern expressed over the effectiveness of this sensor arrangement where the antenna are mounted on the row divider walls, because the row dividers can be individually raised and lowered in the vertical direction independent of the base-cutter height adjustment. For the base-cutter control strategy, this could be a problem as the detector measures ground height with respect to the receiver array and moving the row dividers will therefore produce a similar shift in the measured response as a change in ground level would.

During the preliminary testing that was undertaken for this project, the mounting location was considered satisfactory to at least test the measurement principle. The antenna position would have to be evaluated for the situation where the output is actually controlling the base-cutter height and an alternative mounting arrangement may be required to ensure that the correct data is measured. One option would be to mount the antennas from the chassis of the harvester, so that they do not move vertically when the row dividers are adjusted to track the row profile. The practicalities of such a mounting arrangement have not been studied in detail; however some potential problems include having to modify the row dividers to allow the transmitted signal to be unobstructed. This however raises concerns about fouling of the modifications by cane or trash, which would significantly affect signal strength and possibly interfere with the row divider movement mechanism that is positioned inside the row divider cavity. Figure 4.7 shows the typical amount of trash collected behind the row divider cavity after only fifteen minutes of operation.

Another alternative that may be more practical would be to include an auxiliary sensor that would measure the position of each row divider. This measurement could then be employed to correct the ground height measurement from the antennas that would be mounted directly to the row divider walls as in the prototype system.

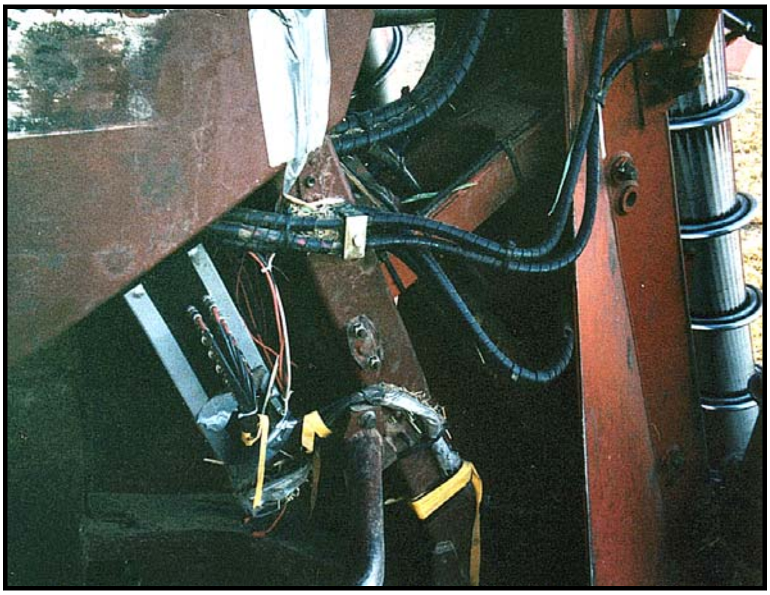
Figure 4.7: A photograph of the trash caught behind the row divider cavity after 15 minutes of operation

4.5 Summary

The prototype system that was constructed was trialled on an Austoft Research & Development harvester for one week. The input from the sensor was logged to test the performance of the unit under actual harvesting conditions. The results of these measurements are detailed in Chapter 5: Figure 4.8 and Figure 4.9 shows photographs of the "black box" that was used to house the switching, automatic frequency control and signal level detection circuitry, as well as the analogue and digital input/output interface that was used to connect the equipment to the laptop.

Figure 4.8: Photograph of the "black box" of the prototype sensor.

Figure 4.9: Photograph of the "black box" mounted on the sugar cane harvester during the week long trial.



Chapter 5: Harvester Testing

5.1 Introduction

The suitability of the prototype ground detection sensor was tested onboard a sugar cane harvester during normal harvesting operation. The primary objective of this test was to verify if the sensor did in fact respond to the ground height as required by this application. However, this test also had a more fundamental aim of checking whether or not the equipment that had been selected would actually work in and survive the harsh conditions onboard a sugar cane harvester during operation.

5.2 Harvester Trial

The prototype configuration that was described in Chapter 4: was installed on the Austoft Pty. Ltd. research and development harvester in Bundaberg and was trialled during the period from the 24th to the 28th of September 2001. The harvester was used to cut various varieties of green sugar cane that had been planted in a "dual-row" BSES trial for all of the measurements that were recorded during this period. The varieties of sugar cane that were harvested during the trial period including the following five types:

- Q170
- Q151

- Q141
- Q138
- Q124

Some general observations were drawn from the data that was measured during this trial and are listed below:

1) Strong received signal strength levels were recorded at the receiver even while harvesting. This indicated that the selected 2.5GHz frequency of the radio signal was penetrating the higher than expected amounts of sugar cane in the throat of the harvester and is therefore suitable for this application.

2) The measurement system was operated continuously while the harvester was operated for one week without any major problems. The position of the antennas on the inside of the row divider walls meant there was only small amounts of dirt build up on the antenna arrays, apart from a slight coating on the lowest few elements of the receiver array. Surprisingly, given the exposed location of both the transmitter and receiver array the mechanical damage to the antennas was also minor consisting mainly of slight scratching of the copper surface. It should be noted that metal guards were installed in front of the antennas to protect them from

the sugar cane that was scraping along the face of the row dividers. It seemed that any dirt or damage of the antennas did not have any noticeable effect on the signal levels that were measured.

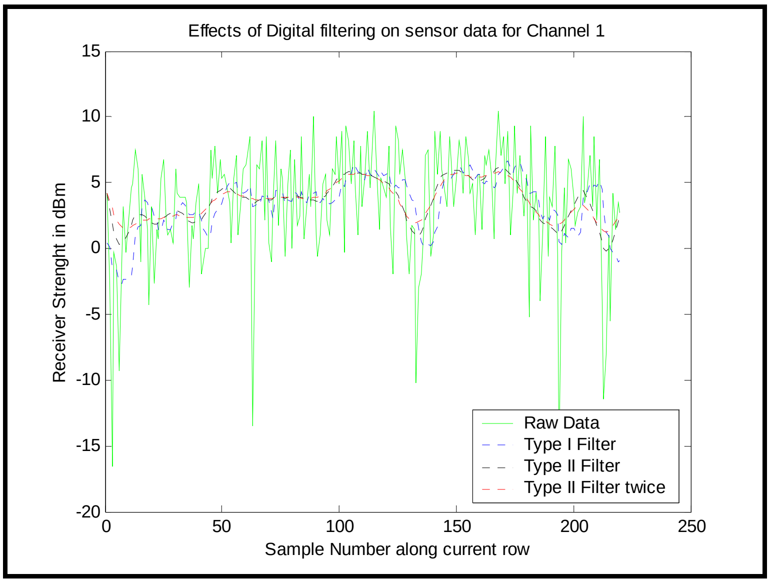
3) During the week long trial, the location and speed of the harvester was also recorded as a time stamp for the received signal strength levels. The purpose of recording the location of the harvester was to correlate the data that was recorded by the ground detection sensor to several hand recorded measured results that would have been taken at specific positions in the paddock. Unfortunately, in practice it proved difficult to correlate the measured GPS position data with the actual base-cutter height setting that had been used during harvesting at a specific position in the sugar cane paddock. One problem was the limited accuracy of the GPS data which meant it was only possible to distinguish ten metre intervals at best. This was not sufficient to accurately pinpoint a single row in the paddock. Furthermore, since the sugar cane was harvested green, the blanket of trash coverage that had been left over after harvesting made it very difficult to determine if the base-cutter had been adjusted too high or too low. The usefulness of the recorded position data was therefore very limited.

4) As it was not possible to correlate an independent measurement of the ground height to a particular position along a sugar cane row, it

> was impossible to determine the absolute accuracy of the measurement technique from the tests conducted. A further complication that was noted earlier was that the two row-dividers can be moved independently of each other and the base-cutter height. This meant that the sensor would most probably detect a change in ground height due to an adjustment of the row divider settings. Again, this meant that the configuration used for this test did not allow the response of the sensor to be directly compared with the ground height under harvesting conditions.

Given the obvious shortcomings of the harvester testing identified above, the data collected was processed to observe the operation of the sensor. A typical example the time plot of the amplitude measurement for one channel of the receiver as the harvester travelled along the sugar cane paddock row is shown in Figure 5.1. It can be clearly seen from this data that the raw data measurements, which are shown in green, contain a significant amount of “noise”. It was noted during the laboratory simulations and the field-testing that was performed using the portable test unit that there would be “random fluctuations” in the measured signal strength levels due to the orientation of the sugar cane along a row which would appear as a “random fluctuation” upon the measured signal. It was therefore decided to filter or smooth the “raw” data in order to better observe any underlying trends that may have been present. The effect of applying different amounts of smoothing to the "raw" data is shown in Figure 5.1 by the red, black and the blue dashed lines. It can be noted that smoothing had the desired effect of removing the random variations while retaining and highlighting the important underlying trends that were present. The "Type I Filter" uses the Matlab filter function and the "Type II Filter" uses the Matlab filtfilt function. The "Type II Filter" was eventually selected as the most appropriate filter to analyse all of the data.

Figure 5.1: The effects of digital filtering to smooth the sensor output

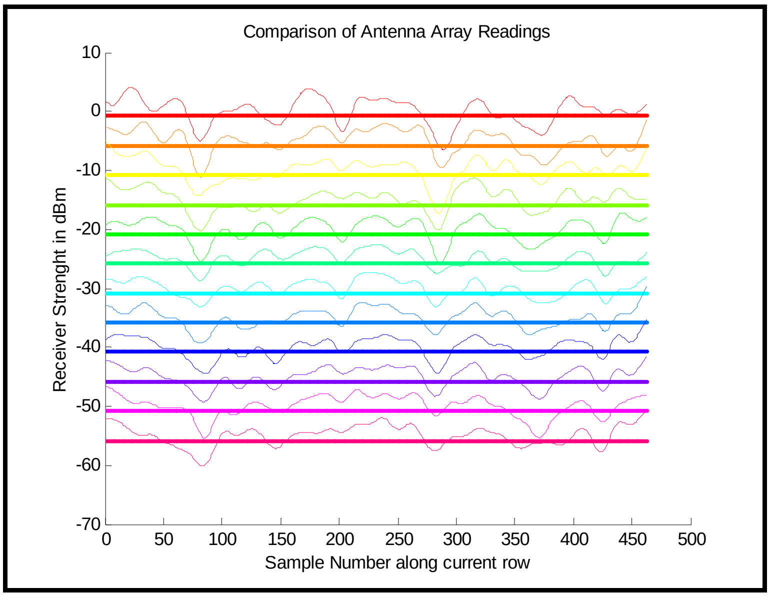


By smoothing the raw data, it was also possible to compare the responses that were measured on all of the receiver channels at the same time. Figure 5.2 shows the typical trend that was measured when all twelve receiving antenna levels were plotted as they varied along a sugar cane row during harvesting. Channel 1 was the lowest positioned antenna at approximately ground level, while channel 12 was the highest at approximately five hundred millimetres. It should be noted that all of the data in this graph has been filtered to remove any random variation and highlight the underlying trends.

The different channel measurements were also offset by 5dB to assist in distinguishing the different responses of the twelve channels. It can be seen by the shape of these graphs that they all tend to follow a similar pattern. This most likely indicates that there were changes in the density of the sugar cane or its orientation along the length of the row and that these changes have a similar effect on all of the measured signals. This is most clearly seen around sample 80, 375 and 425 of Figure 5.2. However, if the graphs are studied closely it can also be seen that there are some instances where a decrease in the signal strength level was only measured on the lower positioned channels and is much less noticeable on the higher positioned channels. One such event is clearly depicted around sample 205 and 275 in Figure 5.2.

The most probable reason for this trend is that this occurs when there is a change in the ground level that causes a change in measured signal strength levels on the lowest positioned antennas only. Most importantly, these results suggest that with the correct signal processing of the measured data it should be possible to be able to use this sensor to measure the effect of ground height through sugar cane using a non-contact measurement technique.

Figure 5.2: Measured amplitude trends on all twelve channels of the ground detection sensor receiver



Other parts of the trial data were also processed in a similar way. The trends observed in these tests were similar to those mentioned above and have not been included in this report.

5.3 Conclusions

The testing that was performed using the microwave ground detection sensor configuration that was developed for this project showed that the measurement technique was suitable for measuring ground level even on an operating sugar cane harvester. Obviously, a device that was permanently installed on a harvester would need to be designed to be much more robust when compared to the prototype system that was used to conduct the measurements gathered for this project. However, the basic measurement principle seems to work appropriately and provide data that could be used to determine the actual ground height using a non-contact measurement technique. These results indicate that with the proper signal processing, the sensor could be used to measure ground height and could therefore be used to control the base-cutter height on a harvester during operation.

Further tests need to be carried out to address the issue of not being able to identify the absolute accuracy of the sensor in the field. Ideally these tests should incorporate an independent measurement of the ground height before or after the sensor is used. This type of measurement would then allow the best method of signal processing and an appropriate control strategy to be developed.

Chapter 6: Conclusion

6.1 Conclusion

This project was successful in achieving what it set out to do, which was to test the suitability of a new microwave ground detection measurement technique that could be developed to automatically control the base-cutter height of a sugar cane harvester. Initially laboratory tests and the later electromagnetic field simulations were utilised to both verify and determine the level of signal obstruction that was caused by the row profile when a microwave frequency signal was transmitted from one side of a sugar cane row to the other.

The simulations and the experiments both led to similar conclusions that the closer to the top of the row profile the receiver was positioned, the greater the level of signal attenuation that could be expected. These tests laid the fundamental foundations for this project by establishing not only the basic sensing technique but also the preferred operating frequency, the optimum signal polarisation and the antenna gains that were later used in the field trials and for the design of the prototype equipment. The experimental testing that was conducted in the field further extended upon this work and highlighted that the sugar cane density and stalk orientation had a marked influence on the measurements and there was a requirement to average the data that was measured. A sensor able to make measurements on a cane harvester was then designed and developed. The prototype that was constructed used low profile microwave patch antenna arrays for both the transmitter and receiver antennas. These antennas proved ideal for mounting on the inside of the row divider walls of a sugar cane harvester. The receiver array incorporated a switching network that allowed individual elements of the receiver array to be connected to the amplitude level detection circuitry. Thus by scanning one antenna at a time over the length of the receiver array, the received signal height profile was able to be sampled. This allowed an instantaneous signal strength profile versus height to be obtained with no mechanical moving parts. Dedicated electronic circuits were built to generate and detect the microwave frequency signals as required by the prototype sensor. A laptop was utilised to provide the required control and data logging features.

The prototype sensor was built and installed on a sugar cane harvester. The sensor was operated under actual harvesting conditions to guarantee that the technique was not flawed and that the design of the equipment suited the conditions likely to be experienced on a working harvester. While the interpretation of the results obtained during these tests could not be verified by using an independent height measurement of the ground height, the trial did provide evidence that the proposed technique would work as designed. Importantly, all of the equipment used in the prototype unit survived the

extremely harsh conditions that they were subjected to while the harvester was in operation.

After smoothing the measured data using digital signal processing the results that were collected looked very promising. It could be clearly seen that the lower elements in the receiver array measured a lower signal level than the higher antennas and that the level seemed to respond to changes in ground height. This demonstrated that the sensor was working as expected and would be suitable to track changes in the ground level along the length of the row of sugar cane.

It was estimated that the hardware cost of installing a commercial version of the prototype sensor on a harvester would be less than A$2000. However, with economies of scale and some redesign of the system, the cost would probably be much less than this amount, and even as low as A$1000.

6.2 Future Work

This project has successfully laid the foundations for using the microwave ground detection technique and developed equipment suitable for measuring the signal response on an operational harvester. However, further work will be required to get this product to the stage where it can be used to control the base-cutter height on a harvester, and hence be developed into a commercial product.

It will be essential to know the accuracy, repeatability and response time of the sensor in determining over what time frame the measurements are required to be averaged before the base-cutter setting should be adjusted. It is anticipated that this will involve a relatively low gain control system.

To provide this type of information it will be necessary to perform further field tests using the prototype sensor. It is strongly recommended that this testing be performed with the sensor mounted on a high clearance tractor. The use of a high clearance tractor rather than a sugar cane harvester will allow multiple measurements of the same profile to be performed so that a comparison could be made as to the repeatability of the sensors response.

The response measured by the sensor could then be converted to a height value and verified/calibrated by using an independent measurement technique such as the surveying of the sugar can row profile. Furthermore, by using a high clearance tractor greater flexibility is allowed when performing measurements as the speed of the tractor can be increased, decreased and even stopped so that specific situations can be investigated.

Towards the end of the project it was planned to perform some measurements using a high clearance tractor that would be hired from Irving Farm Services in Ingham. A mounting bracket to attach the antenna arrays to a hydraulically adjusted bracket on the back of the high clearance tractor was built and some time was spent learning how to operate this machinery. However, due to time constraints imposed by this project and the priority to perform the measurements on a harvester, this additional testing was not performed as a supplement to the original project.

When the dynamic operational characteristics of the ground detection sensor are known, the next stage in the development of this project would be to install the sensor and a control system on a harvester and allow it to control the base-cutter height. One measure of such a test would be to compare the amount of extraneous matter that was collected with and without the automatic control of the base-cutter height being used. As this type of testing may involve significant modification to a sugar cane harvester, it is strongly suggested that this stage of the development of the commercial product be performed as a joint venture with a commercial harvester manufacturer such as Case IH/Austoft.

As with any radio transmitting device a commercially available unit will have to comply with the Australian Communications Authority regulations and either operate at a license free frequency and transmission level or a license may be required by the harvester operator to operate the equipment. The ongoing cost of such a license is typically only AUD$30 and is considered to be a small cost to the operator.

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