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ASSESSMENT OF STANDING HERBAGE DRY MATTER USING A RANGE  
IMAGING SYSTEM

A THESIS SUBMITTED IN FULFILMENT OF REQUIREMENT FOR  
THE DEGREE

of

**Master of Engineering**

at

**The University Of Waikato**

by

**Mark Benseman**

Supervisor

**Professor Jonathan Scott and Dr Michael Cree**



**School of Engineering  
Hamilton, New Zealand  
June, 2013**

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# Preface and Acknowledgements

This thesis is for the completion of my masters in engineering majoring in electronics. It is a reflection of my interest in agriculture and in particular the difficulties posed in measurement of dry matter content in standing herbage.

Firstly I would like to thank my supervisors Dr Michael Cree and Professor Jonathan Scott. Dr Cree was extremely helpful and knowledgeable with image analysis and camera related topics. Prof Scott was the person who first touted this idea and sowed the thoughts of a masters project in my head. I would like to especially thank the Hicks Trust and the National Agriculture Fieldays committee for awarding me their respective scholarships. These scholarships were the deciding factor in my decision to carry out this important research.

I would like to thank DairyNZ staff for allowing me to accompany them on their farm walks, without their co-operation data collection would have taken much longer to complete. Special thanks especially to Chris Roach for providing me with the data each week.

Thanks to Dr Lee Streeter for interfacing the SoftKinetic DS325 camera to a PC. This was a crucial development stage in the project. Thank you to Dr Adrian Dorrington for assisting with initial field trials using the SR4000.

Special thanks to Graham Lynch from Novel Ways Ltd for starting me out on the long journey of pasture measurement.

# Abstract

It has been known for a long time that a device that could quickly and accurately ascertain dry matter (DM) content would be very useful to pastoral farmers. Despite many years of various products being developed there is still a lack of consistent and accurate measurements available. We present a proof of concept using a time of flight (TOF) imaging system to measure standing herbage DM. Scenes of herbage were captured using the SoftKintec DS325 range imaging camera. Each scene included range and intensity images as well as colour images. Simple statistical analysis of the images was carried out and related to DM content. Twenty data points were gathered in late autumn growing conditions. The best correlation achieved was 0.9 with a standard deviation of 337 kgDM/ha. This was achieved using a multivariate linear regression. The predictors used were average depth, and standard deviations of both depth and intensity frames. The worst correlation achieved using a multivariate linear regression was 0.89 with a standard deviation of 365 kgDM/ha. Thirteen data points were also gathered during severe drought conditions. The same statistical analysis resulted in a best fit of 0.52 and a standard deviation of 533 kgDM/ha. Range cameras show promise when compared to currently available methods of DM measurement.



# Statement of Originality

The idea of using a TOF camera for measuring standing herbage dry matter is that of professor Jonathan Scott. I collected the data and developed all algorithms with the help of Dr Michael Cree. The use of the intensity information for predicting dry matter content is my own idea.

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# Chapter 1

## Introduction

Pasture is the backbone of the New Zealand farming industry and is the cheapest feedstock available to ruminants. Bearing this in mind it is essential for pastoral farmers to make best use of the pasture available to them. To do this a farmer needs to know exactly how much pasture, or more importantly, dry matter (DM) is available to them. Pastoral farmers use estimations of DM to make decisions on certain aspects of farming such as stock rotations, fertiliser application and irrigation. However inaccuracies in feed estimation lead to incorrect decision making and always result in a lower return than if the exact quantity were known [1].

It has long been known that a device that could accurately and quickly measure standing herbage DM would be very useful to pastoral farmers. Many devices have been developed to do this. These devices include; plate meters[2], various capacitance methods [3][4], sward sticks [5], pasture rulers, calibrated visual estimations [6] [7], satellite imaging [8], ultrasonic sensors [9][10], spectral reflectance meters[11], and various optical methods [12].

As of 2007 it was estimated that only 20% of New Zealand farms carry out formal feed management [13]. Some of the reasons for this include perceived lack of accuracy in available devices and time and cost of gathering paddock data [14]. It is the goal of DairyNZ to increase farmers use of objective measurement tools (quantity and quality) in New Zealand from current levels to 80% of farms by the year 2015. To meet these targets the right tools should be available to facilitate change [8].

### 1.1 Thesis Statement

In this thesis we present the novel concept of using a 3-D camera system based on the time of flight (TOF) principle to estimate standing herbage DM. It is the aim of this thesis to:

- Present all known methods available for measurement of DM, along with accuracy information and various advantages and disadvantages.
- Set up a time of flight camera for field measurements of standing DM
- Undertake simple statistical analysis of acquired images and correlate these to actual DM
- Provide guidance for further research

# Chapter 2

## Background

In this section we cover concepts that are important to understand when reading this thesis. This includes a brief look at DM, how it is used and pasture types. We also introduce TOF camera operation along with applications and limitations.

### 2.1 Dry Matter Overview

#### 2.1.1 Dry Matter Definition

Dry matter or dry weight is the portion of pasture which is not water, that is, the weight of the material after it has been completely dried. It is usually expressed in terms of weight per area, for example, kilograms of DM per hectare (kgDM/ha). It consists of crude protein, neutral detergent fibre, acid detergent fibre, organic matter and acid detergent lignin. These quantities are normally expressed as g/kg of DM [15].

#### 2.1.2 Pasture Management

The efficiency of milk production from pasture is a function of annual pasture production, pasture utilisation and the efficiency of milk solid (MS) production per cow [16]. The need for precision pasture management has been seen as important for a long time [17]. It has been recognized that the highest pasture yield and animal production per area results when feed demand is closely matched with supply [18].

DairyNZ are an organisation that represent New Zealand farmers. They are funded by a levy on all milk solids produced in New Zealand and also through government investment<sup>1</sup>. A pasture management tool recommended

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<sup>1</sup>[http://www.dairynz.co.nz/page/pageid/2145855891/Who\\_we\\_are](http://www.dairynz.co.nz/page/pageid/2145855891/Who_we_are)

by DairyNZ is the "feed wedge". The first step of using the feed wedge is to gather DM estimations from every paddock using one of the available measurement techniques. Individual paddocks are ranked in order as shown in figure 2.1. A line is drawn from the pre-grazing target on the left to the post-grazing target on the right. Anything above the line is seen as a feed surplus and anything below the line as a shortage. The farmer can use the knowledge of whether there is a surplus or shortage of DM to make pasture management decisions. These decisions include grazing rotation, daily feed allocations and the use of feed supplements [19].



Figure 2.1: The "Feed Wedge" ranks paddocks by DM content and is a tool recommended by DairyNZ for use in feed management. [Source: DairyNZ farmfact URL: <http://www.dairynz.co.nz/file/fileid/36306>, used with permission.]

### 2.1.3 Herbage Species

Between species variation has been found to be a factor in DM prediction using some of the currently available measurement methods [9] [20]. New Zealand pasture has consisted predominately of two main species since the 1930s. These are perennial rye grass (*Lolium perenne*) and the legume white clover (*Trifolium repens*). However as of 1999 there have been 109 certified cultivars available [21].

In this section we briefly look at the two main herbage types used in this trial. We also mention four species of "weeds" which were found on the both the Crosby and Scott farm used for field trials.

Perennial ryegrass grows in tufts and consists of long thin blades which end at a sharp point. It is the most widely used grass species in NZ and grows

well in fertile conditions (figure 2.2,left). It is easy to establish and forms a compatible mixture with white clover. Ryegrass however performs poorly in dry hot conditions due to its shallow root structure. White clover consists of a stolon with small broadleaf foliage on the end (figure 2.2, right). It is a perennial legume that spreads by stolon branching and naturally reseeding itself. Similarly to ryegrass clover is also a poor performer in hot dry conditions.



Figure 2.2: The two most predominant species in New Zealand Pasture; Rye Grass (left) and White clover(Right) [Source: <http://pastureinfo.massey.ac.nz/grasspages> used with permission]

The other species that were involved in the trial were creeping mallow (*Modiola carolinian*), dandelion (*Taraxacum officinale Asteraceae*), yarrow (*Achillea millefolium Asteraceae*) and broad-leafed dock (*Rumex obtusifolium*). These species are generally seen as weeds and represented a small portion of the herbage on both the DairyNZ Scott farm, and the Crosby farm used in the trials. Figure 2.3 shows the morphology of all the weed species.

## 2.2 Time of flight Cameras (TOF)

### 2.2.1 Range imaging Systems

Time of flight (TOF) or range imaging cameras have been commercially available for more than half a decade now [22]. These cameras return an image which includes distance information for every pixel within a scene. Various applications have been reported [23] [24] [25]. The majority of these fall under three broad categories: these are scene related tasks, object related tasks and human related tasks [26]. Scene related tasks normally consist of reconstruction of walls and furniture or other larger objects. Object related tasks usually involve small distances and the reconstruction of small objects. Human related tasks normally involve gesture recognition. This is the primary use of such cameras as the SoftKinetic DS325.



Figure 2.3: Four common species of weeds found on both the Scott and Crosby farms where the cameras were trialled; top left, creeping mallow, top right, dandelion, bottom left, yarrow bottom right, broad leaf dock [Source: [http://http://weeds.massey.ac.nz/](http://weeds.massey.ac.nz/) used with permission]

Typically cameras return two images; these are a depth image and an intensity image. Some cameras such as the SoftKinetic DS325 also return an RGB colour image. Camera specifications vary between manufacturers. The resolution of commercially available cameras is normally quite low (less than 320 x 240 pixels). The absolute distance accuracy of these cameras differs between models; however modern cameras such as the SR4000 are capable of ranging precision of less than 1 cm in ideal conditions. Figure 2.4 shows a number of commercially available cameras as of April 2012, along with useful specifications [27].

### 2.2.2 Operation

A time of flight camera measures the time it takes for light to travel from a light source to an object and back to the camera as depicted in figure 2.5. The time of flight is converted by way of electronics to a distance measurement. There are two standard methods for achieving this, the direct method and the

## 2.2. TIME OF FLIGHT CAMERAS (TOF)

Manufacturer	ToF Camera Model	Working Principle	Max Sensor Resolution [Pixel × Pixel]	Max Range [m]	Focal Distance [m]	Max Framerate [fps]	Signal wavelength [nm]	Default Modulation Frequency [MHz]	Measurement Accuracy/ Repeatability ( $\sigma$ )	Weight [kg]
Canesta Inc.	XZ422	Phase shift	160 × 120	n.a.	n.a.	n.a.	n.a.	44	n.a.	n.a.
Canesta Inc.	Cobra	n.a.	320 × 200	n.a.	n.a.	n.a.	n.a.	n.a.	millimetric	n.a.
Fotonic	Fotonic B70	Phase shift	160 × 120	7.0	n.a.	75	808	44	±0.015 m at 3–7 m (accuracy) and ±0.030 m at 3–7 m (uncertainty)	1.049
Mesa Imaging AG	SR-3000	Phase shift	176 × 144	7.5	0.008	25	850	20	n.a.	n.a.
Mesa Imaging AG	SR-4000	Phase shift	176 × 144	5 or 10	0.010	54	850	30 or 15	±0.010 m or ±0.015 m	0.470 - 0.510
Optima NV	OPTRICAM DS10K-A	Phase shift	120 × 90	10.0	0.0037	50	870	n.a.	noise level <0.03 m at 3.5 m	n.a.
Panasonic	D-Imager (EKL3104)	Phase shift	160 × 120	9.0	n.a.	30	870	n.a.	±0.04 m and $\sigma = 0.03$ m (no ambient ill.) or $\sigma = 0.14$ m (ambient illum.)	0.52
PMDTechnologies GmbH	PMD19k	Phase shift	160 × 120	7.5	0.012	15	870	20	centimetric	n.a.
PMDTechnologies GmbH	CamCube3.0	Phase shift	200 × 200	7.5	0.013	15	870	21	centimetric	1.438
PMDTechnologies GmbH	A2	Phase shift	64 × 16	9.4–150	n.a.	15	870	16–1	±0.10 m (distance < 40 m)	n.a.
Stanley Electric Ltd.	P-300 TOFCam	Phase shift	128 × 128	15	n.a.	30	850	10	repeatability 1% of the distance (at 3 m)	0.25
Advanced Scientific Concepts Inc.	DRAGONEYE 3D FLASH LIDAR	Direct ToF	128 × 128	1,500	0.017	10	1570	n.a.	±0.10 m and $3\sigma = \pm 0.15$ m	3
Advanced Scientific Concepts Inc.	TIGEREYE 3D FLASH LIDAR	Direct ToF	128 × 128	60–1,100	n.a.	n.a.	1570	n.a.	±0.04 m at 60 m	1.6 ÷ 2.0
Advanced Scientific Concepts Inc.	PORTABLE 3D FLASH LIDAR	Direct ToF	128 × 128	70–1,100	0.017–0.500	15	1570	n.a.	n.a.	6.5
SoftKinetic	DS311	Direct ToF	160 × 120 + RGB 640 × 480	4.5	n.a.	60	infrared	n.a.	depth resolution <0.03 m at 3 m	n.a.
3DV Systems	ZCamII	Direct ToF (Shutter)	320 × 240 + RGB	10.0	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
3DV Systems	Zcam	Direct ToF (Shutter)	320 × 240 + RGB 1.3 Mpixel	2.5	n.a.	60	n.a.	n.a.	±0.02 m	0.36

Figure 2.4: A list of commercially available range cameras with useful specifications [Source: Piatti and Rinaudo, Ref. [27]. Used with permission.]

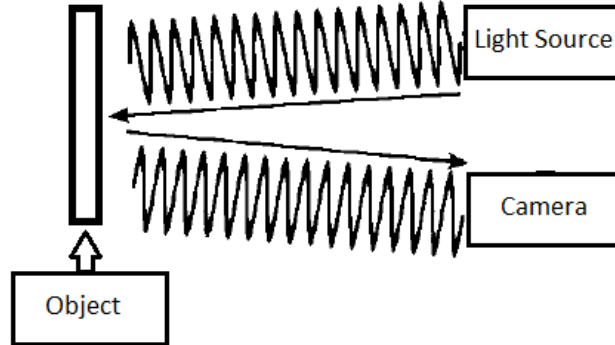


Figure 2.5: A simplistic representation of the operation of a range imaging camera

indirect method. The direct method involves measuring the time a light pulse takes to travel from the light source to the object and back to the sensor. There are different ways of implementing this, for example; a shutter based system [28] or a LADAR based system using a 2-d array of avalanche diodes [29]. The time of flight is calculated by the range or distance( $d$ ) and the speed of light( $c$ ) by 2.1.

$$TOF = \frac{2d}{c} \quad (2.1)$$

In this thesis however we are primarily interested in cameras which use the indirect method to ascertain distance measurements. These cameras illuminate

the scene with a modulated light source. The TOF is encoded into a phase shift that represents the delay of the received modulation in comparison to the transmitted signal [30]. The distance to the scene is given by 2.2.

$$d = \frac{c}{4\pi f_{mod}}\omega \quad (2.2)$$

where;  $\omega$  is the phase shift of the received modulation ( $f_{mod}$ ).

If we look more closely at the transmitted and received light we can see exactly what is occurring. We explain the principle in reference to figure 2.6. A modulated signal is emitted by a light source with amplitude PA. When the emitted signal is obstructed by an object a signal is returned with amplitude kPA, where k is some constant indicating the amplitude received in proportion to the amplitude emitted. This amplitude datum is used by the camera to generate the active brightness or intensity image. The phase offset is measured when the light signal returns to a sensor or pixel. PB is an offset in the returned signal which is mainly caused by background lighting and also imperfect demodulation [31].

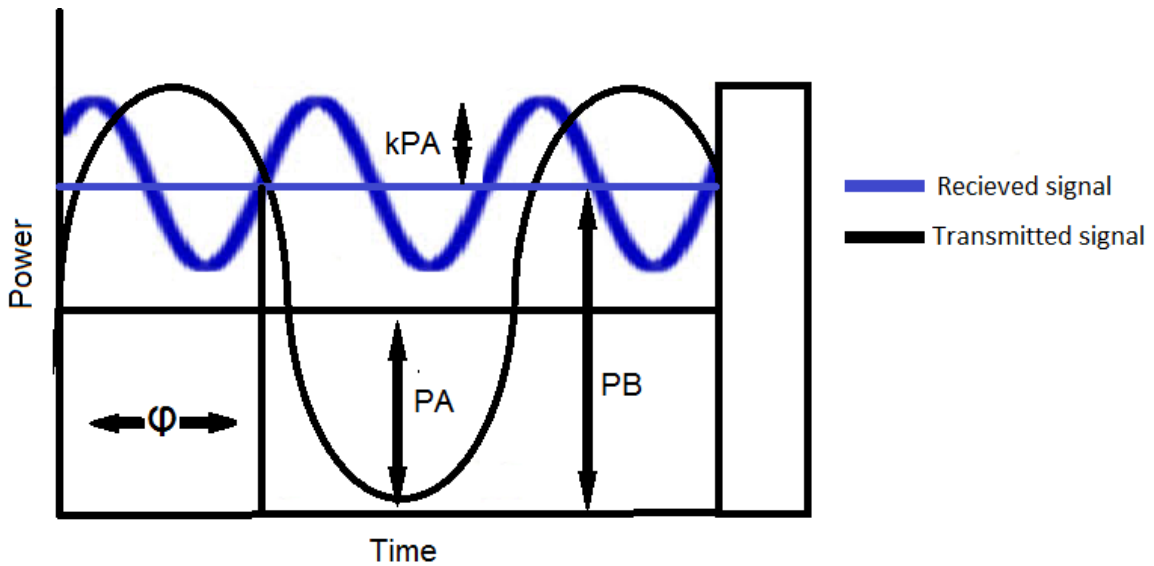


Figure 2.6: The properties of a modulated light wave reflected by an object

The received signal is sampled at phase offsets of 0, 90, 180 and 270 degrees or  $Q_1$ ,  $Q_2$ ,  $Q_3$  and  $Q_4$ . The phase is calculated from these values using a four point Fourier transform, namely 2.3

$$\omega = \arctan \frac{Q_4 - Q_3}{Q_1 - Q_2} \quad (2.3)$$

and the intensity is given by 2.4.

$$I = \frac{\sqrt{(Q_4 - Q_3)^2 + (Q_1 - Q_2)^2}}{2} \quad (2.4)$$

Note that this is a Fourier transform so any odd harmonics may be aliased onto the fundamental frequency and thus corrupt the phase calculations. There are more sophisticated methods to reduce the effects of harmonics, however covering these is beyond the scope of this thesis.

### 2.2.3 Camera Limitations

TOF cameras have two major problems in resolving depth images. These are multiple path reflections and mixed pixel distortion. Another more specific problem in this project was the effect of background lighting.

#### 2.2.3.1 Multiple Path Reflections

Multiple path distortion has been known to be a problem with time of flight cameras for some time [32]. This occurs when the emitted light is reflected multiple times in object space. These multiple signals may super impose or distort parts of the signal which is directly reflected from the scene [33]. A simple example involving a corner wall is shown in figure 2.7. In reference to this; when emitted light interacts with wall A, it will be both reflected directly back to the sensor, and also onto Wall B and then back to the sensor. This phenomenon causes an erroneous estimation in the actual measured distance.

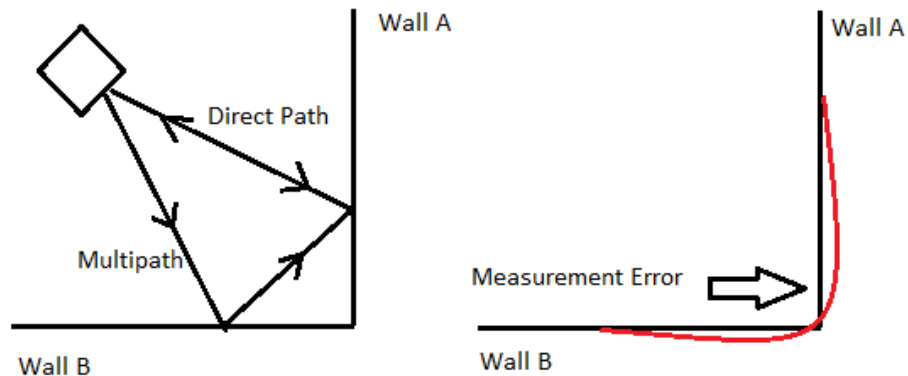


Figure 2.7: Multipath distortion which occurs when indirect light paths interfere with the direct light path

There have been numerous attempts in the literature to fix this error both with custom made cameras [34] and off the shelf cameras [35]. Due to the nature of standing herbage we can expect that there will be multiple path distortion occurring within the images.

### 2.2.3.2 Mixed pixel distortion

Mixed pixel distortion occurs when light is returned from multiple sources within a single pixel. It is particularly exacerbated around the edges of objects. Figure 2.8 shows a simple four pixel image. The red area represents the foreground and black represents the background. Each of the four squares can be considered to be one pixel. The upper left pixel contains both information from the background and the foreground. Light incident on this pixel will be reflected from both the foreground and the background. This will result in a distance measurement that corresponds to neither and may not necessarily be a value between the two distances.

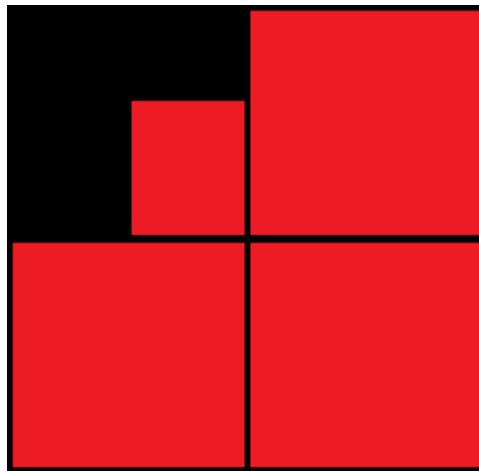


Figure 2.8: A "four pixel image" showing an example of mixed pixel distortion

There has been some work done to improve resolving range data by correcting this error [36]. Because herbage has multiple edges and the cameras are low resolution this will certainly cause some uncertainty in distance information.

### 2.2.3.3 Background lighting

Another major problem with both cameras trialled in this project is they suffered severe pixel saturation when in an outdoor environment. Author [37] conducted a study using the IFM Efector 3D and PMD CamCube TOF cameras to measure plant phenology. The distance errors generated by background lighting were compared with a reference image at 6000 lux. They noted an increase in the distance measured and also an increase in the noise associated with an increase in background light (figure 2.9).

Author [38] carried out a study in 2010 also on plant phenology using TOF cameras. They used a PMD[vision] S3 to determine whether colours behind the plants affected distance measurements. The PMD camera is not supposed to be affected by background light. They tested this by placing the camera facing

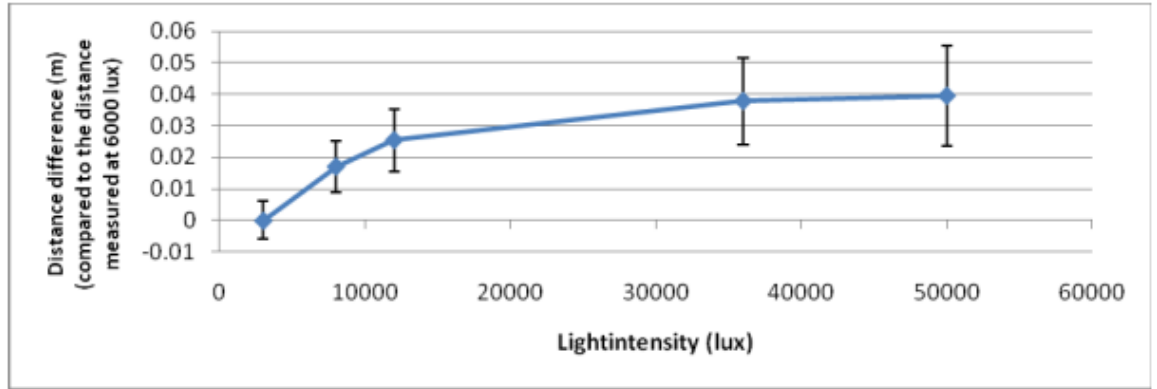


Figure 2.9: The effect of water droplets on distance measurements using the PMD CamCube. [Source: Klose and Penlington and Ruckelshausen Ref: [37]]

Table 2.1: Results obtained in outdoor conditions using the PMD S3 [Source: Kraft and Salomao de Freitas and Munack, Ref. [38]. Used with permission.]

Illumination	PAR( $\frac{\mu\text{mol}}{\text{sm}^2}$ )	Actual (mm)	Measured (mm)	Std. dev. (mm)
Sunlight	1371	1775	1816.9	16.3
Shadow	211	1775	1809.3	8.6
Sunlight	1399	1630	1600.4	15.6
Shadow	208	1630	1602.6	8.0

vertically downwards above turf at two different heights. From table 2.1 they concluded that background lighting did not severely impact measurements.

The cameras available at the University of Waikato during the course of this project were the SwissRanger SR4000 and the SoftKinetic DS325. Neither camera was designed for outdoor use so did not have sufficient background light suppression. Thus light had to be physically excluded from the scene.

# Chapter 3

## Literature Review

In this section we briefly look at previous methods used for estimation of standing herbage dry matter. These include both commercially available devices and devices mentioned in literature.

### 3.1 Currently Available Measurement Techniques for Estimating Herbage Mass

#### 3.1.1 Cut Weigh and Dry (The gold standard)

The "gold standard" method for dry matter (DM) measurement is to cut and weigh dry herbage. This is a destructive process. It involves removing herbage from a paddock, drying it until all of the water has evaporated, and weighing the remaining material to determine the DM content. The area of the sample is then multiplied by a factor to give units of kgDM/ha. This is considered to be the most accurate method available. However the results may not be known until after the pasture has been grazed, thus making it impractical for feed management decisions in everyday farming.

The standard way in which a DM instrument is developed is to measure a certain physical, electrical or optical property of the herbage. An empirical relationship is developed by comparing the measured property to actual DM content obtained from using the cut, weigh and dry method. This is termed a calibration equation. Most calibration equations used in industry are single variable linear regressions of the form  $y = mx + c$ .

#### 3.1.2 Visual Assessment

A visual estimate of herbage biomass is the only method that does not use any equipment. It is perhaps the simplest of all the methods and is also seen as

the most subjective. The method used by DairyNZ for visual assessment and visual calibration is to place ten  $0.25\text{ m}^2$  quadrants in a representative area of herbage. Each quadrant is given a visual score, where each number represents 300 kgDM/ha. For example a score of 10 would indicate an estimate of 3000 kgDm/ha. The herbage is then clipped to ground level and dried in the oven to provide an actual quantity of DM. Various studies have been carried out using the visual estimation technique. Author [6] carried out a visual assessment calibration which was shown to be suitable for inexperienced observers. In their 1975 study they "calibrated" the visual observers by placing five reference quadrants into a paddock. One quadrant was placed at the lowest level of pasture and one at the highest level of pasture. The three remaining quadrants were placed on intermediary levels of pasture. Forty quadrants were placed in another paddock and scored by the observers in relation to the reference quadrants. The scoring was done using a scale of 1 to 5 with incremental scores of 0.25. The reference quadrants were then harvested and observed quadrants scores were related to these. It was found doing this resulted in correlations ranging from 0.95 to 1. In another study Author [7] found correlations of between 0.23 and 0.9. Both authors noted between observers differences thus the measurement technique is not considered to be objective. As with all manual methods the DM measurements must be either recorded by hand or stored manually into a portable database.

### 3.1.3 Pasture ruler

The pasture ruler is a simple device which may either be a direct measurement in centimetres [39] or consist of a graded scale with a conversion to DM mass. There have been a number of studies evaluating various pasture rulers. Author [40] compiled a table of correlation coefficients from four published studies. Average correlations varied between 0.11 and 0.86. One further study was carried out by Author [41]. This was designed to develop calibration equations for pastures throughout New Zealand and involved 2598 measurements. They found correlations for each part of the season varied between 0.38 and 0.56.

Figure 3.1 shows an example of a pasture ruler available from Meat and Livestock Australia. The manufacturers recommend using by placing the base on the soil and sliding the thumb down until a blade of herbage is touched. This particular ruler is calibrated for 100% green pasture. Pasture rulers have the advantage of being very cheap, light and portable in comparison to other methods. However significant time must be put into collecting and recording



Figure 3.1: A Calibrated Pasture ruler available meat and livestock Australia [Source: Improving pasture use with the MLA pasture ruler URL: <http://www.mla.com.au/News-and-resources/Publication-details?pubid=1879>]

data.

### 3.1.4 Sward stick

A sward stick consists of a graded scale and a sliding Perspex sleeve. The stick described by Author [5] was 45 cm in length, had graduations of 0.5 cm and a Perspex sleeve measuring 2 cm by 1 cm. In use the ruler is held vertically in the pasture and the Perspex sleeve is lowered down by hand until it touches the highest piece of non-flowering herbage [42]. The height of the herbage is then recorded and converted to DM content via means of a pre-determined equation. Various studies have been undertaken using a sward stick. Author [40] compiled correlation coefficients from six studies and found they ranged from 0.1 and 0.91 with a mean correlation of 0.68.

### 3.1.5 Capacitance Meter

The capacitance method for pasture measurement was first proposed by [3] in 1956. Since then various other geometries have been reported [4]. In general the capacitance method consists of a positive and negative conductor. The device is placed on the ground so that pasture is situated between the two conductors. A capacitance reading is taken and converted to kgDM/ha via a calibration equation. Multiple calibration equations have been developed with differing coefficients of determination reported [41] [40] [1]. These have been found to range from 0.42 to 0.96. Two different constructions are shown in figure 3.2 the left depicts the first capacitance device reported and the right shows the modern GrassMaster II by Novel Ways LTD.

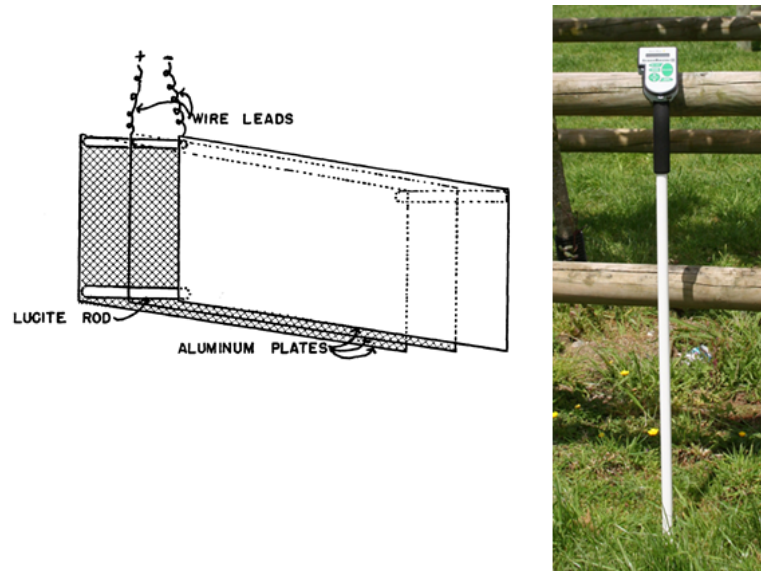


Figure 3.2: Two Capacitance measurement devices. The first device developed by Fletcher for pasture measurement (left). A modern capacitance probe built by Novel Ways LTD [Source: Fletcher [3]] [Source: GrassMaster II Drymatter instrument URL <http://www.novel.co.nz/webapps/site/76545/134711/shopping/shopping-view.html?pid=356250>, used with permission.]

### 3.1.6 Rising Plate Meter

The rising plate meter (RPM) is one of the most commonly used devices for estimating herbage mass in New Zealand. The first plate meter was very simple in design and consisted of a weighted disc and a ruler. The weighted disc was placed on the herbage and allowed to settle for a certain period of time, after which the height was recorded using a ruler. Author [2] further developed this idea by placing the disc on a shaft with a graded scale. This was mounted onto a tripod which ensured more accurate mean compressed height measurements

occurred as shown in figure 3.3 (left).



Figure 3.3: The first rising plate meter developed (left). A modern day rising plate meter made by Farmworks (right)[Source: F300 Electronic rising plate meter user manual, [online].FARMWORKS Precision Farming Systems Ltd, Feilding, New Zealand, October 2008]

The modern RPM is shown on the right of figure 3.3. It consists of a graded rod inserted loosely through the centre of a plate. Pasture is measured by placing the rod vertically on the ground. The pasture under the plate holds the plate at a certain distance up the rod. The vertical displacement is measured manually by number of clicks or by electronic means. A calibration equation is used to convert plate height to kgDM/ha. There have been numerous studies carried out using the rising plate meter. The correlation coefficients reported have ranged between 0.31 and 0.97 [40] [42]. Rising plate meters have an advantage over other methods in that they measure both forage height and forage bulk [43].

### 3.1.7 Automation

Pasture management has become a very time consuming task using traditional methods. The average sized New Zealand dairy farm and sheep farm are 172.2 ha and 443 ha respectively [44]. Due to this more advanced products that lend themselves to automation have been developed. Two recent products are the C-Dax Pasture Meter®(CPM) and the Farmworks Feed Reader. Both of these devices are vehicle mounted. These new devices are much faster and results are far less influenced by the operator than aforementioned methods.

### 3.1.8 C-dax Pasture Meter®

The CPM was originally developed by Massey University and then later commercialised by C-Dax Ltd. The CPM as shown in figure 3.4 consists of a rectangular tunnel for pasture to pass through with an array of sensors on either side. The sensor consists of 18 infrared light beams spaced at 20 mm apart. The lowest sensor is set at 20 mm so the total pasture height measurable is 360 mm. When standing herbage passes between the two sensors a height reading is taken. The device takes 200 samples per second and can be towed at speeds of up to 20 km/h. This allows for a height sample every 27 mm. Height is converted to kgDM/ha by one of the available calibration equations [45].

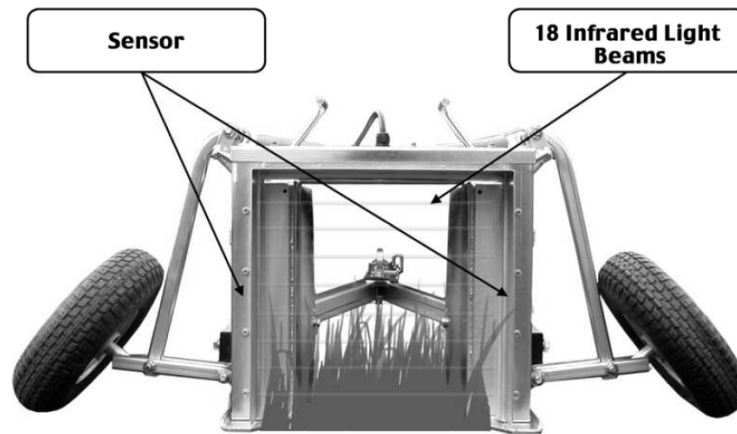


Figure 3.4: The C-dax Pasture Meter [Source: Assembly and operation Manual [45] Used with permission]

Initial trials using the CPM gave correlations ranging from 0.63 to 0.91 with an average correlation coefficient of 0.76 for 376 pasture cuts [12]. Other than initial studies there have been very few studies carried out due to the CPM being relatively new. One such study was done by author [20] where the pasture meter was calibrated for Northland kikuyu pasture. The Northland specific calibration equation achieved a root mean square error (rmse) of 515 kgDM/ha. A kikuyu covariate was taken into account and reduced this error to 437 kgDM/ha. Regression coefficients were not published. Author [46] did a masters project to test and calibrate the CPM for Danish pastures. The Pasture consisted of 15% clover and 85% perennial rye grass. Their results gave correlations of between 0.63 and 0.89. These equations were however linear with the response (DM) and log<sub>10</sub> transformed with the predictor (pasture height). This form of equation was not published by the manufacturers however they did mention other forms of equations were trialled [12]. Author [46] also noted that the draw bar had a tendency to bend tall blades of grass

thus may have affected measurements.

### 3.1.9 Ultrasonic

The ultrasonic method for DM was first proposed by author [10] in 1990 and named the sonic sward stick (figure 3.5(left)). Ultrasonic rangefinders operate by emitting a pulse of ultrasound and measuring the time that elapses before an echo is detected. Author [10] compared the ultrasonic device to a sward stick similar to that described in section 3.1.4. They found the ultrasonic method had a similar standard deviation to that of the sward stick. They also related the sonic sward stick values to sward mass and found correlation coefficients varied between 0.06 and 0.8. Author [9] carried out a study in 2011 which showed ultrasonic sward height measurements predicted 74.8% of the variation in sward mass with a standard error of 1.05 tonnes per hectare. They reported improved regression coefficients when legume specific equations were developed, these ranged between 0.799 and 0.855.



Figure 3.5: The "sonic sward stick" first developed in 1990 (left) and the modern day FARMWORKS FEED READER [Source: Hutchings and Phillips and Dobson, Ref: [10] ] [Source: Farmworks Feed Reader: URL:[http://www.farmworkssystem.co.nz/cms/docs/feed\\_reader.pdf](http://www.farmworkssystem.co.nz/cms/docs/feed_reader.pdf)]

The most well-known commercially available ultrasonic device available in New Zealand is the Farmworks Feed Reader. This product has been in development since 2001 and is mounted on the front of an ATV. It is recommended to travel at speeds from 5 to 20 km/h whilst measurements are being recorded [47]. To date there have been no papers published which show correlations versus sward mass. Author [48] reported an issue with the ATV needing to remain stable during operation. Any change in weight on the ATV changes the height and thus may affect readings. The manufacturer is in the process of fixing this

problem.

### 3.1.10 Other Methods

In this section we cover methods that are not readily used in New Zealand or are not yet commercially available.

### 3.1.11 Spectral Analysis

Spectral analysis of light is primarily used to measure quality characteristics of herbage. This includes chlorophyll, water status, brown pigments, green biomass and photosynthetic efficiency [49]. However there have also been limited studies carried out which use spectral analysis to predict DM. Author [50] carried out a study using the C-dax pasture meter, a rising plate meter and a CropSpec<sup>TM</sup> multispectral sensor to estimate herbage biomass. The CropSpec<sup>TM</sup> is an active sensor with wavelengths centred around 730 nm and 800 nm. The author did not report correlations versus actual biomass but reported good prediction of pasture mass in high and medium biomass paddocks. However under estimates were reported in freshly grazed paddocks. Author [11] used a custom built spectral analyser to predict total green DM. Their device used three different sensors centred at 800 nm, 670 nm and 550 nm. They achieved a correlation of 0.927 and RMSE of 262 kg of green DM/ha when data from all three reflectance bands were used in a multivariate linear equation.

Author [51] used a FieldSpec<sup>®</sup>Pro FR spectroradiometer to estimate biomass on 20 herbage plots ranging from 0.22 to 0.33 m<sup>2</sup> in size. Ten measurements were made on each plot where each measurement was the average of 50 readings. They found coefficients of determination varied across the spectrum for fresh biomass and DM, as shown in figure 3.6.

### 3.1.12 Satellite imaging

There has been limited work done using satellite imagery to predict DM content in pastoral herbage. Author [13] started a project in 2005 comparing normalised difference vegetation index (NDVI) to rising plate meter readings. They reported correlation coefficients of between 0.02 and 0.98 in 2005. In 2007 they produced figure 3.7 which shows a correlation of 0.72 when comparing satellite predictions to observed DM. One disadvantage mentioned by [8] was the impact of cloud cover on the availability of satellite images. This

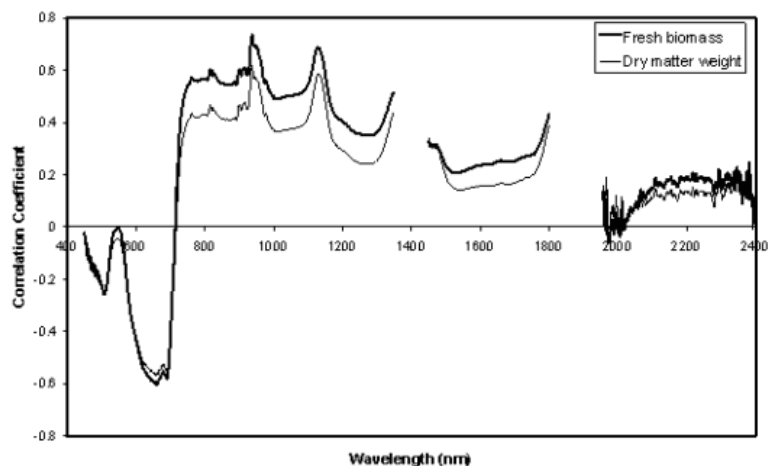


Figure 3.6: Correlations obtained for different wavelengths using the FieldSpec Spectral Sensor for Estimation of Fresh Biomass and DM [Source: Clevers and Van Der Heijden and Verzakov and Schaepman, Ref. [51]. Used with permission.]

could cause some difficulty for farmers wanting to make short term herbage decisions.

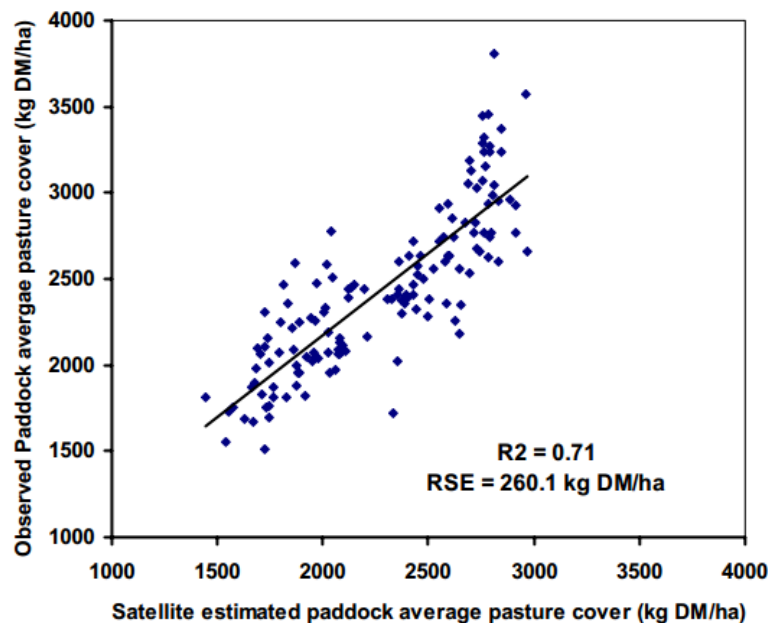


Figure 3.7: Results obtained for two farms across three sampling dates using satellite imaging [Source: Mata and Clark and Edirisinghe and Waugh and Minnee and Gherardi, Ref. [8] Used with permission.]

### 3.1.13 LIDAR

In 2010 Author [52] used a Riegl LPM-25HA LIDAR based system to estimate DM for alfalfa and tall fescue. The LIDAR was mounted at a distance of 2.5

### 3.1. CURRENTLY AVAILABLE MEASUREMENT TECHNIQUES FOR ESTIMATING HERBAGE MASS

Table 3.1: Important specifications for the Riegl LPM-25HA LIDAR

Performance Characteristic	Specification
Measurement range	2 -20 m
Measurement accuracy	8 mm
Measurement resolution	1 mm
Laser wavelength	900 nm

metres from the ground. Measurements were taken both before and after the herbage samples were hand plucked from the ground. The hand plucking was done to emulate how a ruminant would have consumed the vegetation. The volume measurements obtained from before and after scans gave very good estimations of the biomass present, alfalfa  $r^2 = 0.970$  (rmse 3.1 g) and tall fescue  $r^2 = 0.957$  (rmse 3.5 g)).

Each data point took 4 minutes to scan over a 1 m<sup>2</sup> area. Figure 3.8 shows their experimental set up.



Figure 3.8: The LIDAR Setup used which achieved correlations of 0.967 for estimation of alfalfa dry matter [Source: Radtke and Boland and Scaglia, Ref. [52]. Used with permission.]

It is interesting to note the specifications of the LIDAR used (table 3.1). The wavelength of operation is particularly of interest as it is within 50 nm of the TOF cameras tested, with similar accuracy specifications.

### 3.1.14 Accuracy requirements

Author [1] used the economic model DAFOSYM (Dairy Forage System model) to model the effect inaccurate DM measurements had on farm profit. For the model they based their assumptions on a herd of 125 cows grazing 81 hectares of pasture, where production was 5900 kg of milk per cow per year. They found losses induced by inaccurate pasture readings varied between 8 and 31 dollars per hectare. An 8 dollar per hectare loss occurred when pasture was overestimated by 10% in spring and underestimated by 10% in summer. A 31 dollar per hectare loss occurred when pasture was underestimated consistently by 20%. In comparison to this model an average New Zealand dairy farm is 139 hectares consisting of 393 cows producing 4128 litres of milk per cow per year [44].

### 3.1.15 Summary

All the devices mentioned have various advantages and disadvantages. The main disadvantage of all the devices is the accuracy. Most devices return varying coefficients of determination and are not consistently within 10% of actual DM. More work is required to achieve this sort of accuracy and is why time of flight cameras are being explored in this thesis.

# Chapter 4

## Method

In this chapter we include preliminary indoor trials using the SR4000. This includes both the method and results for sward height prediction indoors. We also outline the steps required to set up the SoftKinetic DS325 for outdoor field measurements of DM content.

### 4.1 SwissRanger Experimental Setup

#### 4.1.1 Camera Overview

The camera initially used to test the plausibility of TOF cameras for DM measurement was the MESA Imaging SwissRanger SR4000 (figure 4.1). The primary reason this camera was chosen was that it was readily available at the University of Waikato. The important specifications of the SR4000 are shown in table 4.1.



Figure 4.1: The SR4000 by Mesa Imaging

Table 4.1: Swissranger Specifications [Source: SR4000 Data Sheet Ref.[53]]

Property	Specification
Wavelength	850 nm
Calibrated Range	0.8 m to 5 m
Pixel Array Size	176 x 144
Absolute Accuracy (typical)	10 mm
Modulation Frequency	30 MHz
Field of View	43.6 x 34.6
External Light Disturbances	Designed for indoor use

### 4.1.2 Experimental Setup

The first experiment was carried out indoors to determine whether or not the SR4000 was suitable for measurement of sward height. This was done by comparing camera predicted heights with heights estimated using a ruler. The camera was mounted on a custom built frame at a distance of 1.2 metres from the top surface of a planter box. This height was chosen so that pasture heights ranging from 0 to 40 cm would be within the calibrated depth range of the SR4000. This maximum pasture height is consistent with other available devices such as the CPM (36 cm) and the GM Pro (40 cm). The experimental set-up is depicted in figure 4.2.

The planter box measured 80 x 60 cm. This provided a suitable size so the entire box was visible within the field of view (FOV) of the camera. Three herbage species were gathered during mid-spring growing conditions from the Crosby farm in Newstead. These were white clover, perennial rye grass and broad leaved dock. These species were chosen due to them being predominantly what was available on the farm and also provided three different plant morphologies.

### 4.1.3 Data acquisition

Images were triggered and stored in a laptop connected via USB. Multiple images of each scene were gathered as greater precision and accuracy has been reported when temporal averaging is used [54]. One hundred frames of data were gathered and averaged. Each frame was stored individually as well as an image which represented the average of all the frames. This was done for both depth and intensity frames. The code used to do this was written in MATLAB

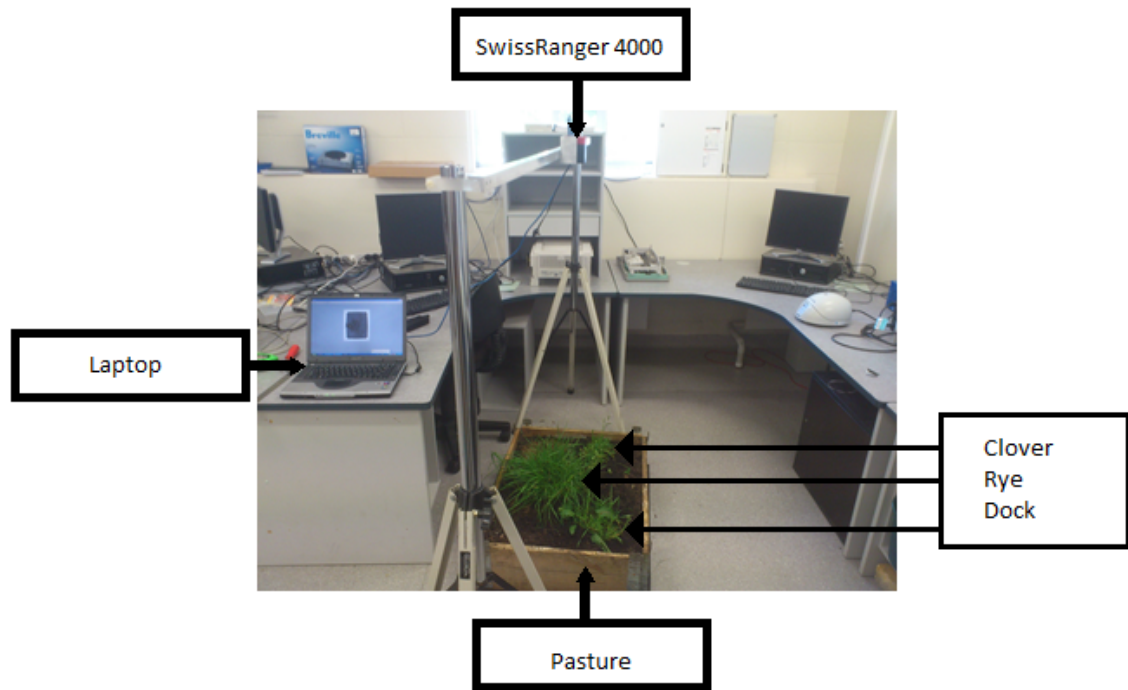


Figure 4.2: The set up used for to test the SR4000 for indoor measurement of herbage height

using the API documentation provided by MESA imaging.

#### 4.1.4 Data manipulation

The range data measured by the SR4000 is the radial distance from the camera to the surface. To make direct comparisons between camera height and herbage height estimates required image manipulation. To achieve this camera height measurements were altered to use the soil height as a reference. The data was transformed into  $x$ ,  $y$  and  $z$  Cartesian coordinates using the `srcoordtrf` function specified in the MATLAB API. To extract just herbage information required setting thresholds for both depth and intensity images (seen in figure 4.3, A and B respectively). For the depth threshold pixels that were greater than 1.24 m from the camera were set to zero. The intensity threshold was set so pixels less than 2350 were set to zero. This returned image  $c$  in figure 4.3. Heights were then subtracted from the camera height to return herbage heights in relation to the soil. A 3-D representation of the data is shown in figure 4.4.

To get the height measurements obtained by the camera the data cursor shown in figure 4.5 was used. A 40 cm ruler with 1 mm increments ruler was used to estimate the actual height of the herbage. Table 4.2 compares individual heights recorded by the camera and the corresponding height measured with

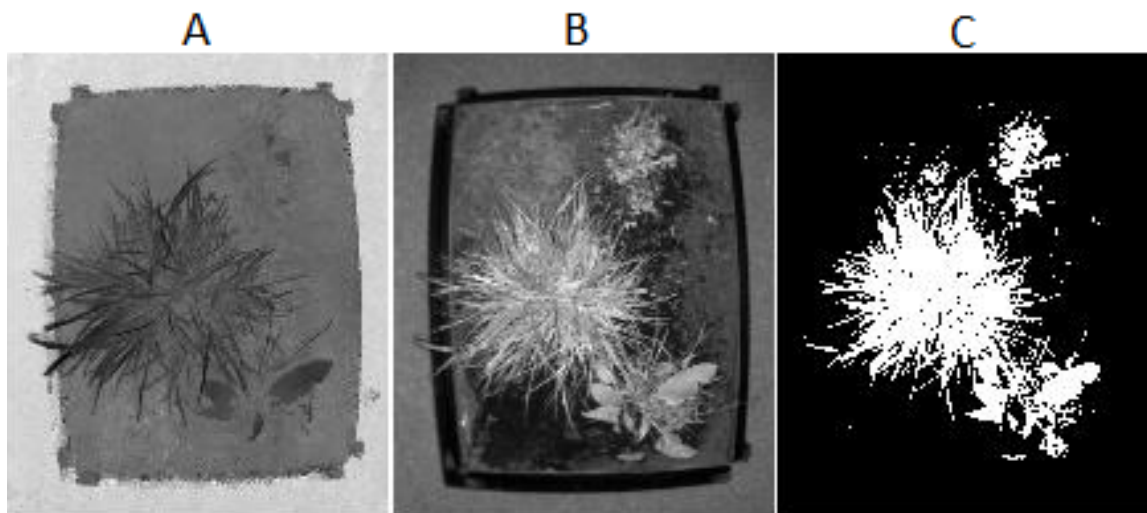


Figure 4.3: Data extraction of pasture information using intensity and depth information to remove unwanted information

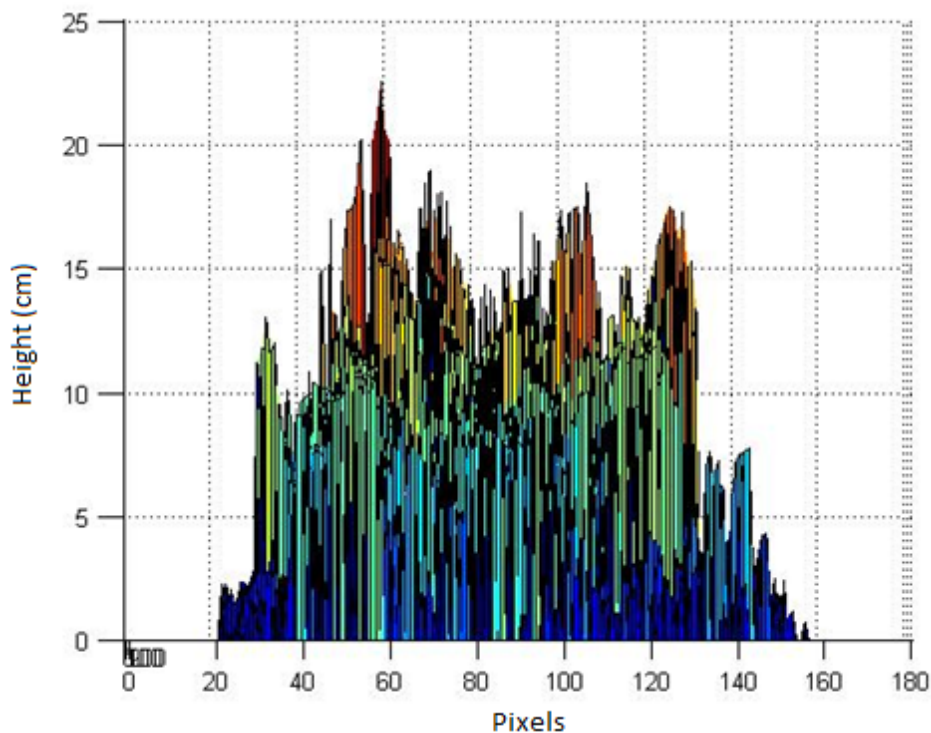


Figure 4.4: A 3-D representation of the acquired depth data

a ruler.

#### 4.1.5 Interpretation of Results

It was obvious there were some differences between the observed heights and the measured heights. The camera tended to overestimate the actual distance. This could have occurred for a number of reasons. Possible reasons include multipath distortion, the mixed pixel effect and the wavelength of operation.

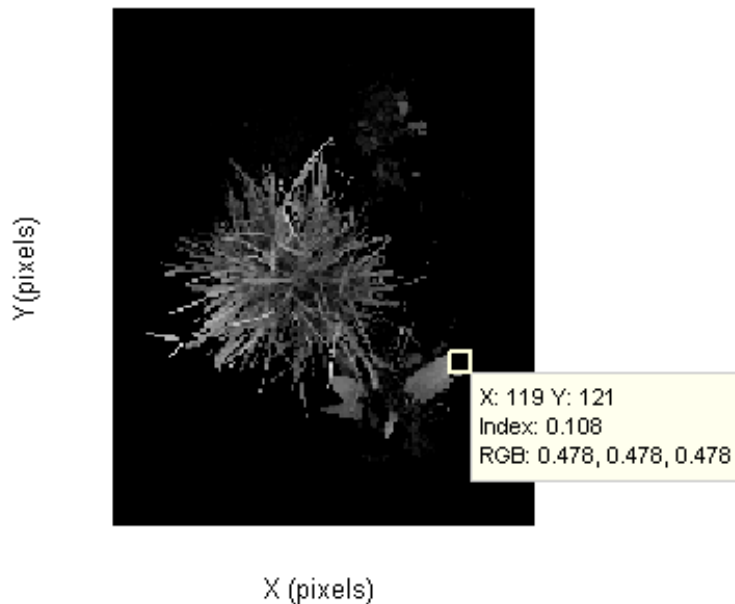


Figure 4.5: A depth map of the test herbage with background data removed

Table 4.2: Herbage heights measured by the camera versus height measurements with a ruler

Pixel co-ordinate	Camera prediction (cm)	Actual height (cm)
(119,121) dock leaf tip	10.8	9.7
(96,142) small dock leaf leaf tip	12	10.4
(120,75) rye blade	17	16.4
(104,40) (clover petiole)	6.2	7.5
(87,48) (clover petiole)	5.5	9
(19,112) (rye grass on edge of planter box)	15.5	14
(75,123) Rye blade next to dock leaf	18	16.5
(22,117) highest point	22.5	20.5

As explained in the background section multipath reflections result in altered distance estimations. It is easy to imagine multiple light reflections occurring between blades of pasture. The effect that mixed pixel could have had is depicted in figure 4.6. This shows part of an 8 MP image with a 176 x 144 grid overlaid on top of it. Numerous pixels within the figure have both herbage information and background information. Range data within each pixel is returned from two different depths thus may result in incorrect depth information.

The wavelength of operation can affect the distance due to the reflectance, transmittance and absorption properties in the region between 800 and 1000 nm. The level of reflectance is  $\approx 50\%$  with  $\approx 40\%$  transmittance and  $\approx 10\%$  absorption [55] [56]. This level of reflectance provided a strong signal back to the camera as can be seen in the intensity image. However the transmitted



Figure 4.6: Camera resolution of the Swissranger used for pasture measurement

light may go through the leaf and be reflected by the surface behind it [38]. In the case of herbage the surface behind could either be another piece of vegetation or soil. The reflectance for soil at the operation wavelength of the SR4000 (850 nm) is between 0.2 and 0.05 [57]. This suggests there will be some signal returned to the camera from the soil and thus some distance error could be induced.

Despite the slight inaccuracies there was some promise shown by the SR4000. Actual height vs. measured heights gave a correlation of 0.94. A limitation of this experiment was the difficulty in obtaining a wide representation of ruler height measurements from the images.

#### 4.1.6 SwissRanger field testing

The SwissRanger was trialled at the Crosby farm in Newstead. However trials were abandoned for three main reasons:

- The background light caused pixel saturation even with a low integration time setting. A tent was purchased to rectify this however the frame became impractical to transport around the farm.
- The large FOV caused by the calibrated depth range meant large pasture samples had to be removed. This took approximately 1.5 hours per sample using scissors.
- The SoftKinetic DS325 with a suitable calibrated depth range became available.

All work using the SR4000 was ceased at this point.

Table 4.3: SoftKinetic specifications in comparison the the SR4000

Property	DS325	SR4000
Pirce (US)	240	4295
Calibrated (m)	0.15 - 1	0.8 - 5
Intensity Image	yes	yes
Wavelength	Infrared	850 nm
Colour Image	yes	no
Portable	yes	yes
Accuracy	1.4 cm @ 1 m (50% Reflectivity )	±1 cm (typical)

## 4.2 The SoftKinetic DS325

### 4.2.1 Camera Overview

During the course of the project the DS325 by SoftKinetic became available to the market. The camera was originally developed for gesture recognition. The cameras main benefit over the SR4000 was the calibrated depth range as this allowed a much smaller more portable measurement device to be manufactured. The DS325 also includes a 640 x 480 colour camera which was thought to be of use for herbage estimations. The colour camera however is offset from the depth camera and has a smaller FOV. It also does not capture data at the same time as the depth camera. Table 4.3 compares some of the other key specifications with the SR4000.



Figure 4.7: TheDS325 by SoftKinetic

The DS325 is a lot cheaper than other comparable cameras on the market. Author [58] tested the effect of the low cost on the accuracy of the camera. The author tested the camera out to a range of 3 m and obtained the results shown in figure 4.8. It must be noted that the object was a gray card placed in the centre of the FOV. Error would be expected to be larger on the outer areas

of the image. For measuring standard herbage DM the maximum height the camera was mounted at was 65 cm above the soil surface. Based on information from figure 4.8 we would expect central pixels to have an accuracy error no greater than 1 cm.

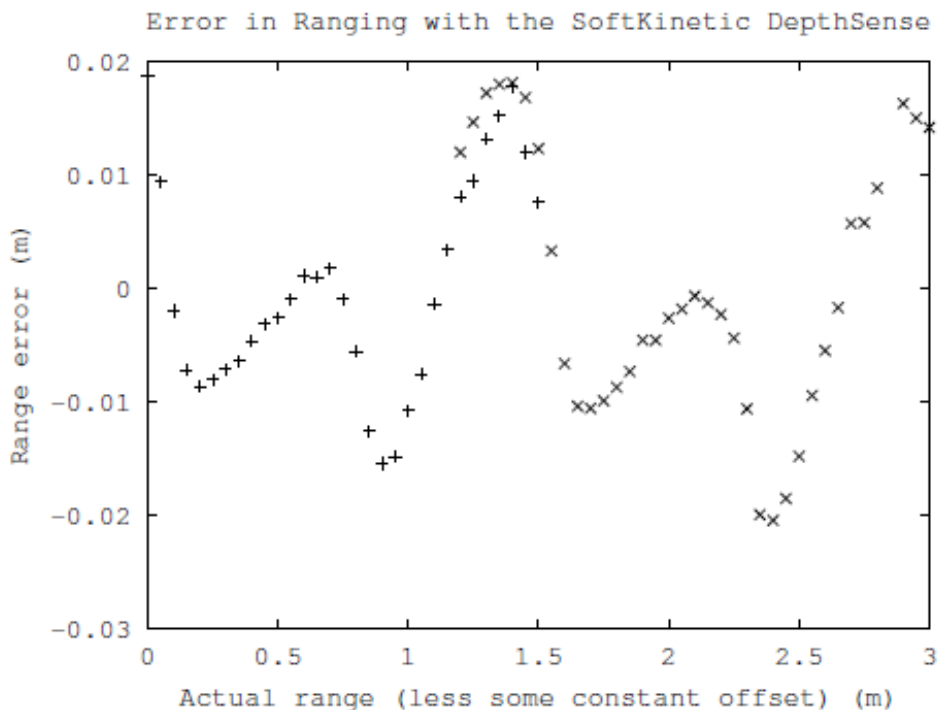


Figure 4.8: Accuracy Measurements obtained when using the SoftKinetic to a distance of 3 m [Source: Cree and Streeter and Conroy and Dorrington, Ref. [58]. Used with permission.]

## 4.2.2 Experimental setup

To carry out trials easily a rig had to be manufactured that was light, quick to set up and easily transportable for multiple field measurements. The camera was setup on an adjustable tripod structure as shown in figure 4.9.

The entire structure was made from aluminium and was designed to be run from a laptop. The camera was mounted so that the lowest adjustment level achievable was 60 cm. This allowed for calibrated pasture height measurements of up to 45 centimetres. The mounting height also provided a FOV that could enclose a standard DairyNZ quadrant as shown in figure 4.10.

## 4.2.3 Initial Camera Setup

The DS325 had not previously been trialled by the University of Waikato therefore the camera had to be set up to gather herbage data. The following

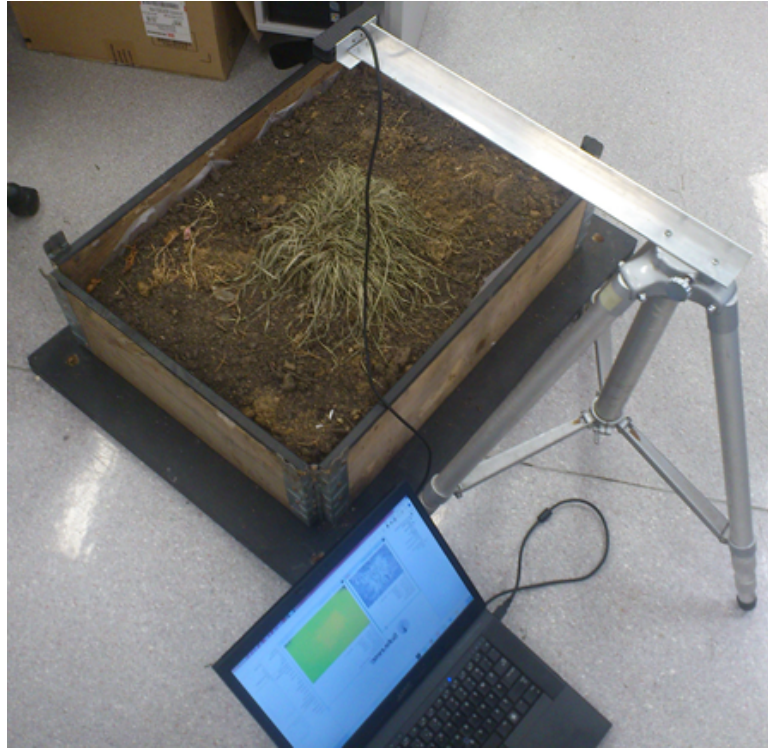


Figure 4.9: The experimental rig used to initially setup the DS325 and take field measurements

steps were taken to do this:

- Interfacing the camera to a PC
- Storing and loading multiple frames of data
- Transforming the colour image into the same co-ordinate system as the depth frame.
- Preparation for outdoor measurements

#### 4.2.3.1 Interfacing the DS325 to a PC

The code to interface the camera to a PC was written by Dr Lee Streeter and later modified by Dr Michael Cree. The program is a console application designed to be run from the command window. It triggers camera acquisition of confidence<sup>1</sup>, colour, depth and phase frames and writes them to a text file. The code was written in the C++ programming language.

#### 4.2.3.2 Data Storage

To make the image data readily available and easy to use it had to be transformed from text format to image format. The code to achieve this was written

<sup>1</sup>This is equivalent to an intensity or active brightness frame



Figure 4.10: The DairyNZ quadrant used in field trials this was taken during pre-drought conditions in February 2013

in MATLAB. The program creates a directory to store all information acquired for one particular scene. It then creates a subdirectory which stores all data associated with a single image capture, i.e., a subdirectory contains a frame for each colour band, depth, intensity and phase frame. The number of subdirectories created for a scene is dependent on how many frames are captured. The program could also load the stored frames from the directories back into MATLAB for analysis. The code is included in appendix B code.

#### 4.2.3.3 Image Registration

As aforementioned the colour camera is offset from the depth camera and also has a smaller FOV. It was thought that colour information would be of use when analysing herbage DM. To get colour data into the same co-ordinate system as the depth data required "registering" the images. This transforms the image so that each pixel represents the same point in object space.

The scene was set up using the DepthSense® software provided with the camera. This enabled continuous viewing of both the depth and colour images simultaneously. A scene consisted of multiple pieces of wood with varying heights. Different heights were selected so that the z component of the image would be translated as well as the x and y components. The pieces of

wood were arranged as shown in figure 4.11. Care was taken to include pieces of wood on the outer most regions of the image to attempt to correct for any inter frame barrel or pincushion distortions present. Multiple frames were captured and loaded into MATLAB using the code written in the previous two sections. The images were registered manually using the cp2transform tool. This tool brings up the GUI shown in figure 4.11 where both colour and depth frames are displayed.

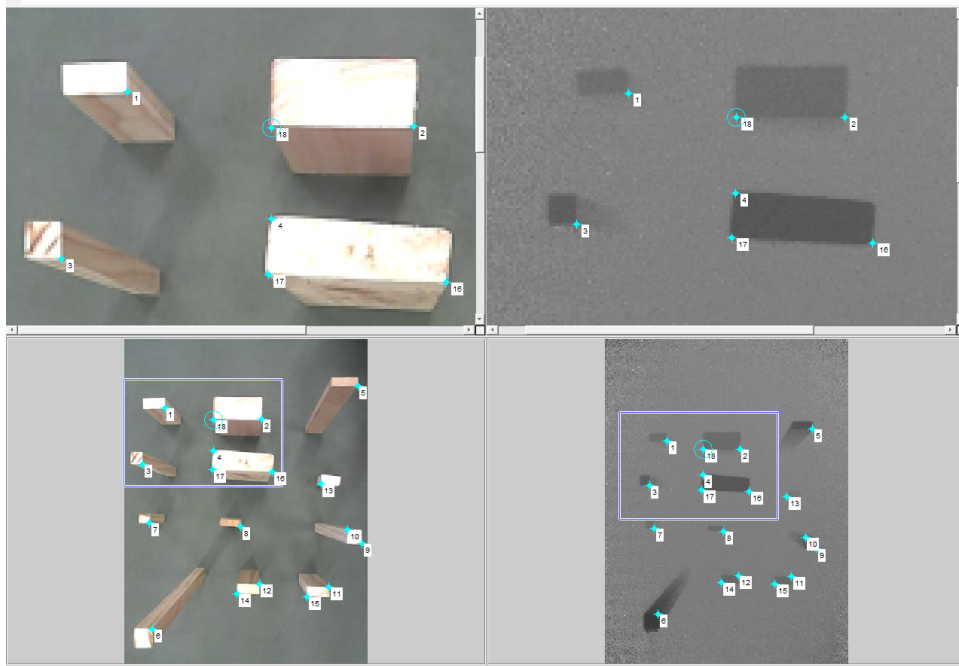


Figure 4.11: The MATLAB cp2transform tool used for registration of the colour image onto the depth image

To use this tool requires selecting an input image and a base image. The input image is the one to have its coordinates transformed and the base remains in its own co-ordinate system. Due to the colour image having a smaller FOV than the depth image it was chosen as the input image. This was done so that no colour information would be lost. It also meant the "less accurate" outer regions of the depth image would be removed from the final dataset. To translate the images control points were manually selected. These are the points which are common to both images and are labelled as 1 to 17 in figure 4.11. MATLAB calculates a transformation matrix based on these data points. This experiment was repeated multiple times with wood in varied locations to ensure good agreement between matrix values for separate image captures. There were some marginal differences between each; however these were most likely to have occurred in the process of manually selecting control points. The image registration data is extractable from the camera, however it was decided that extracting this would be very time consuming given the limited

documentation available.

#### 4.2.3.4 Setting camera up for outdoor use

The DS325 operates in the near infrared region. Although the exact wavelength is not specified by the manufacture we assume it is between 800 and 900 nm. The sun also emits approximately  $1 \text{ Watt}/m^2/\text{nm}$  in this region as shown in figure 4.12. To test the effect this had, the camera was placed outdoors in various lighting conditions. Different levels of pixel saturation occurred depending on the scenario. It was found all pixels saturated in direct sunlight, approximately half in morning cloud and none during night conditions. The effect of sunlight and the cameras illumination dropping away significantly with distance meant external light had to be omitted. A large cardboard box was used to achieve this.

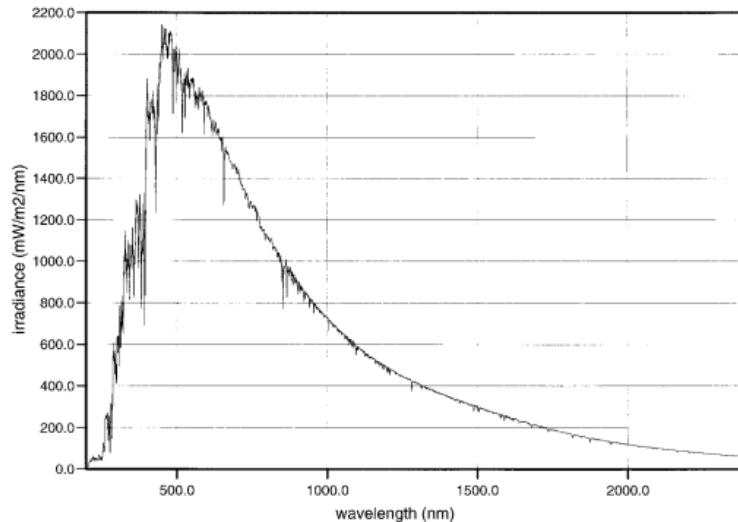


Figure 4.12: Solar irradiance of the sun[Source: L’Huillier and Thomson, Ref. [39]. Used with permission.]

## 4.3 Outline

The overall outline of the experiment from gathering images to obtaining equations and correlations for predicting DM is shown in the flow chart in figure 4.13.

## 4.4 Field Trials

On every Tuesday morning at 9 am DairyNZ staff conduct herbage measurements on the Scott farm. This farm is located on Vaile road, Newstead, Hamil-

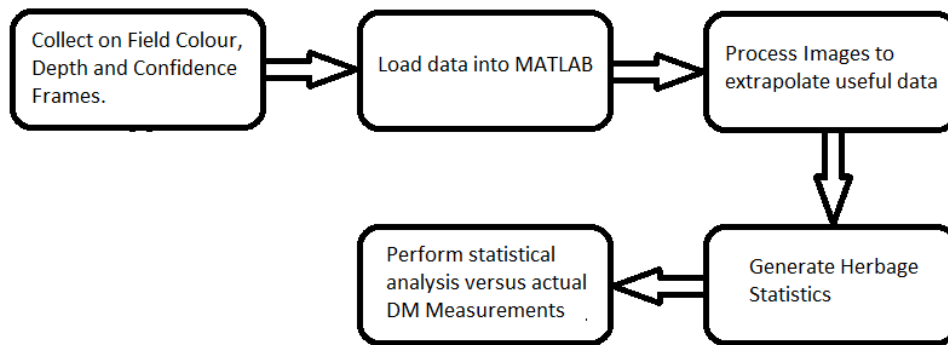


Figure 4.13: Overall process used to correlate camera data with dry matter measurements obtained by the cut weigh and dry method

ton, New Zealand. Each morning two paddocks are chosen by staff which fit into the farming schedule. One paddock is pre-grazing and the other is post-grazing. Six measurements are obtained on the pre-grazing paddock and four on the post-grazing paddock. Each herbage measurement consisted of the following steps:

- Placing a  $0.25 \text{ m}^2$  quadrant in a representative area of herbage
- Visual assessment of the DM content by trained staff
- Use of a rising plate meter (RPM) to assess the DM content
- Camera set up
- Gathering 20 frames of colour, range and intensity data with the DS325
- A DairyNZ staff member cutting the herbage to ground level
- Obtaining actual DM content by drying in an oven at 95 for 36 hours

Camera field trials were carried out between the 26th of February and the 14th of May 2013. A total of 33 data points were collected. A further description of the cut, weigh and dry method used by DairyNZ is provided in appendix A, Pasture.

#### 4.4.1 Camera Setup notes

The setup of the camera prior to taking images required three steps, these were:

- Positioning the light omitting cardboard box over the quadrant
- Getting the camera level

- Setting the camera height

To get the camera level a spirit level was used in both the x and y dimensions. The camera was set at a height of between 63.5 and 64.5. An exact height was difficult to achieve due to paddock undulations. Most images were taken at heights very close to 64 cm from the soil surface.

## 4.4.2 Image Processing

The FOV of the DS325 extended beyond the perimeter of a standard DairyNZ quadrant as depicted in the confidence frame seen in figure 4.14 . Due to this, the area inside of the quadrant had to be extracted. This was done so that analysis was only carried out on the herbage that was physically cut, weighed and dried. An automated method was thought to be of use owing to the large quantity of data ( 100 images per sample). The automated method required development of the following stages. These included:

- Filtering the image
- Finding the quadrant within the image
- Specifying pixel locations of the corners
- Cropping each depth, colour and intensity frame

### 4.4.2.1 Median Filtering

To allow for easier detection of edges the image first required filtering. A median filter was used as this is known to preserve edges. As the name suggests a median filter takes the median of a set of data. In the case of an image it takes an array of pixels surrounding the pixel of interest, calculates the median and then returns this value to the pixel. In our case the majority of the light fell on the centre of the image so the median filter was used to distribute this light more evenly whilst maintaining edges.

### 4.4.2.2 Hough Transform

To find the quadrant the Hough transform (HT) was used. The HT is an image processing technique used for shape analysis in noisy images. 4.15 provides a graphical description of how it works. The Hough transform first takes each edge pixel and plots all lines of slope (m) and intercept (c) that pass through this pixel. Each m and c value is then accumulated according to whether or



Figure 4.14: The 0.25 X 0.25 m quadrant used for cut weigh and dry measurements in field trials

not it passed through this pixel. It does this for each pixel along the edge. The  $m$  and  $c$  values which pass through each individual edge pixel the most frequently therefore also passes through all edge points. This is therefore the slope and intercept of the line or edge we seek.

Due to the possibility of infinite values of slope author [59] proposed adapting the method using the parametric equation of a line (equation 4.1).

$$\rho = x \cos \Theta + y \sin \Theta \quad (4.1)$$

where;

- $\rho$  is the distance from the origin to the line
- $\theta$  is the rotation from the x axis

This is depicted in figure 4.16.

This uses the same accumulation method aforementioned however instead each point in image space is represented by a sinusoid in parameter space. A maxima or a line in image space is represented where multiple curves intersect. If we apply this to a real herbage image we get the resultant HT shown in figure 4.17. The four maxima represent the four lines in image space.

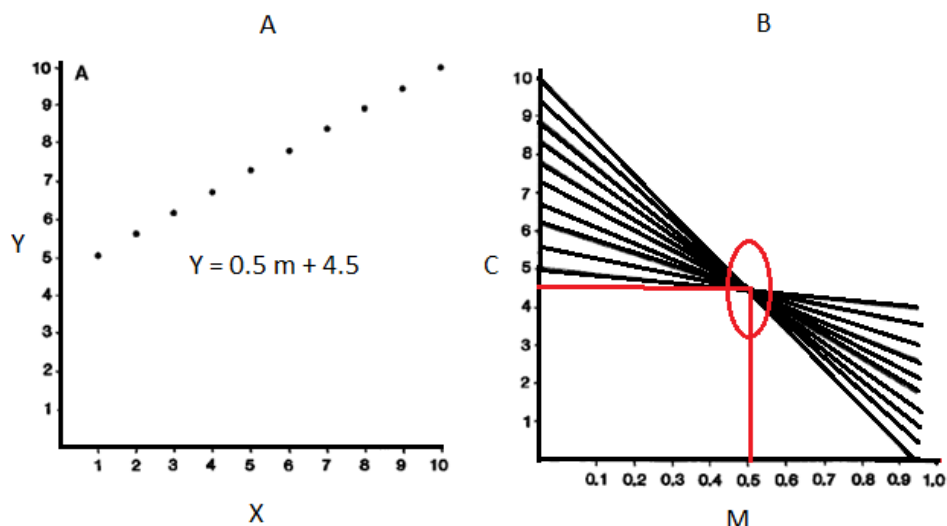


Figure 4.15: A graphical representation of how the Hough transform operates to find a straight line

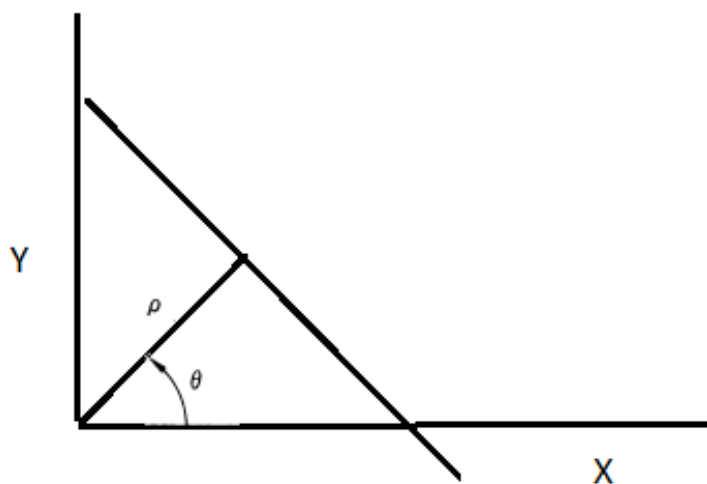


Figure 4.16: The Hough transform represented in rho and theta space

#### 4.4.2.3 Corner Pixels

To find the corner pixels of the quadrant the parametric equations of perpendicular pairs of lines were solved for  $x$  and  $y$  simultaneously using MATLAB. These equations were in the form of 4.2 and 4.3.

$$\rho_1 = x_1 \cos \Theta_1 + y_1 \sin \Theta_1 \quad (4.2)$$

$$\rho_2 = x_2 \cos \Theta_2 + y_2 \sin \Theta_2 \quad (4.3)$$

The final image obtained is shown in figure 4.18. There were slight imperfections in the process so each corner pixel was shifted towards the centre of the image to ensure only data within the quadrant was analysed. It must be noted

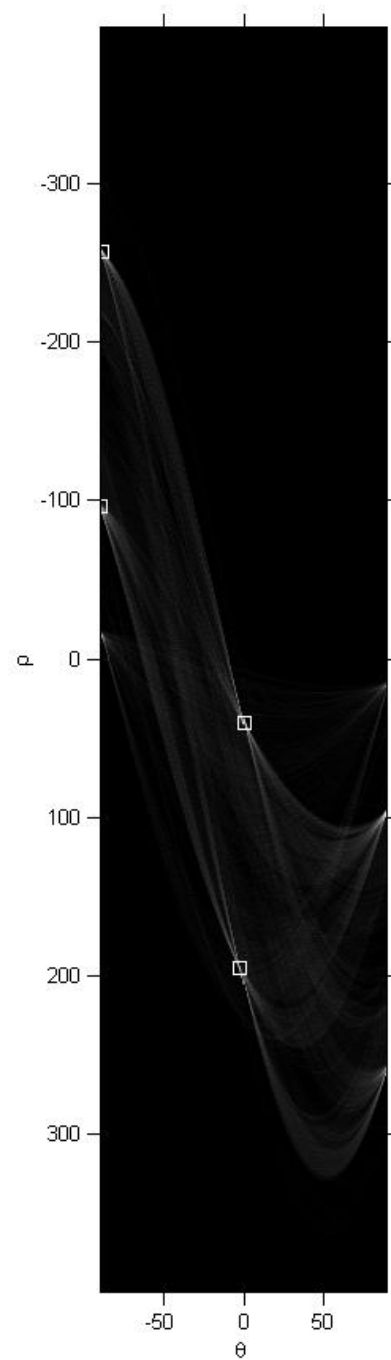


Figure 4.17: Hough transform obtained from actual field trials

that the HT failed to work on samples which contained large amounts of pasture due to lack of quadrant visibility in the near infrared. For these samples corner pixels were entered manually. Painting the quadrant a different colour could fix this problem.

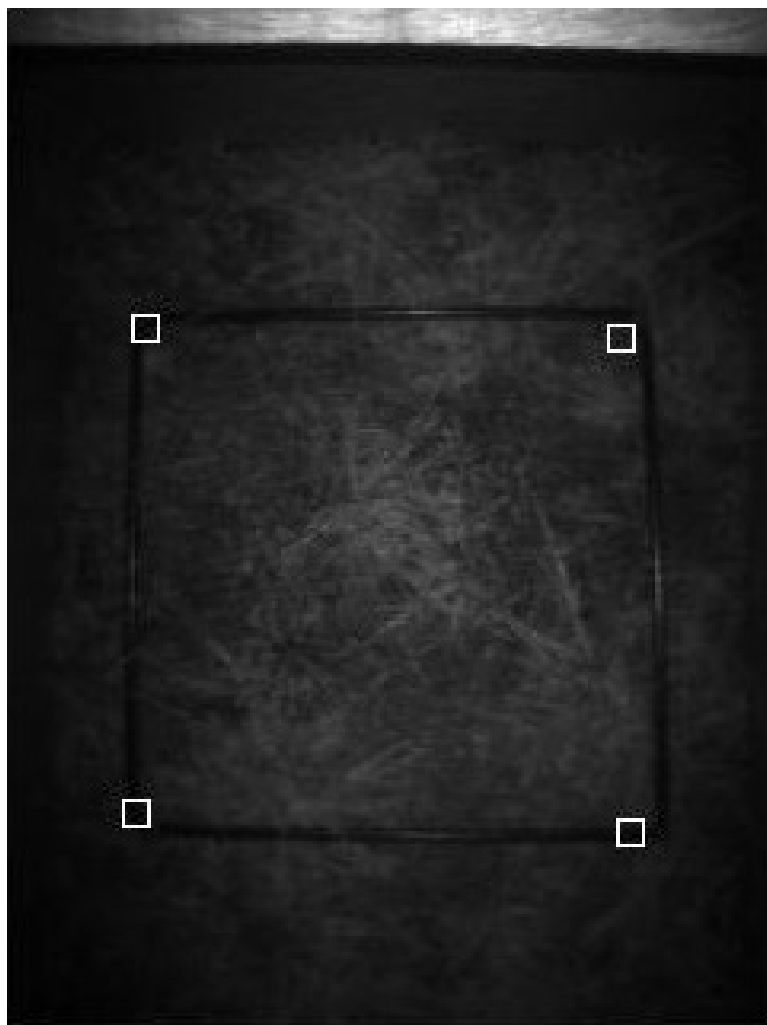


Figure 4.18: A plot of the corner pixels on the edge of the quadrant obtained by performing a Hough transform

#### 4.4.2.4 Cropping image

The image had to be cropped to exclude information outside of the quadrant. The quadrant however was not always square within the frame so a standard rectangular cropping method was insufficient. To do this the MATLAB function `poly2mask` was used. This takes numerous input co-ordinates and returns a binary image containing ones for the data within the lines interconnecting these. It must be noted that to automate this procedure co-ordinates had to be rearranged so that they were ordered sequentially in an array from the top left corner, back to the top left corner in a clockwise manor. If this was not done a mask image with intersecting lines was created. Extracting the image data simply involved multiplying the mask by the image data for each separate frame.

### 4.4.3 Image Statistics

The results consisted of two main datasets gathered in different environmental conditions. The first subset of data was accumulated between the 26th of February and the 5th of March 2013. This set of data consisted of 13 data points and was gathered during the onset of a severe drought. The second subset consisted of 20 data points and was carried out on lush late autumn herbage. For each set of data simple statistics were calculated. These were:

- The mean depth data
- The standard deviation of the depth data
- The mean intensity data
- The standard deviation of the intensity data
- The mean of all three colour bands

Because of the drastic changes in herbage conditions each set of data was grouped individually. It is highly likely that different algorithms are required for both drought and lush growing pasture.

# Chapter 5

## Results

All of the correlations for predicted herbage versus actual herbage mass were obtained using either a single variable linear regression or a multiple variable linear regression.

### 5.1 Late Autumn Growing Conditions

Herbage samples were taken between the 7th and 14th of May. The best correlation was found when the mean depth, confidence standard deviation<sup>1</sup> and depth standard deviation were taken as the predictive factors (figure 5.1). Table 5.1 shows the coefficients for each predicting variable as well as the standard error and statistical significance. A residual plot is included to show the extremities of errors which occurred in measuring DM (figure 5.2). Table 5.2 shows the correlation coefficients and respective standard deviations for all other single and multivariate equations.

#### 5.1.1 Individual days

Pasture conditions vary between days due to altering ground and weather conditions. We have included the best correlations for individual days which were both found using the confidence mean and standard deviation as predictors.

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<sup>1</sup>standard deviation is referenced as  $\sigma$  in all tables

Table 5.1: Coefficients for prediction of dry matter and statistical significance

Predictor	Coefficients	Standard Error	P-value
Intercept	-7181.51	3645.557	0.066408
Confidence $\sigma$	15.71339	3.050779	0.0000967
Depth Mean	8.794642	5.008759	0.098235
Depth $\sigma$	24.46928	20.15598	0.242365

Table 5.2: All correlation coefficients obtained in autumn growing conditions, standard deviation( $\sigma$ )

Predictor	Std. dev. (kgDM/ha)	$r^2$
Confidence mean	406	0.84
Depth mean	852	0.32
Confidence $\sigma$	349	0.886
Depth $\sigma$	531	0.73
Depth mean ,Depth $\sigma$	357	0.89
Confidence mean, Confidence $\sigma$	359	0.886
Depth $\sigma$ , Confidence $\sigma$	342	0.89
Confidence mean, Depth $\sigma$	365	0.897
Confidence mean,Confidence $\sigma$ ,Depth mean,Depth $\sigma$	348	0.906
Confidence mean,Confidence $\sigma$ , Depth $\sigma$	365	0.89
Confidence $\sigma$ , Depth mean ,Depth $\sigma$	337	0.906
Confidence mean,Depth mean, Depth $\sigma$	363	0.89
Confidence mean,Confidence $\sigma$ , Depth mean	348	0.899

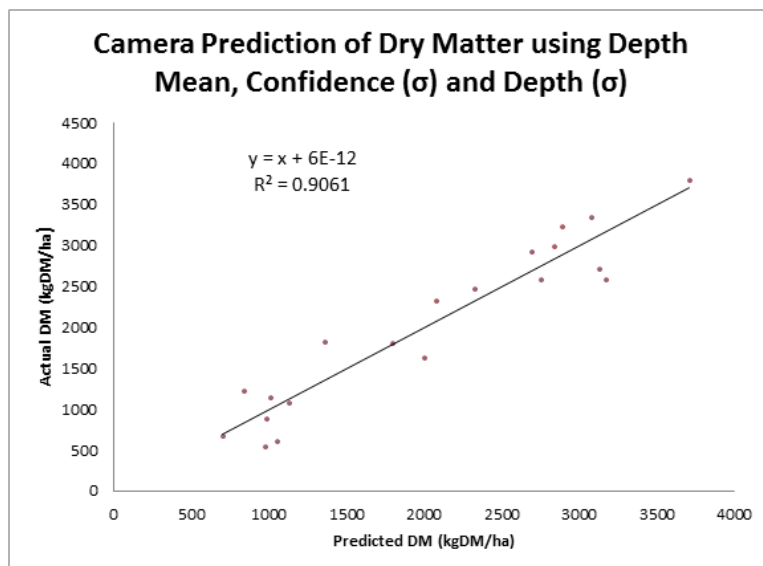


Figure 5.1: The best fit for data obtained for 20 measurements obtained between the 7th and 14th of May using the SoftKinitec camera

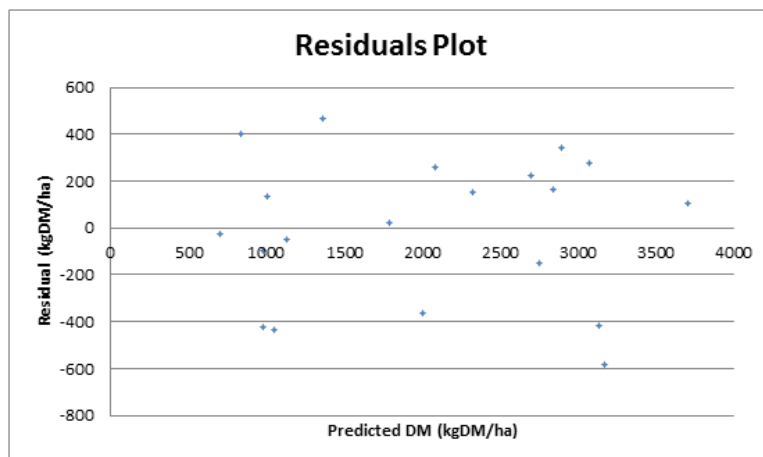


Figure 5.2: Residuals obtained when comparing predicted Dm to actual DM for the data 7th - 14th of May (n =20)

Figure 5.3 and table 5.3 show the correlation and equations for the 7th of May. Figure 5.4 and table 5.4 show the correlation and equations for the 14th of May. The respective standard deviations for this data were 225 and 350 kgDM/ha.

## 5.2 Severe Drought Conditions

The correlation coefficients and standard deviations for all single and multivariate equations obtained in severe drought conditions are shown in table 5.5.

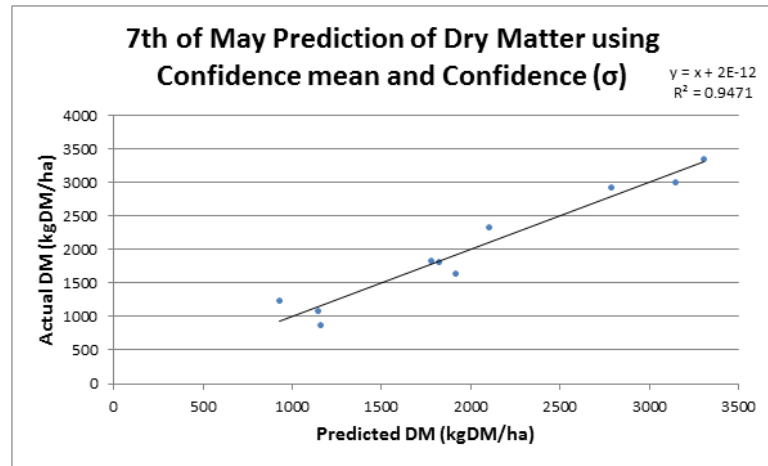


Figure 5.3: The best fit of the data gathered on May the 7th

Table 5.3: Equation for prediction of dry matter and statistical significance from May 7th 2013

Predictor	Coefficients	Standard error	p-value
Intercept	-782	311	0.0403
Confidence mean	-2.44	1.7	0.195
Confidence $\sigma$	26.6	7.12	0.00737

Table 5.4: Equation for prediction of dry matter and statistical significance from May 14th 2013

Predictor	Coefficients	Standard error	p-value
Intercept	-1218.74	385.1219	0.015828
Confidence mean	-0.16765	3.011641	0.957162
Confidence $\sigma$	19.04494	10.59783	0.11538

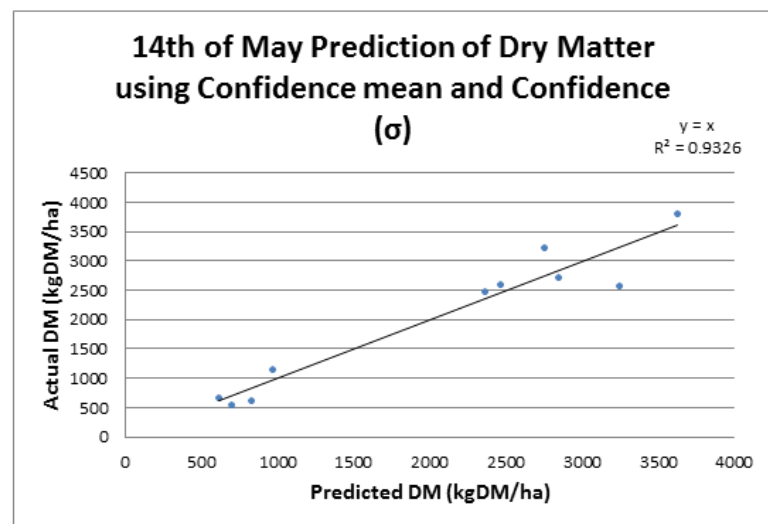


Figure 5.4: The best fit of the data gathered on May the 14th

Table 5.5: All results obtained in drought conditions, standard deviation( $\sigma$ )

Predictor	Std. dev. (kgDM/ha)	$r^2$
Confidence mean	611	0.23
Depth mean	693	0.01
Confidence $\sigma$	690	0.02
Depth $\sigma$	697	0.005
Depth mean, Depth $\sigma$	725	0.021
Confidence mean, Confidence $\sigma$	517	0.5
Depth $\sigma$ , Confidence $\sigma$	722	0.03
Confidence mean, Depth $\sigma$	634	0.25
Confidence mean, Confidence $\sigma$ , Depth mean, Depth $\sigma$	565	0.52
Confidence mean, Confidence $\sigma$ , Depth $\sigma$	533	0.52
Confidence $\sigma$ , Depth mean, Depth $\sigma$	756	0.041
Confidence mean, Depth mean, Depth $\sigma$	668	0.25
Confidence mean, Confidence $\sigma$ , Depth mean	544	0.5

# Chapter 6

## Discussion and Interpretation

### 6.1 Late autumn herbage

For the data gathered between the 7th and 14th of May the SoftKinitec DS325 provided some useful correlations with standing herbage DM. When a multivariate equation was used the best and worst correlations achieved were 0.906 and 0.88. The respective standard deviations were 337 and 363 kgDM/ha. These results compared favourably with previously mentioned measurement devices. Better correlations were achieved when only herbage from each respective day was taken into account. The best correlations were achieved using the mean and standard deviation of the confidence image as predictors. The same predictors returned the best correlations for both the 7th and 14th of May data. It was evident however that larger error occurred for the data collected on May the 14th. Another important observation from the results is the lack of useful correlations achieved by the depth parameters. Apart from possible errors discussed in section 4.1.6 there were other factors that could have affected the accuracy of the data obtained, these were:

- Herbage conditions
- Ranging issues

#### 6.1.1 Herbage and weather conditions

Pasture measurement conditions may change very quickly. Some of the variation in herbage estimations could have been due to:

- Changes in reflectance
- Pasture types

- Surface water
- Experimental setup

#### 6.1.1.1 Reflectance

Some of the inter day variations could have been caused by differing reflectance values in the herbage. The confidence or intensity data used to achieve the best correlations is directly related to the amplitude of the returned signal. This amplitude is related to the reflectance of the canopy surface. As can be seen in figure 6.1 the reflectance values of a leaf can vary with water content. This is particularly true in the region of interest for the camera. May the 14th was significantly damper than the 7th. This could explain some of the discrepancies observed in day to day variations.

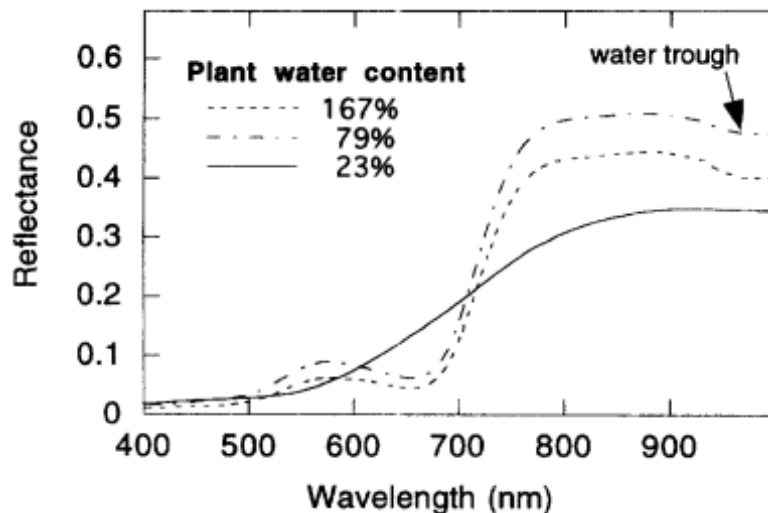


Figure 6.1: The change in reflectance that occurs with changing water content [Source: Penuelas and Filella, Ref. [49].]

#### 6.1.1.2 Pasture types

Previous papers have reported improved regressions when only using specific herbage species in their predictions [10]. In our experiment a large portion of the quadrants contained more than one species. The majority were dominated by a mixture of clover and rye. However there were some quadrants that were dominated by yarrow. Plant reflectance is governed by leaf surface properties, internal structure and biochemical properties [49]. All of the herbage species have different morphologies thus some intra and inter day variation could be expected because of this.

### 6.1.1.3 Surface Water

All of the herbage measurements were carried out between 9.30 AM and 11 AM. There was a distinct difference between herbage conditions for data collected on the 7th and the 14th. The first set of data was taken on a sunny morning where herbage had dried nicely before measurements. The second set however was on a particularly foggy morning which left residual dew from the previous night. From figure 6.1 we could also expect some reflectance variation due to higher water content.

### 6.1.1.4 Experimental method

An issue with the experimental method that could have somewhat affected end results was the prior use of the RPM on each quadrant. The RPM physically compresses the herbage to a state that is not how it would have been found naturally. Every care was taken to ensure the pasture was returned to a more natural looking state before gathering data. However it cannot be stated that no error was introduced because of this tampering.

## 6.1.2 Ranging issues

When predicting standing herbage DM there were comparably poor correlations observed when using the depth measurements obtained (depth mean = 0.32 and depth standard deviation = 0.73). Some issues that could have caused this were;

- Poor camera precision
- Water on leaf surface
- Multipath interference
- Mixed pixel interference

### 6.1.2.1 Poor Camera Precision

Author [58] showed reasonable values for the accuracy of the DS325 however the author also reported less precision. The mean square error in precision is shown to be about 2 cm at the mounting height of the camera. The precision of the camera could have had some effect on the poor depth correlations achieved.

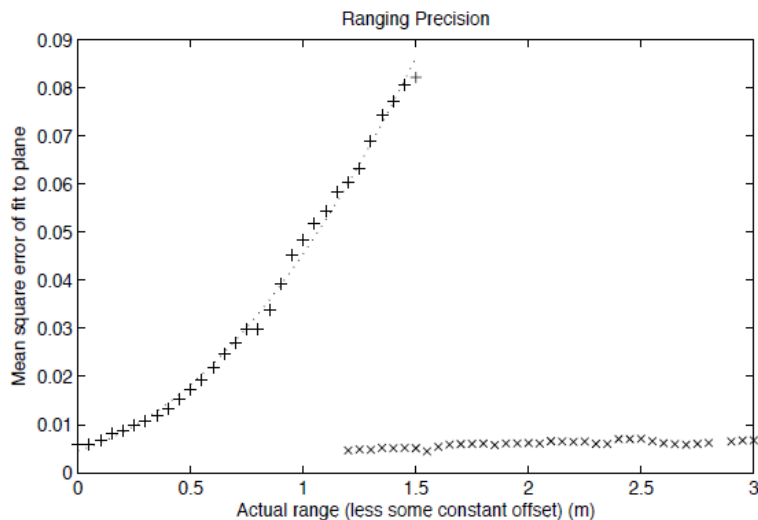


Figure 6.2: Precision of the SoftKinetic DS325 [Source: Cree and Streeter and Conroy and Dorrington, Ref. [58]. Used with permission.]

### 6.1.2.2 Multipath interference

Aside from multipath interference caused by the nature of standing herbage there was also likely to have been some created by the experimental set up. The cardboard box used to omit background light was large enough to be excluded from most frames. However in some depth frames the bottom of the box can be detected on the outer regions of the FOV. The main cause of this was the slight variations in mounting height due to paddock undulations. This could have caused at least some multipath interference that was not intrinsically caused by the herbage itself.

### 6.1.2.3 Mixed pixel

As with the SR4000 the DS325 will also experience mixed pixel distortion this is illustrated in figure 6.3. It can be seen that some distance errors will occur due to two different depths being included in a single pixel. The effect is not expected to be as large as the SR4000 due to the higher resolution of the camera.

### 6.1.2.4 Surface water

As mentioned previously there were some water droplets on some herbage samples. Author [38] tested the effect of water droplets on depth measurements for an IFM Efector 3D and the PMD CamCube. They found that adding water droplets increased the depth measurements obtained by the IFM camera. They didnt analyse the PMD data due to variation in measurements being



Figure 6.3: A grid representing the SoftKinetic resolution overlaid on top of an 8 MP image

interpreted as noise. However this shows that water droplets could have had some effect on the range measurements.

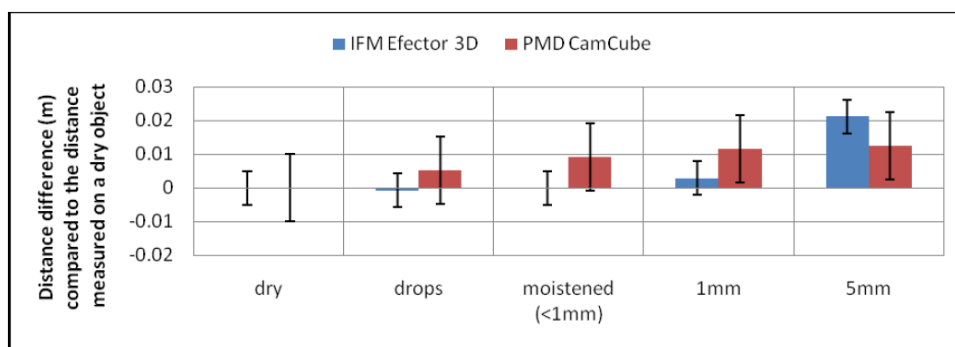


Figure 6.4: The effect water has on distance measurements using the PMD Camcube and IFM Efector 3D [Source: Klose and Penlington and Ruckelshausen, Ref. [37].]

## 6.2 Drought conditions

The DS325 was received by the University of Waikato around halfway through December 2012. The decision had to be made whether or not to go ahead with the use of the camera. It was decided that this camera would be used due to the extra colour information and the calibrated depth range. It took until the 15th of February to get the camera fully ready to use in field trials. This included getting the camera interfaced to the computer, synchronising the colour and depth camera and writing MATLAB code to store all gathered data. Unfortunately this coincided with one of the driest periods in New Zealand in 40 years. This is the first time a drought has been declared across the entire north island in 30 years. As shown in figure6.5 The drought was officially declared in the Waikato on the 6th of March 2013, however it was extremely dry up to this period also.

In these severe drought conditions the same statistics gathered in green growing conditions did not correlate well with DM. We can see that all single variables



Figure 6.5: A New Zealand map showing the scale of drought that coincided with the completion of the DS325 set up [Source: URL <http://www.mpi.govt.nz/Portals/0/Documents/environment/initi-funding/natural-dr/drought-declaration-6-march-2013.pdf>] Used with permission.

correlated extremely poorly with DM. Depth mean was the worst with an  $r^2$  of 0.05 and confidence mean the best with an  $r^2$  of 0.23. The best correlation of 0.52 was achieved when the mean and standard deviation of the confidence image was used alongside the standard deviation of the depth image.

Poor correlations were likely to have occurred due to some of the same factors aforementioned. Some other factors that may have contributed to larger errors in drought conditions were:

- Poor target reflectivity
- Soil herbage reflectance ratio

### 6.2.1 Target reflectivity

The DS325 is specified to give less than 1.4 cm of noise out to a distance of 1 m when target reflectivity is at 50%. It can be seen from figure 6.6 that stressed herbage has a reflectance of less than 0.3 in the near infrared region. This could have resulted in insufficient signal return to provide useful herbage information. The camera manufacturer does not specify noise with lower reflectance targets.

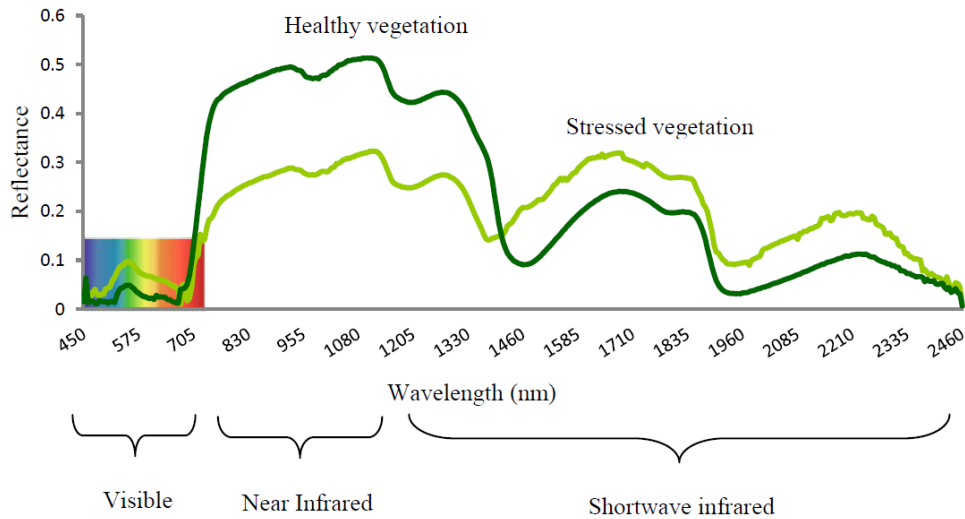


Figure 6.6: The change in reflectance caused by stress on pasture [Source: Pullanagari and Yule and King and Dalley and Dynes Ref [60]]

### 6.2.2 Soil herbage reflectance ratio

The lack of useful correlations from the confidence information could be due to the ratio of herbage reflectance to soil reflectance. It can be seen from figure 6.7 that the reflectance of soil increases when it is dry. As mentioned previously the reflectance of herbage is decreased when it is in stressed or drought conditions. This alters from green growing conditions where herbage reflectance increases and soil reflectance decreases. Thus the herbage stands out less in the near infrared in drought conditions. This could especially decrease the prediction obtained when using the confidence image data.

### 6.2.3 Camera Noise

Author [58] reported a precision of around 2 cm at a distance of 65 cm from the DS325. In drought conditions herbage was much shorter than in green growing conditions. Thus the noise level was high in comparison to pasture heights. This could have been a contributing factor to the more inaccurate results.

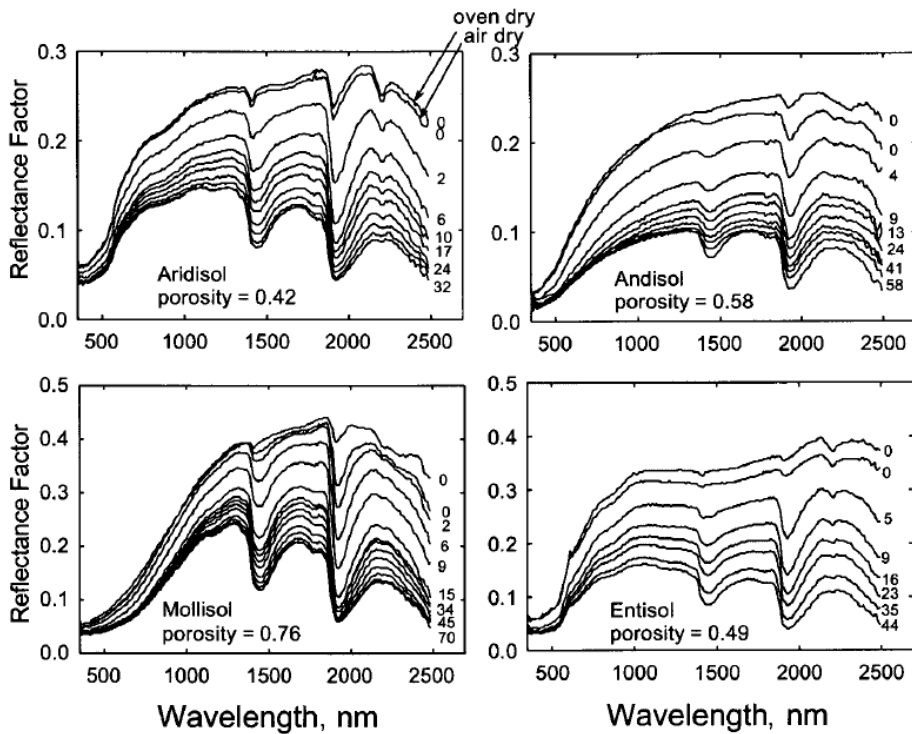


Figure 6.7: The effect of soil moisture on reflectance properties [Source Lobell and Asner, Ref. [57]]

### 6.2.4 Colour information

Initially it was thought that colour would be a useful parameter in the prediction of DM. However whereas the depth camera required light omission, the colour camera required a light source consisting of the visible spectrum. Although colour was trialed as a prediction method it was found that the experimental set up was not conducive to accurate colour measurement. Figure 6.8 shows the between frame colour variations obtained when using the DS325 in the field. Each of these frames was captured approximately 33 ms apart. The main reason this occurred was because the visible spectra was mostly removed from the scene.

These images were taken in pre-grazing paddocks during the drought period. We can see how reliable sensing of colour may be helpful for herbage detection. Due to variations between frames and between sets of frames it is hard to form a correlation using simple statistical data (e.g. average colour values). Therefore they were not used in the analysis stage.

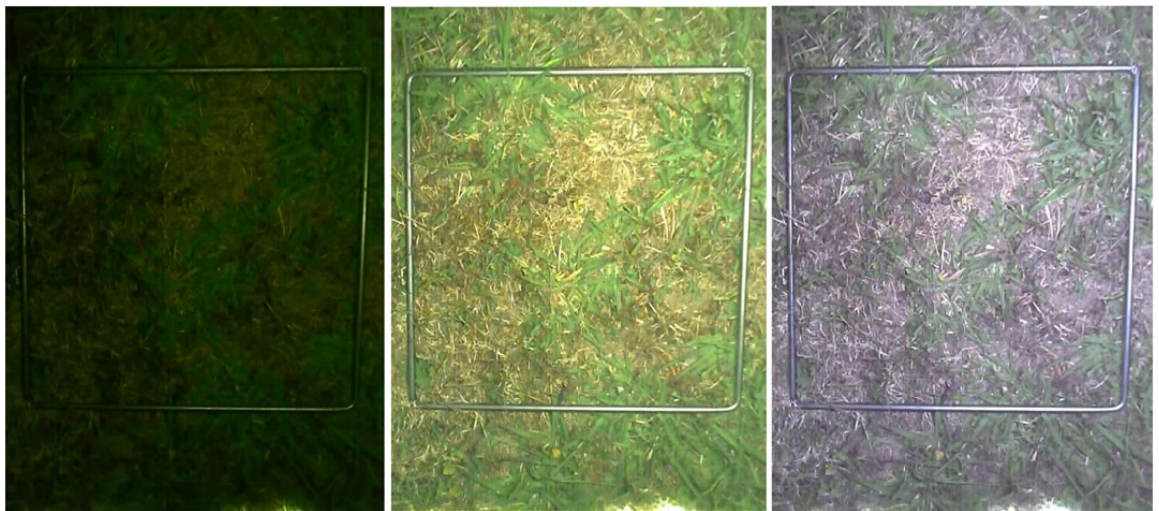


Figure 6.8: The effect of poor lighting on colour frames obtained using the SoftKinetic DS325

# Chapter 7

## Conclusion

The object of this thesis was to trial the usefulness of range imaging cameras in the measurement of standing herbage DM. We used simple statistical analysis of depth and intensity data to provide correlations with DM. A best fit of 0.9 was achieved when the mean and standard deviation of the depth image was used in conjunction with the standard deviation of the confidence image. This was achieved in late autumn growing conditions using 20 data points in a multivariate linear regression. We also showed that single day data could be predicted with a correlation of up to 0.94 and sigma of 224,  $n = 10$ . These results compare favourably with currently available pasture measurement devices. In drought conditions the best correlations achieved were 0.52 with a standard deviation of 533.

### 7.1 Future recommendations

This thesis shows the potential for a low cost imaging system to be used to estimate DM. Due to the large quantity of data obtained during the capture of each image (depth, and four bands of colour information). There is a lot of scope for development of image processing and statistical analysis of data. The main problem found when using range cameras for measurement of standing herbage DM was background lighting. The effect of background lighting has been reduced in some newly available cameras. One such camera is the PMD[vision] S3. Research should be done into more suitable cameras for the application.

To determine the plausibility for range cameras in commercial measurement of standing herbage DM requires the following steps;

- Gather more image pairs over a larger variety of herbage and growing conditions

- Carry out a more extensive numerical investigation to determine the correct equation or equations to be used for prediction of DM
- Build a suitable under carriage for the instrument to be mounted to an ATV or similar vehicle

A further aspect that could be developed is species recognition or herbage shape recognition using colour or intensity images. There is a current problem in NZ agriculture where different equations are specified for each different species.

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# Appendix A

## Pasture

### A.1 Cut, Weigh and Dry Method

# PASTURE YIELD MEASUREMENTS: Quadrat cuts

- **Avoid sampling around fence lines, troughs, pugged areas, faeces and unrepresentative areas of paddocks.**
- **Always record comments eg pugging, uneven grazing, dominant species, disease/insect damage, N deficiency, pasture density.**

## **QUADRAT CUTS**

Ground level cuts are done to estimate total herbage yield. These are commonly used for calibration cuts on farmwalks, where visual scores of the areas to be cut are done and a calibration equation developed by relating the score against the dry matter (DM) yield of usually 10, 0.2m<sup>2</sup> or 0.33m<sup>2</sup> cuts on paddocks pre- and post-grazing. This can then be applied to scores given to whole paddocks to estimate their yield in kg DM/ha. Calibrations may also be developed with other equipment eg rising plate meter/pasture probe/sward stick by measuring the area to be cut and relating this height to the DM yield from the quadrat cuts.

### ***Equipment***

Handpiece, 12V battery, combs, cutters, scrubbing brush, oil, screwdriver, quadrat frame (see individual trial details for size), plastic bags, tags, sack, earmuffs, safety glasses, close fitting gloves if desired.

### ***Method***

The aim is to cut all herbage growing within a set area to ground level, but not below ground level ie *“shear the sheep, not skin it!”*.

### ***In the field: Double sampling technique (for ground level cuts)***

Double sampling helps reduce the amount of work, especially in long pasture, by reducing washing required. For shorter pasture, especially small post-grazing cuts, it may be easier to just sample to ground level and wash the entire sample, rather than double cut.

- Put quadrat frame on ground in area to be sampled.
- Pull herbage rooted inside quadrat area into the quadrat.
- Check the area to be cut, if any old cow dung is in the frame, or pulls (these are not rooted, therefore not part of the sample), stones, etc remove these before you start cutting (or you will end up with lots of little pieces of dung to pick out later and/or soil all through your sample!).
- Cut herbage within frame to just above ground level, following the contour of the ground, but avoiding cutting into soil.
- Put herbage cut into a large plastic bag with labelled tag checking it is clean as you go; brush any soil off. Avoid picking up soil or anything other than pasture.
- Cut remaining herbage to ground level (you will end up with some soil in it, but try not to bring back the whole paddock!) and place in a smaller bag rolled up inside the large one. Put in sack.
- Clean handpiece after each cut, using brush and oil.
- Clean thoroughly after use and remove old cutter and comb for sharpening. Put 12V battery on charger to recharge for next use.
- After cuts are done, store samples in fridge until they can be processed.

### ***In Field Lab***

- Wash samples in the sink to remove all soil. Fill deep sink with clean water. Scoop up all floating herbage with a sieve. Soil will sink but watch out for floating cow dung.
- Tip out sample in large bag into tin with labelled tag, checking to ensure no soil in sample. If necessary rinse/wash this sample. If sampled carefully in the field this shouldn't generally need washing (at least for pre-grazing samples). *Note* – often post-grazing samples are soiled with dung and mud, so these may still need washing, even if double cut.
- Then tip out the dirty sample in the small bag into the sink of water and wash this sample.
- Add this to the washed sample from the large bag, so all the herbage from the quadrat cut is in one tin with the relevant tag.
- Place on a labelled tray. Put tray in 95°C oven for at least 36 hours to dry the samples.
- When dry weigh sample to tared tin and discard sample once value is recorded (saved and printed).

# Appendix B

## Code

### B.1 Store image data

```

%% This code reads in colour, range, phase and confidence images from a
% text file. It sets up a new directory for a scene and then
% subdirectories for each frame. It also stores the average images of all
% the data as a separate image

% change to the working directory
% If loading from external harddrive use this
cd('C:\Users\mwb8\Desktop\DairyNZ farmwalk 140513')

%If loading from computer use this
%cd('H:\Masters Project\new camera data\depthsense-32\samples\ds-
capture\release')

fid = fopen('transform_data1.txt');
% create a new folder name to store data
if(number_image < 9)
    folderformat='grass%1.1d'; % ascii sorting...
else
    folderformat='grass%2.2d'; % ascii sorting...
end
foldername = sprintf(folderformat,number_image);
mkdir(foldername); %make a new folder
cd(foldername); %change directory

% open the text file where all the data is stored
% Michael crees routine

while ~feof(fid) % while not the end of file
    % Read next line
    str = fgetl(fid);
    % If End Of File break
    if ~ischar(str)
        break;
    end
    % badline = false;
    % ln = ln + 1;
    % Strip leading and trailing white space
    str = strtrim(str);
    % If line blank then skip
    if length(str) == 0
        continue;
    end
    % If comment marker then skip
    % camera spits out data blue then green than red
    if strcmp(str, '# New Colour Frame')

        str = fgetl(fid);
        B = textscan(str, '%d', 'delimiter', ',');
        coloursplit = reshape(B{1},3,307200); % split matrix so each row is
a different colour
        btemp = coloursplit(1,:); % split each row into different colours
        gtemp = coloursplit(2,:);
        rtemp = coloursplit(3,:);
        r = reshape(rtemp,640,480); % split each row into correct image size
        g = reshape(gtemp,640,480);
        b = reshape(btemp,640,480);
        % store previous data for averaging

```

```

% normalise the colour and display note matlab does rgb camera order
is rgb
% must convert to double to get a number between 0 and 1;
rn1 = double(r);
bn1 = double(b);
gn1 = double(g);
rn2 = (rn1./255);
bn2 = (bn1./255);
gn2 = (gn1./255);
col = zeros(640,480);
col(:,:,1) = rn2;
col(:,:,2) = gn2;
col(:,:,3) = bn2;

    if(colour_imcount < 9)
saveformat='colour%1.1d.mat'; % ascii sorting...
    else
saveformat='colour%2.2d.mat'; % ascii sorting...
    end

% set the file of all frames into a structure
fnam = sprintf(saveformat,colour_imcount);
fprintf(sprintf('using file <%c>',fnam));
eval(['c.green' num2str(colour_imcount) ' = gn2']);
eval(['c.red' num2str(colour_imcount) ' = rn2']);
eval(['c.blue' num2str(colour_imcount) ' = bn2']);
eval(['c.colour' num2str(colour_imcount) ' = col']);
save(fnam,'-struct','c');

colour_imcount = colour_imcount + 1;
%get the average data

rtotal = rtotal + rn2;
bttotal = bttotal + bn2;
gttotal = gttotal + gn2;

end
% get the phase data and save to a mat file
if strcmp(str, '# New Phase Frame')

str = fgetl(fid);
B = textscan(str, '%d','delimiter',' ');
phase = reshape(B{1},320,240);
%write string format
if(phase_imcount < 9)
saveformat='phase%1.1d.mat'; % ascii sorting...
    else
saveformat='phase%2.2d.mat'; % ascii sorting...
    end

fnam = sprintf(saveformat,phase_imcount);
fprintf(sprintf('using file <%p>',fnam));
eval(['p.phase' num2str(phase_imcount) ' =phase']);
%save data
save(fnam,'-struct','p');

%increment phase counter
phase_imcount = phase_imcount + 1;

```

```

    phasetotal = phasetotal + double(phase);

end
% get the depth data in mm and save to a mat file
if strcmp(str, '# New Depth Frame')

    str = fgetl(fid);
    B = textscan(str, '%d','delimiter',' ');
    depth = double(reshape(B{1},320,240));
    if(depth_imcount < 9)
        saveformat='depth%1.1d.mat'; % ascii sorting...
    else
        saveformat='depth%2.2d.mat'; % ascii sorting...
    end

    fnam = sprintf(saveformat,depth_imcount);
    fprintf(sprintf('using file <%r>',fnam));
    eval(['r.depth' num2str(depth_imcount) ' =depth']);
    save(fnam,'-struct','r');
    depth_imcount = depth_imcount +1;
    depthtotal = depthtotal + depth;

end
% get the intensity data in and save to a mat file
if strcmp(str, '# New Confidence Frame')

    str = fgetl(fid);
    B = textscan(str, '%d','delimiter',' ');
    conf = double(reshape(B{1},320,240));
    if(conf_imcount < 9)
        saveformat='conf%1.1d.mat'; % ascii sorting...
    else
        saveformat='conf%2.2d.mat'; % ascii sorting...
    end

    fnam = sprintf(saveformat,conf_imcount);
    fprintf(sprintf('using file <%i>',fnam));
    eval(['i.conf' num2str(conf_imcount) ' =conf']);
    save(fnam,'-struct','i');
    conf_imcount = conf_imcount + 1;
    conftotal = conftotal + conf;

end

if str(1) == '#'
    continue;
end

%choose the number of frames to be grabbed from the text file
if (depth_imcount == 21)
    break;
end

end

% calculate and save averaged data

red_av      = rtotal./colour_imcount;

```

```

blue_av      = btotal./colour_imcount;
green_av     = gtotal./colour_imcount;
phase_av    = phasetotal./phase_imcount;
depth_av    = depthtotal./depth_imcount;
conf_av     = conftotal./conf_imcount;

%Save all the variables as a different name
eval(['a.redav' num2str(number_image) ' = red_av']);
eval(['a.blueav' num2str(number_image) ' = blue_av']);
eval(['a.greenav' num2str(number_image) ' = green_av']);
eval(['a.phaseav' num2str(number_image) ' = phase_av']);
eval(['a.depthav' num2str(number_image) ' =depth_av']);
eval(['a.confav' num2str(number_image) ' =conf_av']);

if(number_image < 9)
    saveformat='averageddata%1.1d.mat'; % ascii sorting...
else
    saveformat='averageddata%2.2d.mat'; % ascii sorting...
end

    fnamav=sprintf(saveformat,number_image);
    fprintf(sprintf('using file <%a>',fnamav));

save(fnamav, '-struct', 'a');

number_image = number_image +1;

```

## B.2 Hough Transform

```

% This code takes in a confidence frame with the DairyNZ quadrant in it
% finds the lines and returns the corners it does so using the Hough
% transform
cd('C:\Users\mwb8\Desktop\DairyNZ farmwalk 060513\grass8')
% load 16 bit confidence image
% I = imread('conf.png');
I = conf1;

figure(14), imshow(I,[]);impixelinfo

% apply a median filter which shows an image which is proportional to the
amount of light that is falling on the area
A = zeros(320,240);
medfilterconf = medfilt2(I,[50,50]);
imshow(medfilterconf,[]);
% divide the original image by the median filtered image so that the light
% looks evenly distributed accross the image
sc = double(I)./double(medfilterconf);
figure(19)
imshow(sc,[0 2]); impixelinfo;
% apply thresholding very important and sensitive

bw = sc < 0.5;

figure(20)
imshow(bw,[]);impixelinfo
[H,T,R] = hough(bw);
RHO_THETA = houghpeaks(H,4);
figure(15)
imshow(H,[],'XData',T,'YData',R);
xlabel('\theta'), ylabel('\rho');
axis on, axis normal, hold on;
plot(T(RHO_THETA(:,2)),R(RHO_THETA(:,1)),'s','color','white');

% convert the values returned by the Hough transform so that they
% correspond to the correct pixel location in image space
% eg scale is from - 90 to 90 for theta and +400 - 400 for rho
RHO_THETA = [((size(H,1)/2) - RHO_THETA(:,1)) (RHO_THETA(:,2) -90)]

%Sort the rho and theta matrix into the same order each time
%

[TEMP1 ind] = sort(abs(RHO_THETA(:,2)))
RHO_THETA_TEMP = RHO_THETA;

% this sorts theta and rho into order 0 0 90 90 so that maths can be done
% on all lines perpindicular to each other
RHO_THETA_TEMP(1,2) = RHO_THETA(ind(1),2);
RHO_THETA_TEMP(2,2) = RHO_THETA(ind(2),2);
RHO_THETA_TEMP(3,2) = RHO_THETA(ind(3),2);
RHO_THETA_TEMP(4,2) = RHO_THETA(ind(4),2);

RHO_THETA_TEMP(1,1) = RHO_THETA(ind(1),1);
RHO_THETA_TEMP(2,1) = RHO_THETA(ind(2),1);
RHO_THETA_TEMP(3,1) = RHO_THETA(ind(3),1);
RHO_THETA_TEMP(4,1) = RHO_THETA(ind(4),1);

RHO_THETA = RHO_THETA_TEMP;

```

```

% % calculate all four corners

% corner 1
r1 = RHO_THETA(1,1);
r2 = RHO_THETA(3,1);
rho1 = [r1; r2];
t1 = RHO_THETA(1,2);
t2 = RHO_THETA(3,2);
M1 = [cosd(t1) sind(t1);cosd(t2) sind(t2)];
a1 = M1\rho1;
a1 = reshape(a1,1,2);

% corner 2
r1 = RHO_THETA(1,1);
r2 = RHO_THETA(4,1);
rho2 = [r1;r2];
t1 = RHO_THETA(1,2);
t2 = RHO_THETA(4,2);
M2 = [cosd(t1) sind(t1);cosd(t2) sind(t2)];
a2 = M2\rho2;
a2 = reshape(a2,1,2);

% corner 3
r1 = RHO_THETA(2,1);
r2 = RHO_THETA(3,1);
rho3 = [r1;r2];
t1 = RHO_THETA(2,2);
t2 = RHO_THETA(3,2);
M3 = [cosd(t1) sind(t1);cosd(t2) sind(t2)];
a3 = M3\rho3;
a3 = reshape(a3,1,2);

% corner 4
r1 = RHO_THETA(2,1);
r2 = RHO_THETA(4,1);
rho4 = [r1;r2];
t1 = RHO_THETA(2,2);
t2 = RHO_THETA(4,2);
M4 = [cosd(t1) sind(t1);cosd(t2) sind(t2)];
a4 = M4\rho4;
a4 = reshape(a4,1,2);

% % get all 4 coordinates
coord = vertcat(a1, a2, a3, a4);
%Values are returned with a negative reference to top left so change to
%positive
coord = abs(coord);
% plot the corners on the original figure
figure(16), imshow(I,[]); impixelinfo; hold on;

% Sift the corner location in so that they are inside the quadrant
shift = 5;
[coord1,I] = sort(coord);

%lowest x and y add a small amount
coord(I(1:2,1),1) = coord(I(1:2,1),1) + shift;
coord(I(1:2,2),2) = coord(I(1:2,2),2) + shift;
% highest x and y values subtract a bit to make corners fit in box
coord(I(3:4,1),1) = coord(I(3:4,1),1) - shift;

```

```
coord(I(3:4,2),2) = coord(I(3:4,2),2) - shift;  
coord = round(coord);  
plot(coord(:,1),coord(:,2),'s','color','white');  
  
x = coord(:,1);  
y = coord(:,2);
```