Water content measurement of biofuel with RF directly in trailers truck containers

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Abstract

The project shows that it is possible to obtain a signal that travels trough large depths of woody biomass, directly in trailer truck containers and by accessing only the surface of the material. Tests showed that it was possible to see the signal for both metallic and plywood containers. The root mean square error of prediction with an independent test set is of 6.5%. A discussion about this value and other results is carried out.

Sammanfattning

Vattenhalten i biobränsle påverkar såväl prissättning som förbränning av bränslet. För att bestämma vattenhalten används idag en gravimetrisk metod där proverna torkas i en ung som referensmetod. Metoden är varken snabb eller representativ då vattenhalten kan variera mellan olika delar av lasset och då proverna tas från bränsleytan. Därför är kraftvärmeverken intresserade av att en metod tas fram för att mäta vattenhalten i biobränsle som dels är snabb och dels är representativ för ett helt containerlass med bränsle.

Near Infrared Spectroscopy (NIR) och Nuclear Magnetic Resonance (NMR) används på vissa verk idag för att mäta vattenhalten online på transportband. Metoderna skulle kunna användas till att styra förbränningen i pannan. Nackdelarna med metoderna är att de inte kan användas vare sig för betalning av bränslet eller för att optimera en bränsleblandning till pannan.

Syftet med denna studie är att fortsätta utvecklingen av den RF-metod som tidigare har tagits fram av Mälardalens högskola i samarbete med Värmeforsk, till ett mätsystem i full skala. Forskningen syftar till att ta fram en prototyp som kan mäta vattenhalten direkt i containerlass med biobränsle som ankommer till verket.

Arbetet delades upp i tre huvuddelar med följande mål: 1. Att få en RF-signal att passera fram och tillbaka genom ett lass med biobränsle. 2. Att studera förhållandet mellan RF-signalen och vattenhalten samt att studera mätstörningar från olika typer av containers. 3. Att visa hur pass bra RF-metoden kan mäta vattenhalten direkt i containerlass med biobränslen och visa hur bra metoden mäter vattenhalten i olika typer av biobränslen och i olika typer av containers.

Mätningarna utfördes vid kraftvärmeverket i Eskilstuna. Projektet omfattar val av antenner och utformning av mätrigg. Som referensmetod till fukthalten användes dels SIS-normens gravimetriska metod men även värden från den NIR-probe som testades av Bestwood i ett systerprojekt till detta inom samma Värmeforskprogram. Proben tog stickprover på fukthalten en bit ner i biobränslet i de ankommande containerlassen. Multivariat dataanalys samt från mätningarna beräknad dielektricitetskonstant användes som korrelationsmetoder.

Projektet visar att det är möjligt att driva en signal genom hela containerlass med biobränsle. Mätapparaturen arbetar vid ytan av bränslet och låter radiovågorna penetrera bränslet på djupet. Tester visar att det är möjligt att se signaler såväl för metall- som plywoodcontainers. Minsta felet (mätt med RMSEP – root mean square error of prediction) var 6.5% och uppnåddes med en mulitvariat modell.

NYCKELORD: Biobränsle, fukthalt, radiofrekvens

Summary

The water content of woody biomass is important for the runnability of the plants as it influences the heating value and thereby the combustion control and pricing. Currently water content is determined using the gravimetric method by drying samples in an oven. This method neither fast nor representative, as the water content can vary in different parts of the container and samples for the oven are taken from the fuel surface. This raised the need to develop sensors that are able to measure water content of biofuels on-line and in a representative way.

Near infrared spectroscopy (NIR) and nuclear magnetic resonance (NMR) are methods used for water content measurements on biomass on conveyor belts at some cites today. The drawback is that these methods cannot be used for either the payment of the fuel or for optimization of the fuel blend into the boiler.

The aim of this study is to further develop the RF method earlier developed by Mälardalen University in cooperation with Värmeforsk, into a full-scale measurement system. The research is based on the application of the theory of electromagnetic waves interaction with materials to bulk measurements of water content.

This aim was divided in three main parts with the following objectives: 1- to obtain a signal that was able to pass through a container loaded with biofuel; 2 - to study the dependence of the RF signal of water content and disturbance from different types of containers; 3 - to show the ability of the RF method to measure moisture content directly in containers, presenting prediction values for measurements of different biofuel types and in different types of containers.

The project execution included the choice of an antenna and set-up for performing full-scale measurements of biofuel directly in arriving containers. These were performed at the combined heat and power plant in Eskilstuna. Samples were taken for determination water content reference value with the standard gravimetric method but also with values determined with the NIR probe that was installed at the entrance of the plant. As correlation methods were an estimation of the dielectric constant and multivariate data analysis used.

The project shows that it is possible to obtain a signal that travels through large depths of woody biomass, directly in trailer truck containers and by accessing only the surface of the material. Tests showed that it was possible to see the signal for both metallic and plywood containers. The minimum root mean square error of prediction with an independent test set was 6.5% for a model build with multivariate data analysis.

KEYWORDS: Woody biomass, water content, bulk measurement, radio frequency

Table of contents

1 INTRODUCTION 2

1.1 BACKGROUND 2
1.2 DESCRIPTION OF THE RESEARCH AREA 2
1.3 THE PURPOSE OF THE RESEARCH ASSIGNMENT AND ITS ROLE WITHIN THE RESEARCH AREA . 3
1.4 GOAL AND AUDIENCE 3

2 THEORY 4

2.1 RADIO FREQUENCY WAVES 4
2.2 INTERACTION OF THE ELECTROMAGNETIC WAVES WITH MATERIALS 4

3 EXPERIMENTAL PROCEDURE 6

3.1 CHOICE OF THE ANTENNA 6
3.2 MEASUREMENTS SET-UP 10
3.3 REFERENCE METHOD 11
3.4 SAMPLE INFORMATION 12

4 MEASUREMENT ANALYSIS 13

4.1 SIGNAL PROCESSING 13
4.2 CORRELATION MODELS 14
4.2.1 Multivariate data analysis - Partial least square 14
4.2.2 Estimation of the dielectric constant 14
4.2.3 Evaluation of the models 15

5 RESULTS 16

PART 1 16
5.1 BOTTOM REFLECTION 16
5.2 MEASUREMENTS REPEATABILITY 16
5.3 DISTURBANCES 17
5.4 CORRELATION AND PREDICTION MODELS 18
5.4.1 Multivariate Data Analysis – Partial Least Square 18
5.4.2 Estimation of the dielectric constant 21
5.5 VARIATION IN THE REFERENCE VALUE 23

6 CONCLUSIONS 24

PART ONE 24
PART TWO 24
PART THREE 24

7 RECOMMENDATIONS AND APPLICATIONS 26

8 REFERENCES 27

Appendices

A. Database

1 Introduction

This chapter gives a background to the problem of water content measurement in biofuel. It describes why and how to measure, who is interested and what was previously done within the area.

1.1 Background

The attempt to replace fossil fuels related to concern for climate change, future energy supplies and increasing oil prices have led to growing interest in the use of biomass for energy purposes. The use of woody biomass was found especially successful in combined heating and power plants in countries with large woody feedstock. In Sweden woody biomass is the main fuel in heat and electricity production when excluding nuclear fuel and hydro power.

The water content of woody biomass is important for the runnability of the plants as it influences the heating value and thereby the combustion control and pricing. Currently water content is determined using the gravimetric method by drying samples in an oven. Drying time can be up to 16 hours and the samples are taken from the surface of the biofuel in the containers (Nyström & Dahlquist, 2004). This makes the method neither fast nor representative, as the water content can vary largely in different parts of the container. This raised the need to develop sensors that are able to measure water content of biofuels on-line and in a representative way.

There are online methods for measurement of water content of woody biomass in conveyor belts using different techniques as near infrared spectroscopy (NIR) (Axrup *et al.* 2000) and nuclear magnetic resonance (NMR) (Barale *et al.* 2002). A review on the methods for determination of water content in woodchips is presented by (Nyström & Dahlquist, 2004). There are also several measurement applications for water measurement in different materials at microwave frequencies (Okamura, 2000). Although none of these methods are able to perform a bulk measurement in a truck trailer container, before the biofuel is on the conveyer belt on its way to the boiler.

1.2 Description of the research area

The importance of fast and representative measurement of water content in biofuel has been pointed out earlier by Värmeforsk studies. This studies include the test of x-ray frequency instruments (Nordell & Vikterlöf, 2000), near infra red (NIR) (Aulin, *et al.* 2008) (Dahlquist, *et al.* 2005) and radio frequency (RF) (Dahlquist, *et al.* 2005). A review of the tested and promising methods for water content measurement of biofuel has also been published (Eriksson, *et al.* 2002). Water content measurement with RF has been pointed out as a possible technique that requires further proof.

Nyström (2006) developed a method to measure water content in samples of biofuel with about 0.1 m^3, equivalent to about 0.5 m material in a circular sample holder with a diameter of 0.57 m. The method used reflection data accessing only one side of the material. An antenna was placed over the material and sent a signal that was reflected at the bottom of the material back to antenna. A frequency sweep between 310 - 800 MHz was used. The signal was transformed into time domain in order to select the reflection

at the bottom of the sample holder. This part of the signal was used to correlate with water content by using multivariate data analysis methods.

The measurement of water content with RF and microwaves (see figure 1) is based on the same physical principles that water molecules "react" to the electromagnetic waves. There are several laboratory and online applications using these frequencies for measurements within a variety of areas as agriculture, geology or construction. Compared to those methods, the concept of this study is although, a new one, since it attempts to make a bulk measurement by using reflection data and accessing only one side of the material.

A RF method using this concept at laboratory scale was developed by Mälardalen University and is reported in (Nyström, 2006). This method showed promising results measuring water content in a volume of 0.1 m^3.

After the project mentioned above, the challenge was to perform the same measurements in full-scale, which means directly in the containers arriving at the plants. The present report describes the steps and results from that challenge.

1.3 The purpose of the research assignment and its role within the research area

The aim of this study is to further develop the RF method into a full-scale measurement system, which means measurement of woody biomass directly in transport containers. The research is based on the application of the theory of electromagnetic waves interaction with materials to bulk measurements of water content.

1.4 Goal and audience

The definitive aim of this project is to provide a concept for performance of bulk water content measurements of biofuel directly in containers. This aim was divided in three main parts with the following objectives:

PART 1 - to obtain a signal that was able to pass through a container loaded with biofuel.

PART 2 - study the dependence of the RF signal of water content and disturbance from different types of containers (metallic and plywood containers).

PART 3 - show the ability of the RF method to measure moisture content directly in containers, presenting measurement accuracy values for measurements of different biofuel types and in different types of containers.

The audiences for this project are engineers and technicians at are power plants and also biofuel suppliers. This group is naturally extended to every operator dealing with wood based products in which water content is an important parameter.

2 Theory

This chapter illustrates the general theory that explains why it is possible to determine water content with RF.

2.1 Radio frequency waves

The electromagnetic spectrum is represented in Figure 1. The wavelength and frequency of the different electromagnetic waves are schematized. It can be seen that the radio waves are considered at frequency below 10^9 Hz, with a wavelength larger than microwaves, infrared or visible light. This characteristic is especially important to the application in this study. The fact that RF have long wavelength means that its penetration depth in a material is larger and propagation easier because waves are less attenuated. This is the reason why RF waves can travel several meters in a material while the penetration depth of the infrared wave is in the centimetres range.

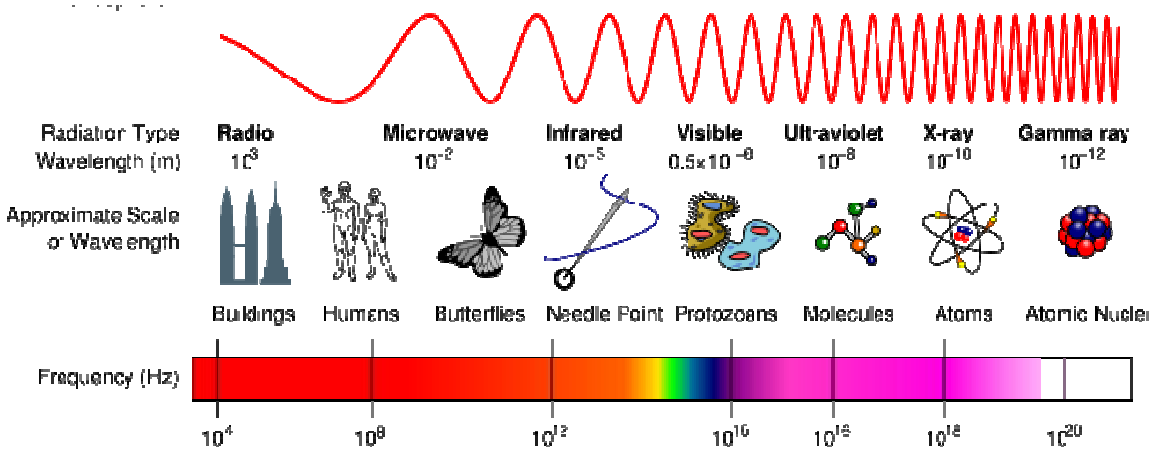


Figure 1. The electromagnetic spectrum. Radio waves have lower frequency and longer wavelength than the other represented types of electromagnetic waves.

2.2 Interaction of the electromagnetic waves with materials

A wave travelling through a material suffers delay, attenuation and changes in the wavelength. This is due to the occurrence of different polarization phenomena. Polarization is a conjunct of changes that occur in electrons, molecules and dipoles location under the influence of a varying electrical field.

A measure of how much a material is polarized when an electromagnetic field is applied is called the permittivity, ε. The permittivity can be represented as a complex number, as seen in equation (1):

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

The real part, ε', is called the dielectric constant and the imaginary part, ε'', the dielectric loss factor. The dielectric constant affects the speed of propagation and the

wavelength of the signal. The loss factor represents the power that is absorbed by the material, which means attenuation of the signal, but, to a first order approximation, does not influence the travel time of a propagating microwave. Materials with lower conductivity can often be considered low-loss materials and the approximation in equation (2) can be used:

$$\varepsilon \approx \varepsilon' \qquad (2)$$

Equation (2) assumes that the interaction between the electrical field and the material can be described using the dielectric constant, ε'. The dielectric constant is usually expressed in relation to the dielectric constant of the air and therefore called the relative dielectric constant which is unit-less. This parameter is used in this study. ε' can be calculated using equation (3),

$$\varepsilon' = \left(\frac{c}{v}\right)^2 \qquad (3)$$

where c is the velocity of the electromagnetic waves in the air and v is the velocity in the material. In practical applications the travel time and the length are the measured parameter and equation (3) can be rewritten as in (4),

$$\varepsilon' = \left(\frac{c}{v}\right)^2 = \left(\frac{c.tt}{L}\right)^2 \qquad (4)$$

where tt is the travel time through the length L of a material.

The water molecule has a permanent dipole charge as a result of its two negative charged hydrogen atoms and one positive oxygen atom. This permanent dipole contributes to a large polarization at frequencies below 10^9 GHz. At these frequencies the dielectric constant of water is of about 80 while it is only about 3 for most solids (as is the case of wood). This means that water molecules react in a much larger extent to an electrical field than molecules of solids and this is what makes these frequencies adequate for water content measurement (Nyfors & Vainikainen, 1989).

3 Experimental Procedure

The different procedures presented in this chapter are related with the goals in the different project parts as presented in the introduction:

- The first challenge of the project was to be able to see a signal that passes through a whole container loaded with fuel and different types of antennas were tested

- The second goal was to verify that the signal was independent of the type of container, as there are different types of transport containers, as its dependence of the water content.

- At last a measurement concept was defined and several measurements were made in order to study the accuracy of the method.

3.1 Choice of the antenna

The object of the first part of this project was to choose a proper antenna for the measurements. The previous studies using RF performed by Nyström (2006) where made at laboratory scale. A log periodic antenna was used and signal with bottom reflection was obtained from samples with about 0.5 m height. The antenna and the sample were in a closed structure that worked as a wave guide and that could be accurately calibrated. This differs from the full-scale in this study, where the signal is required to travel through a larger sample (a sample height of about 0.50 m in the laboratory scale compared to the full scale having sample heights of several meters) and having an open air set-up which does not allow the same kind of calibration procedures.

Experiments were carried out with different antennas to test which could show better results for bottom reflection. Tests consisted of the antennas hanging at different heights from the bottom of an empty container and also with different heights of fuel in the container. A total of five antennas were tested, the broadband antennas: log periodic antenna, guide, a bilog antenna and linear tapered slot antenna; and two ground penetrating radar antennas.

- Three broadband antennas: log periodic antenna with and without waveguide, a bilog antenna and linear tapered slot antenna;
- Two ground penetrating radar antennas.

Log periodic dipole antenna

This antenna was selected as it was wide banded, worked within the selected frequency range, and gave a rather directed signal. The antenna had been used for the laboratory scale measurements of water content in biofuel. The antenna was efficient in a frequency range of 400-3000 MHz, but worked down to about 300 MHz. The size of the antenna was 300x650x50 mm and it is shown in Figure 2 (a).



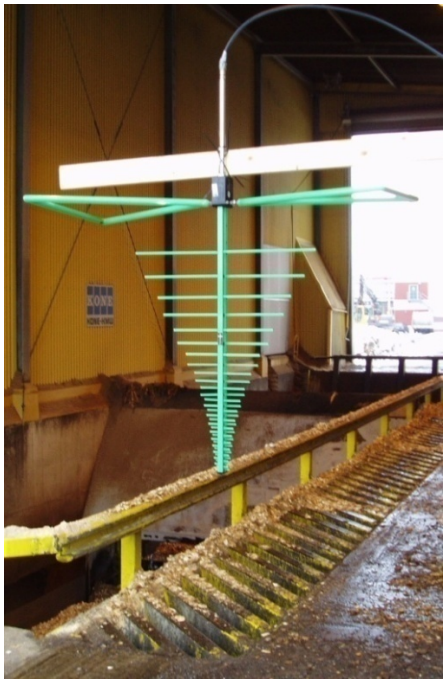
(a)



(b)



(c)



(d)

Figure 2. (a) Logperiodic dipole antenna, efficient in a frequency range of 400-3000 MHz.
(b) Logperiodic antenna surrounded by a wave guide efficient at frequencies between 310 and 3000 MHz.
(c) Linear tapered slot antenna, constructed at Uppsala University, efficient at frequencies between 100 and 1300 MHz.
(d) Bilog antenna, borrowed from Ericsson. The antenna was efficient at frequencies between 100 and 1300 MHz.

Log periodic dipole antenna with wave guide

A construction with a steel barrel surrounding the log periodic dipole antenna as described above, was also selected for tests. The steel barrel guided the signal downwards, forming a so called wave guide, making it more directed than without the steel barrel. The length of the wave guide was 870 mm and the diameter was 570 mm. The diameter also restricted the cut-off frequency to 310 MHz, see Figure 2 (b).

Linear tapered slot antenna

This antenna was constructed for the measurements in this project as an examine thesis by Mikael Bernelind at the Department of Signals and Systems, Uppsala University. The antenna was constructed with thin copper foil glued on expanded polystyrene (EPS)
and it was efficient in a frequency range of 100-1300 MHz. The size of the antenna was 2400x1200x100 mm, see Figure 2 (c).

Bilog antenna

A bilog antenna was borrowed from Ericsson. The antenna was broad banded with a frequency range from 100-1300 MHz and it was made from steel rods which made the antenna very robust, see Figure 2 (d).

Ground penetrating radar (GPR)

GPR is a technology developed mainly to investigate subsurface of earth. GPR antennas send a very short pulse with high energy. This pulse can have a large bandwidth but antennas are usually characterized by the centre frequency for which the amplitude is stronger than for the rest of the bandwidth.. The results are in time domain and represent the travel time forth and back from a reflecting object.
Commercial antennas by the Swedish fabricant Malå Geoscience (Malå Geoscience, 2008) were chosen to perform the measurements. Two antennas with 500 MHz and 250 MHz centre frequencies respectively where tested. In figure 3 the GPR shielded antenna with 500 MHz centre frequency (a) and the GPR shielded antenna with 250 MHz centre frequency (b) can be seen.

Both antennas have similar type: shielded antenna with sender and receiver antennas of the type cavity backed bow-tie, and a control unit that generates the impulse wave and coordinates the received signal. These antennas have very good directivity strictly downwards to avoid reflections from surroundings. A scheme of the antennas in the GPR can be seen in Figure 4.

The centre frequency of the GPR antennas tested was chosen thinking about the penetration depth, which is larger the smaller the wave frequency and the wavelength which has to smaller than container dimensions in order to propagate inside it. The wavelength in air of a signal with 500MHz centre frequency is 0,6m while the one of a 250MHz is 1,2 m. The wavelength of the signal will necessarily decrease inside the material because the propagation velocity increases[1].

[1] This is a consequence of the formula relating signal frequency with velocity and wavelength $f=v/\lambda$.

The chosen antenna

None of the antennas tested before the GPR antennas could give satisfactory results. It was not possible to see the bottom reflection clearly as various reflections were present in the reflected time domain signal. From these**,** the best antenna was the linear tapered slot antenna showing some clear results for test with empty container. This antenna was destroyed by the wind when performing the tests, which also showed it not to be sufficiently robust to perform full-scale measurements.

First results from 500 MHz GPR antenna showed that it was possible to see the bottom reflection from containers with biofuel. Although, parallel tests with both 500 and 250 MHz showed that the latest could fail in giving a clear bottom reflection when very large amounts of biofuel where measured as the penetration depth decreases with increasing frequency. Based on this results the GPR antenna with 250 MHz centre frequency was chosen continue the project.



(a) *(b)*

Figure 3. (a) GPR shielded antenna from Malå Geoscience with 500MHz centre frequency.

(b) GPR shielded antenna from Malå Geoscience with 250MHz centre frequency. This antenna has the dimensions: 0.94x0.48x0.24m.

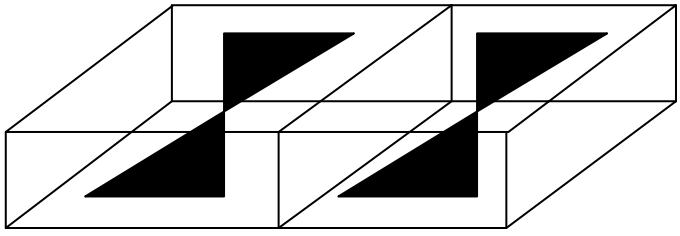


Figure 4. Scheme of the GPR with sender and receiver bow-tie antennas

3.2 Measurements set-up

There are several commercial measurement methods, at microwave and RF frequencies, where transmission is measured (by assessing two sides of the material) or reflection methods where superficial reflection is used. As mentioned in the introduction, one of the originalities of this project is the attempt to measure assessing only one side of the material. A scheme of the measurement set-up, representing a container with an antenna on the fuel surface, is shown in Figure 5.

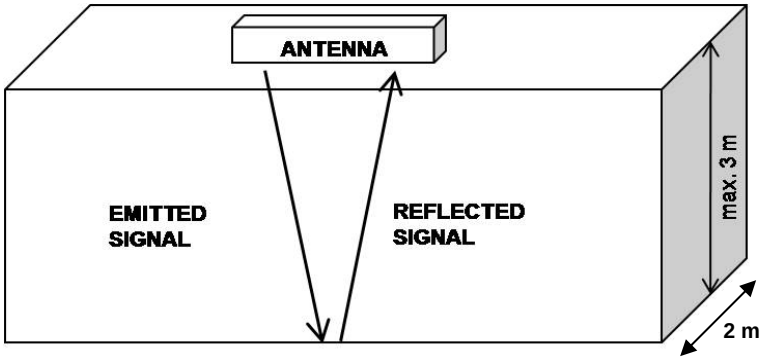


Figure 5. Set-up scheme for the measurements of biofuel directly in the container.

The antenna chosen to perform measurements was a GPR antenna. These antennas are made to be placed on the soil surface but can also be air-coupled. In this study it was decided to test both.

The measurements were performed on biofuel in containers throughout all the parts of the project. A freestanding container of about 42 m^3 was used for the measurements in the first and second part of the project. The empty container was filled with fuel, a measurement was performed and then the container was emptied. In the third part the measurements were performed directly in the container in which biofuel was transported, with the container still positioned on the truck.

In the first part of the project the surface of the fuel was scanned by pulling the antenna over the surface of the fuel manually. In the second part of the project a rig was build to pull the antenna over the fuel, automating the scan of the surface. The rig was rebuilt during the third part of the project, so the trucks could drive under the antenna. In the third part the measurements were both performed on the surface but also air-coupled with the antenna hanging in the air, at a certain distance from the fuel surface.

The measurement rig consists of a crane in which the antenna is hanging so that the trucks can drive and stop beneath. Once the truck had stopped it was possible to adjust the height of the antenna and to move the antenna along the surface of the material. A platform was build at a level above the container top to allow the operator to control the antenna position and to perform the measurements. The rig with the antenna and a trailer truck driving beneath the antenna is shown in Figure 6. The rig was built by and at the local municipal combined heat and power plant, Eskilstuna Energy and Environment (EEM).



Figure 6. The rig for RF full-scale measurements constructed at EEM, with trailer truck driving beneath the antenna.

3.3 Reference Method

The gravimetric, or oven dry method was used as reference method throughout the project. In this method a sample of the material is collected and water content determined by using the difference in the sample's weight before and after drying. The gravimetric method for determining is the standard method for water content in biofuels and peat (Swedish Standard, 1997). The oven gravimetric method provides accurate results but the difficulty is to sample the material which water content is to be determined.

There a standard for biofuel and peat sampling for water content determination with the gravimetric method (Swedish Standard, 1999). This sampling standard describes the size, quantity and distribution of the samples. For deliveries having a weight less than 30 ton at least ten samples have to be taken. One of the requisites of the standard is that all parts of the fuel in the container can be accessed to take the samples. This condition is, of course, difficult to satisfy. One of the advised cases in the standard is that samples are taken from biofuel piles, tipped in the ground. This procedure was followed for ten deliveries. The procedure was not applied to more deliveries because of lack of space in the oven for drying ten samplers per delivery. It would also be difficult to tip all deliveries on the ground because of lack of space and further work to remove the biofuels from there. This procedure was done in order to verify the water content variation between samples within a container.

It is worth to note that technical specifications for water content determination and sampling of biofuels are being developed to European standards (CEN/TS, 2004), (CEN/TS, 2005).

The measurement procedure that was followed in the third step was to measure a specific point in the container from were samples to the reference water content were also taken. Two reference samples for the gravimetric method were taken from the NIR measurement spot. The aim was to take the samples from as deep as possible, although the achieved depth mostly was between 30 and 50 cm.

It should be noticed that the RF measurement measures the entire depth of material and an area which can vary between 0.4 and 0.8 m. This is a larger volume than the one represented by the samples[2].

In the third step, taking advantage of the fact that the measurement method using NIR probe was being tested at the same time, RF measurements were made in the same part of the fuel as measurements with NIR probe.

3.4 Sample information

A database with the measurements done and its parameters is presented in attachment 1. The measurements were done with all the types of fuel received at EEM: woodchips, bark, sawdust, GROT, salix, residual woodchips and "städflies" (very dense and wet wood-based residues from floor cleaning of warehouses). The water content range in the samples measured was between 16% and 68%.

The volume and the weight were also registered for each delivery. The weight of the delivery is calculated by the difference between the weight of the truck trailer filled with fuel (when arriving at the plant) and empty (when leaving the plant). The volume was estimated by the operators at the reception of the plant, by measuring the amount of fuel in relation to the dimensions of the container.

The weight and volume was used for calculate the density of the biofuel which is the total weight of the fuel divided by its volume. The density varied from 0.16 to 0.59 m^3/ton. Two main types of containers are transported by the trailer trucks to the delivery station; metallic containers which are completely made of metal and plywood containers. Some of the plywood containers have a metallic plate beneath the plywood bottom. A reflection from a metallic surface is stronger than a reflection from a plywood surface and it was therefore important to test if bottom reflection was visible with both container types.

[2] This values can be obtained from the relation wavelength=velocity/frequency. The wave length of the waves with 250MHz frequency in air is 1.2 m, but in the material it will decrease depending on the water content, because the velocity also decreases. In the measurements a minimum velocity in the sample of 1.1E8 m/s (for a water content of about 65%) was obtained, which results in a wavelength of 0.44 m. The highest velocity was obtained for a sample with about 20%, which results in a wavelength of 0.8.

4 Measurement analysis

4.1 Signal Processing

A succession of processes occurs from the moment the signal is registered, until the desired parameter, water content, is obtained. A processing flow diagram of GPR data is shown in Figure 7. This diagram is an example and can vary for different applications.

The data acquisition can be interpreted by a real-time image on the computer monitor. This real-time image is a figure, also called radargram, with different tones for different reflection amplitudes. This is the only necessary step for many applications where only a qualitative answer is required. In this project basic and advanced processing are also done. In basic processing the raw data is recorded and converted so that further processing and calculations can be done. The aim of advanced processing if to obtain a signal in which the desired reflection, in this case reflection from the bottom of the container, is easier to identify. Finally the processed signal is correlated with water content to obtain a prediction model that is able to determine water content. All processing was done using Matlab®.

In a commercial application the further process of the signal and the correlation model between the signal and water content are in-built and result in a real-time value which is required in on-line control applications.

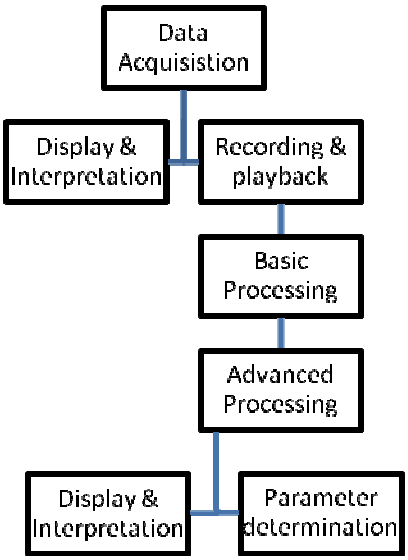


Figure 7. Processing flow of GPR data.

4.2 Correlation Models

4.2.1 Multivariate data analysis - Partial least square

Multivariate methods can be used for data analysis and correlation. Partial least square (PLS) regression was performed using the program The Unscrambler®, version 9.2 (The Uncrambler, 2008). PLS identifies the principal components that contribute in a larger extent to the explanation of the total variance of the data set. The first PC explains the largest part of information, followed by the second PC and so forth until the variation modelled by a new PC is mainly noise.

In this analysis the whole signal was used in the regression. The number of dependent variables was 390. These dependent variables are the reflection amplitudes at the different times (see figure 8 for a visual representation of these variables). Advantages of this method when compared with the method using the dielectric constant is that there is no need to identify the bottom reflection and that a series of disturbances can be compensated by the use of many variables.

4.2.2 Estimation of the dielectric constant

As explained in point 2.2, the velocity of electromagnetic waves in a moist material is related with the material water constant. This relationship was modelled in this project by using an estimate of the dielectric constant. The dielectric constant, ε', is defined as in equation (4).

In Figure 8 an example of the reflected signal is presented. Bottom reflection, surface reflection are identified. The two-way travel time is the difference between bottom and surface refection.

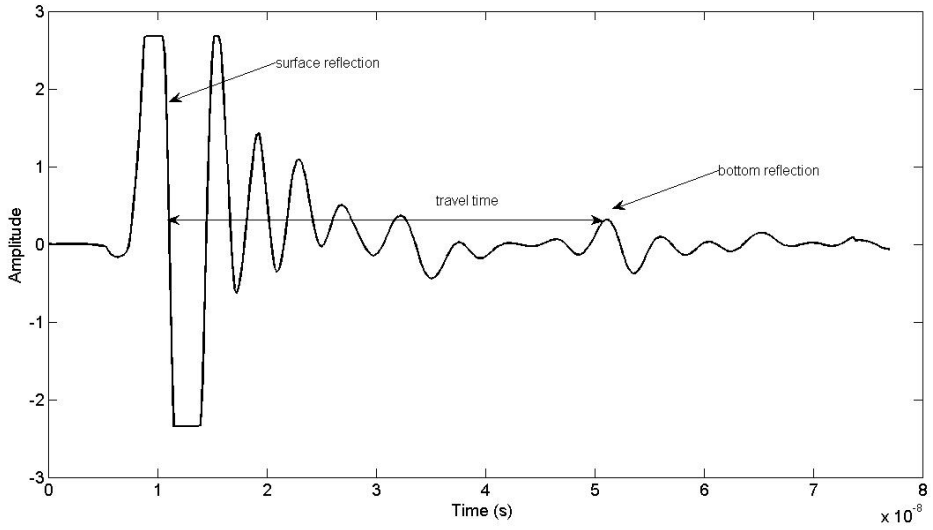


Figure 8. Time domain signal containing reflections at the surface and bottom of the material is shown. The travel time is the difference between the surface and bottom reflections.

The advantage of using this method is that it is based on a physical constant, ε'. This relation is inherent to the material and therefore unchangeable by equipment, set-up or

sample size. It is also known that there is a physical relation between ε' and the water content.

An estimate of this relation can be obtained statistically, for instance using a fitting curve to a series of measurements. This especially interesting in this case because it allows to compare the relation between ε' of biofuel and water content in the full-scale measurements with the one obtained with the laboratory-scale measurements. In lab-scale measurements a smaller sample volume, 0.1 m^3, was measured. The samples were homogenised by turning them in the floor and 5 reference samples were taken for determination with the standard oven method. It can therefore be assumed that the reference value obtained was accurate.

4.2.3 Evaluation of the models

The root mean square error (RMSE) was used to evaluate the models. This is an average error in the same units of the samples used for its calculation. The RMSE is calculated as in equation (5), where N is the total number of samples.

$$RMSEP = \sqrt{\sum_{i=1}^{N} \frac{(calculated - measured)^2}{N}} \qquad (5)$$

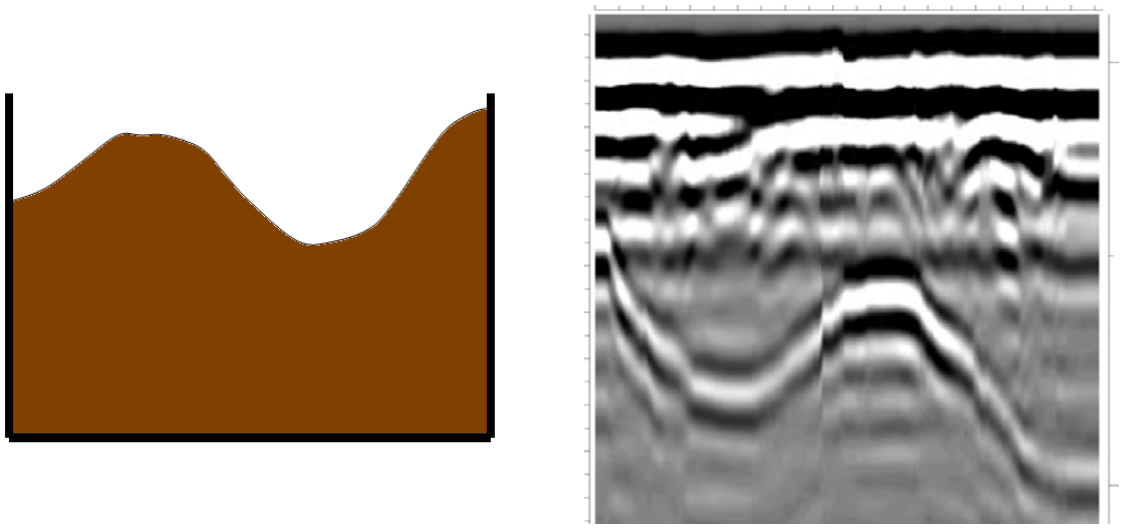
5 Results

PART 1

5.1 Bottom reflection

Figure 9 (a) is a drawing of the measured biofuel, irregularly loaded in different parts of the container. The reflected signal is shown in a radargram in Figure 9 (b) as it appears in the real-time GPR display. The horizontal axis represents the position of the antenna and the vertical axis represents the time, where time is zero at the top of the figure and increases downwards. It can be noticed that the bottom reflection is mirrored in relation with the surface of the fuel, as larger length of fuel means larger travel time. Other reflections, parallel to the horizontal axis can also be seen in the radargram. These are the surface reflection and its multiple reflections.

The rests also showed that it was possible to see the bottom reflection independently from the container type and that the bottom reflection was visible also in plywood containers.



(a) (b)

Figure 9. (a) Drawing of a container filled with fuel with irregular surface.
(b) Radargram from the measurement of fuel as in (a). The vertical axis corresponds to the time that is zero at the top of the radargram and increases downwards. The reflection is a mirror of the fuel surface as parts with more fuel have longer travel time.

PART 2

5.2 Measurements repeatability

Repeated measurements were performed in the same biofuel to check the repeatability of the method. This was not a recurrent procedure and it was carried out only on a few

deliveries because statistical results on repeatability are time consuming and it was not a direct aim of the project. Such results are although very interesting when developing commercial applications.

The repeated measurements consisted of scanning the fuel surface three times. An example of such repeated measurements is shown in Figure 10. Here the radargrams of the three repeated measurements is presented showing similar results. The water content predicted in each measurement using the dielectric constant method (point 5.4.2) was 54.4, 54.1 and 53.3%.

A further study in the method repeatability should include repeated measurement of the same biofuel which is tipped on the ground and reloaded into the container between each measurement.

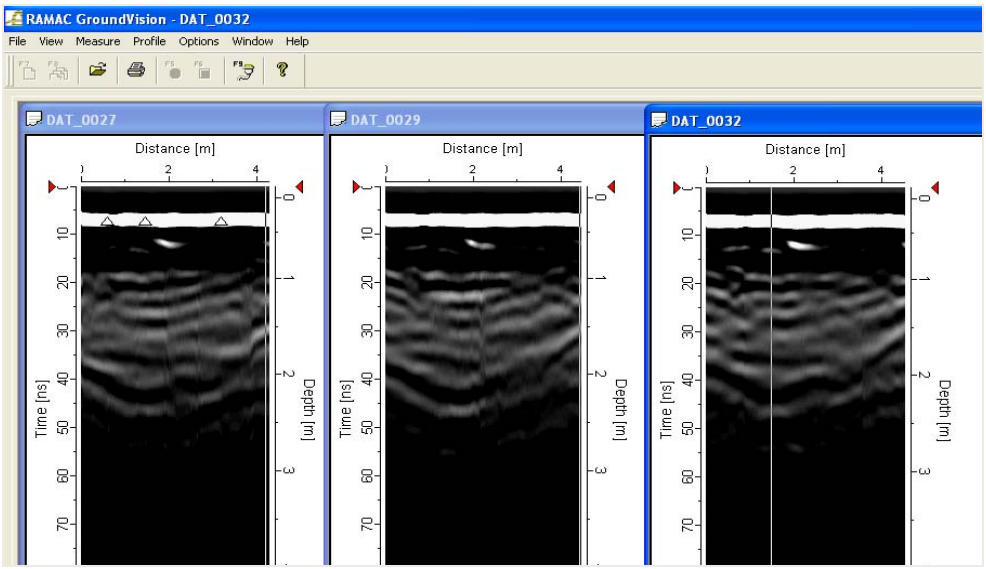


Figure 10. Radargrams of three repeated measurements of same fuel.

5.3 Disturbances

Measurements were also done to test how disturbances as chains or other metal objects would influence the signal. In figure 11, the bottom reflection, highlighted in red, obtained from a scan of a fuel surface can be seen. The fuel had a depth of about 2 m and the two metallic objects were placed at about 0.5 m from the bottom. It can be noticed that the reflection to this objects come before in time.

The suggested solution in this case is that the software calculates average water content for each profile of the fuel and that a warning is shown if variation in moisture is higher than a certain level from one profile to another. In this case this profile can be removed from the average water content calculation for the all container. This is also a warning for the presence of undesirable objects inside the fuel.

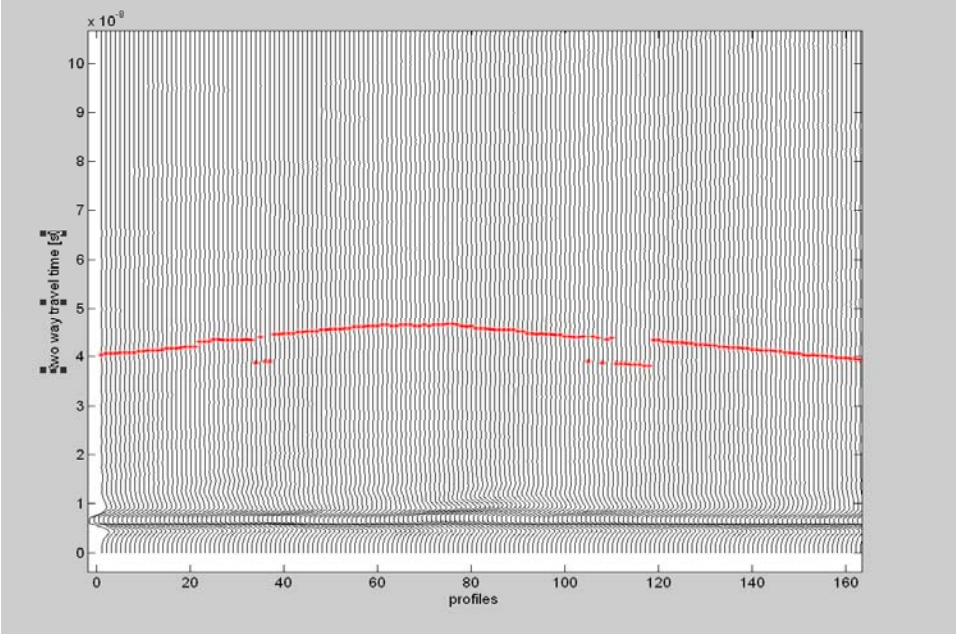


Figure 11. Bottom reflection (in red) altered by metallic objects at about 0.5 m from the bottom. In the horizontal axis are the different spatial positions of the antenna as scanning the fuel surface. The vertical axis represents time with zero on the lower part.

PART 3

5.4 Correlation and prediction models

A total of 112 measurements were performed in 80 different biofuel deliveries. The number of measurements differs from the number of deliveries as one truck can be loaded with more than one container.

Two different calibration procedures were used:

- Multivariate analysis using the received reflection signal (further described in section 5.4.1)
- Estimation of the dielectric constant using travel time to bottom reflection (described in section 5.4.2)

Only measurements with the antenna placed on the surface of the fuel were used in the calibration procedures. It was not possible to obtain a correlation between measurements and water content using the measurements made with the antenna air-coupled.

5.4.1 Multivariate Data Analysis – Partial Least Square

The data set was divided into a calibration and a test set. The calibration set was used to build the model and the measurements in the test set were predicted with this model. The error can be calculated with predicted and reference value according with equation (5). The test set shall be independent from the calibration set. Repeated measurements were performed within several deliveries, but the test set did not include measurements from deliveries that were included in the calibration. The calibration set included 79 measurements and the test set included 33 measurements.

In Figure 12 a PLS model is shown. Blue dots represents measurements included in the calibration set while red dots the ones included in the validation set. The 1:1 line is also plotted, indicating where the predicted value is the same as the measured value. The plot of a model with good correlation and prediction ability shows the samples close to the 1:1 line.

The model was obtained with the variables of density and depth of the samples and the entire time signal, which consists of amplitudes at different times. An example can be seen in Figure 8. Density and depth were divided by the standard deviation. It was noticed that variables until 30 ns (which are surface reflections and resonance, see Figure 8) were important in the model. The density was also an important variable. If the variables that represent the surface reflection were removed from the model, it was still possible to see a correlation, but its strength decreased and the prediction error increased. In this case the density and depth become important.

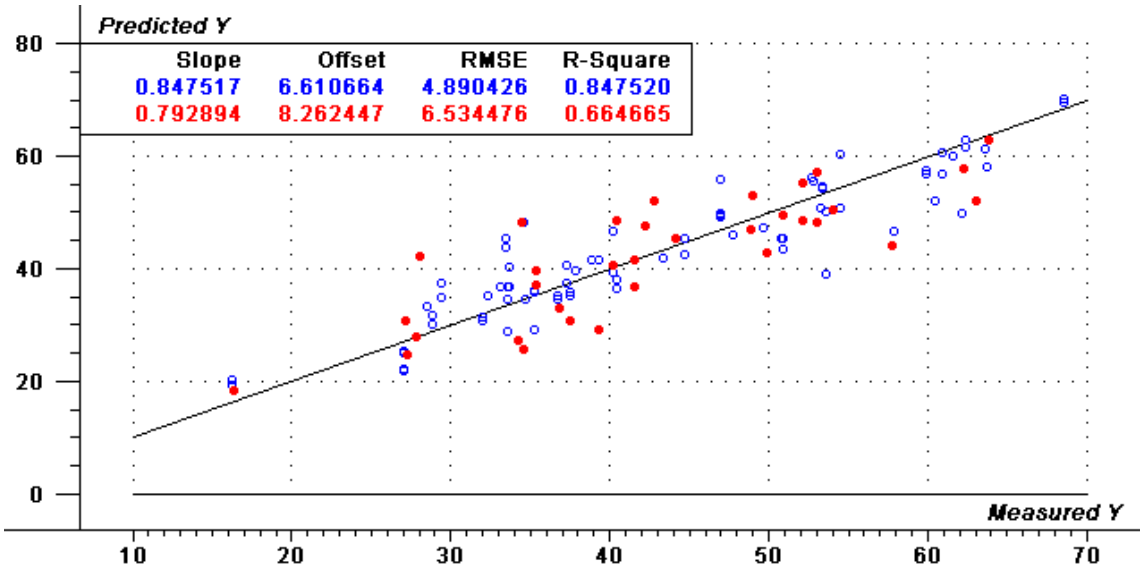


Figure 12. PLS model with both calibration and validation sets. The calibration samples are coloured in blue and the validation samples are coloured in red. The RMSE for the calibration is 4.9 while it is 6.5 for the validation set.

Using NIR as a reference value

As described in section 3.3, the water content determined with the NIR method was also collected. Correlation studies were also done using the NIR value as a reference, instead of the reference value obtained from the standard oven method. Because the NIR value was missing for some measurements (see data set in appendix 1), only 89 measurements were used. A calibration set of 65 and a validation set of 22 samples were build.

A model, having the standard oven method as the reference was built using this calibration and test set. In this way it was possible to compare the model using the standard oven method and the model using NIR as reference. All other parameters remained equal.

The model using NIR as reference is presented in Figure 13. The model using the standard oven method and exactly the same calibration and validation sets as in Figure 13 is presented in Figure 14. Statistical results are very similar for both models. The RMSEP for the validation set is 5.9% when NIR is used and 6.4% when standard method is used. The regression coefficient is 0.86 for the first one and 0.9 for the second.

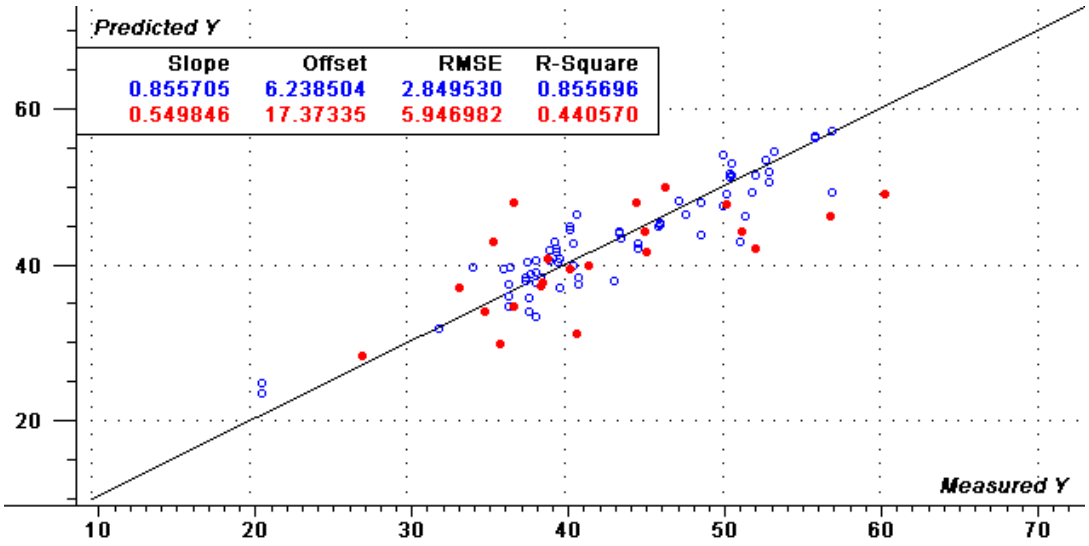


Figure 13. PLS model using water content determined with NIR probe method as reference values.The points in blue are used in the calibration and points in red are used for validation. The RMSEP obtained is 5.9.

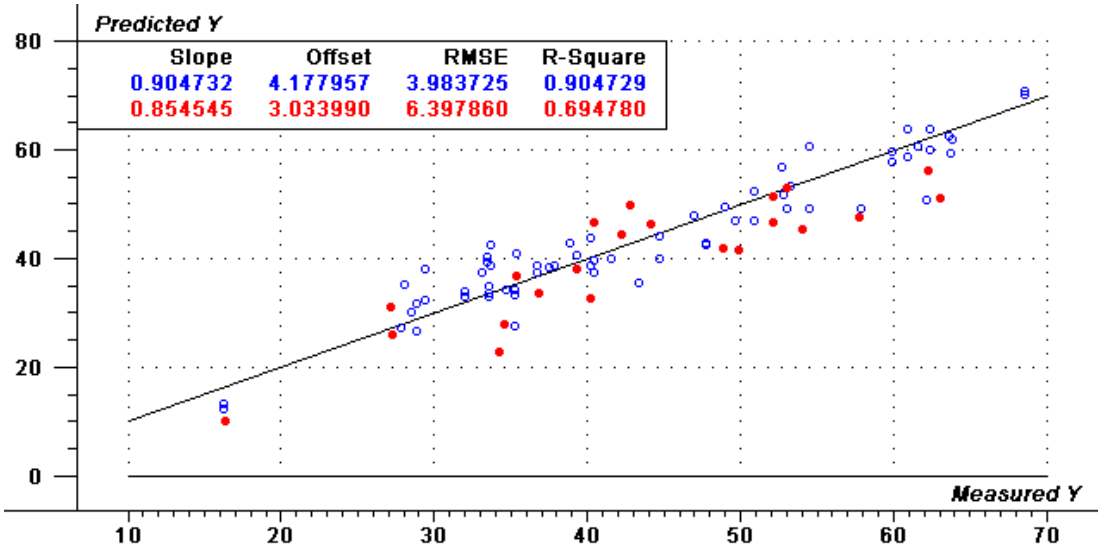


Figure 14. PLS model using water content determined with standard oven method as reference values. The calibration and validation sets are the same used in figure 12 for allowing direct comparison. The points in blue are used in the calibration and points in red are used for validation. The RMSEP obtained is 6.4.

It can be noted that NIR values are larger than oven method for small water contents and smaller for higher water content, this means the samples with 16% with oven

method have 21 and 27% with NIR and the sample 69% with oven method has 56% with NIR. Therefore the water content range when using NIR as reference is smaller.

It is difficult to draw conclusions from the comparison as there are is also uncertainty in the NIR method.

5.4.2 Estimation of the dielectric constant

The bottom reflection was doubtful for some of the measurements. In such cases it was impossible to calculate ε' and to relate these measurements with a known measurement parameter (fuel type, container type). A possibility is that such measurements are related with the way the antenna was placed on the fuel. For some of the measurements one half of the antenna was placed on the fuel while one half was hanging in the air. This might have resulted in multiple reflections that make the bottom reflection unclear. These measurements could not be used for the method of estimating ε'.

A number of 68 measurements were used. In Figure 15 the ε' of the material calculated with equation (3) is plotted against the reference gravimetric water content as determined with the standard gravimetric method. Results for both full scale measurements and laboratory scale measurements are plotted. It can be noted that both data sets follow the same trend in variation of ε' with water content. Fitting curves to full scale and lab-scale measurements have very similar slopes. These results are important to show the physical basis of the RF method.

It can be noted though that the variance in ε' from measurements having similar water content is larger for the full scale than in the data from laboratory scale measurements.

From relations plotted in Figure 15 it is possible to obtain two fitting curves that relate ε' with water content. One for the data from the full scale measurements and one for the laboratory scale data. In the figure legend linear fitting curves obtained for both data sets are shown. These can be used as calibration equations when determining water content by measuring ε'. In Figure 16 the water content calculated with these equations is plotted against the values of the reference water content. To measure the fit of the equations, it is possible to calculate the RMSE as shown in equation (5).

A RMSE of 4.5% was obtained for the laboratory-scale calibration curve and a RMSE of 7.3% for the full-scale.

The reference value used for the full scale measurements did not represent the total load of biofuel in the container as it was taken from the surface of the fuel. It is also possible to relate the larger dispersion in the full scale measurements to the uncertainty of the reference value used.

The larger error in the full scale situation can also be due to the large depth of material and the open air set-up which were not present in the laboratory-scale set-up.

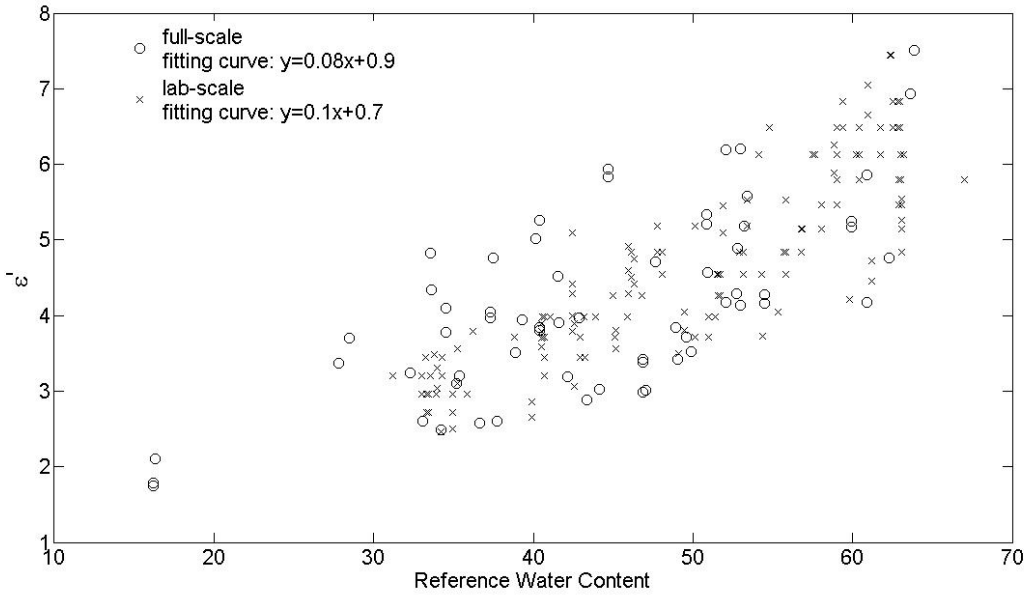


Figure 15. ε' versus reference water content for the full (circles) and laboratory (x) scale measurements. The linear fitting curve equations obtained for each set are also plotted in the legend.

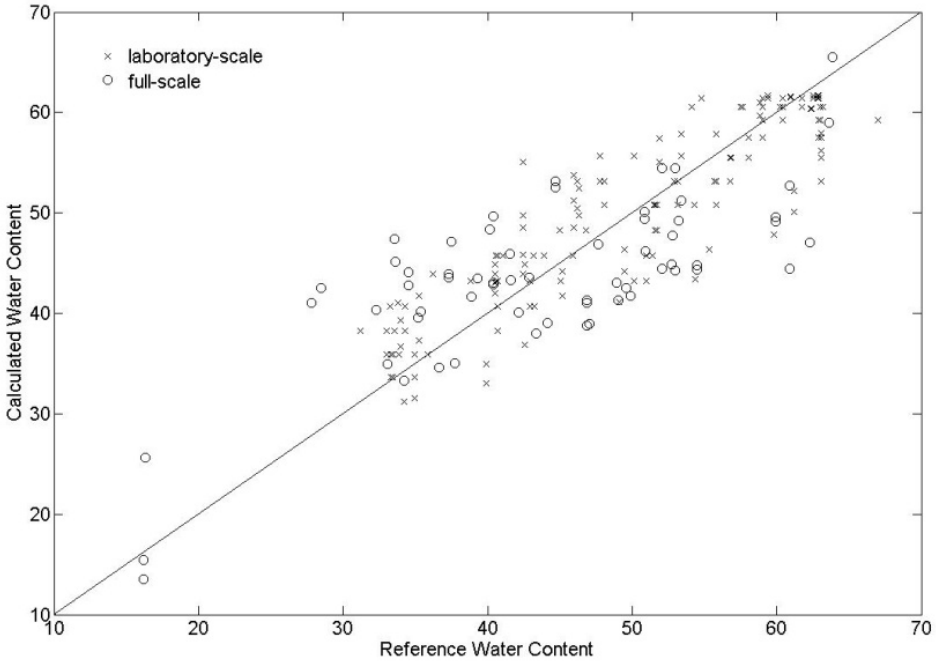


Figure 16. Reference versus calculated water content for full and laboratory scale data. The line 1:1 is also shown.

5.5 Variation in the reference value

The variation in the reference value was investigated from eleven containers with biofuel. The fuel was dumped on the ground and ten samples were picked from different parts of the fuel. Statistics from the measurements are listed in
Table 1. The mean value for the set of 10 reference samples, as well as their maximum and minimum value is shown. The maximum variation in the samples is the maximum difference between the water content in a sample and the mean value of the entire set. The standard deviation shows how much, in average, a sample deviates from the mean value of the entire set.

It can be seen that GROT and Salix (that have largest overall water content values) have the largest standard deviations. The water content value of one of the GROT samples differed with 11.4% units from the mean value. Smaller variations occurred for residual wood chips and wood chips. The average standard deviation for all the samples is table is 3.2% .

Table 1. Statistics for the reference value of biofuel from eleven containers. All values are in %.

Sample	Mean value	Max	Min	Standard deviation	Max variation
GROT	52.4	60.7	41.0	4.8	11.4
GROT	50.4	59.8	44.7	3.7	9.4
GROT	27.8	31.6	22.1	3.3	5.7
GROT	49.8	56.1	44.7	3.9	6.3
GROT	41.2	47.9	35.9	4.2	6.7
GROT	32.4	40.5	24.0	5.6	8.4
residual w.	21.6	22.5	20.6	0.8	1.0
Salix	48.8	51.9	40.9	4.2	7.9
Woodchips	47.4	50.4	44.6	1.8	3.0
Woodchips	39.6	41.6	37.8	1.2	2.0
Woodchips	38.8	41.2	36.8	1.3	2.4

6 Conclusions

Part one

Several antennas were tested and the best results were obtained using a GPR, 250 MHz centre frequency antenna. It was shown that it is possible to obtain a signal that travels trough large depths of woody biomass, directly in trailer truck containers and by accessing only the surface of the material. Tests showed that it was possible to see the signal for both metallic and plywood containers.

Part two

Repeated measurements performed on a single biofuel delivery showed that the measurements have good repeatability. Further studies should show the measurements repeatability of when the container is tipped on the ground and loaded again with same delivery.

Disturbances cause by metallic objects close to the bottom reflection can be identified if the surface of the fuel is scanned and by comparing the water content in neighbouring profiles. If these reflections vary more than a certain degree, a warning can be launched and the profiles removed from the whole delivery water content average.

Part three

Correlation was only obtained with measurements with the antenna placed on surface of the fuel. The PLS model, gave better correlation and prediction results (RMSEP = 6.5%) than the model obtained with an estimation of the dielectric constant (RMSEP = 7.3%).

A slightly lower prediction error was obtained using reference values of the MC measured with NIR than with the standard oven method, (RMSEP was 5.9% with NIR compared to 6.4% with standard oven method). The high RMSEP for both types of reference values indicates that there are unexplained variations within both methods.

When comparing NIR and the standard oven method as reference values in a PLS model the results show very similar prediction errors (RMSEP 5.9% for NIR as reference, 6.4% for oven as reference).

The relation between dielectric constant and water content in the full-scale and the same relation in laboratory-scale measurements follow the same trend in variation of ε' with water content as the fitting curves have similar slopes. When using the calibration equation obtained with full-scale data the RMSE of calibration is 7.3% while the same measure is 4.5% for the laboratory-scale data. The larger error in the full-scale situation when compared with the laboratory-scale can be due to inaccuracy in the full-scale reference value. As it is not representative for the volume of material which is measured with RF. Differences can also be due to the larger depth of material and the open air set-up or performance of the antenna.

The results from sampling according to the standard for sampling of biofuels and peat for water content determination with the standard oven method, show that there might occur large water content variations within a biofuel delivery. The maximum water content difference between two samples was 19.7% . This water content difference was obtained for a sample of GROT having a mean value of 52,4 % .

In the laboratory-scale measurement system the samples, with a volume of about 0.1 m^3, were tipped on the floor, mixed, and 5 samples were taken from different parts to put in the oven. This means, the reference value can be taken as representative for the volume measured. The RMSE of prediction for these measurements, obtained with an independent test set, was of 2.7% (Nyström, 2006).

Therefore the difference between prediction error in laboratory and full-scale measurements is of 3.8%. As mentioned when discussing the larger RMSE of calibration using dielectric constant for full-scale measurements than for laboratory-scale measurements, it is possible to discuss that a part of the prediction error is due to inaccuracy in the value used as reference water content. The results from samples in different parts of the container showed an average standard deviation of 3.2%, which could indeed explain a part of the error. Althought is it also possible that a part of the large error is due to the open air set-up, the larger depth of material or performance of the antenna.

7 Recommendations and applications

The measurements are to be performed with the antenna situated on the surface the fuel. The entire area of the antenna shall be on the fuel. This can be easily done if the instrument can move in perpendicular directions on the fuel.

The aim of this method is to provide a bulk measurement. If the equipment measure at only one place is an average value obtained for the entire depth of that part of the fuel. The antenna can scan the entire surface of the fuel in order to obtain a full bulk measurement. The average value at different points can be averaged and a value for the entire bulk can by that be obtained. If it is impossible to scan the entire surface due to, for instance, the existence of currents on the surface or extremely irregular fuel surface, the measurements can be performed in only a few places within the delivery.

It is important to discuss the desired minimum prediction error for an on-line method. It is necessary to perform measurements with accurate sampling for reference water content determination. The prediction error obtained could also be lowered by better measurement procedures (the entire area of the antenna on the fuel), special antenna design and advanced data processing.

This study used a commercial GPR antenna and control unit available in the market for a broad range of applications. A commercial application for water content measurement in biofuel should use a control unit developed for this purpose in order to decrease the price and to improve the user interface.

8 References

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The Uncrambler homepage. Hämtat från www.camo.no

Appendices

Database

Legend of the database table

Reference number:
This is the number given at EEM heat and power plant to the received deliveries. Data about the deliveries can be consulted by using this number.

Sample Name:
SD- sawdust
ST- woodchips
S – salix
G – GROT
B – bark
ST – dense and very wet “städflies”
RT – residual woodchips

DATE	Reference number	Sample name	MC ref [%]	NIR [%]	Density [m³/t]	Depth of fuel [m]	Container type
15_2	80119358	SD53	53.4	m	0.39	2.83	plywood
15_2	80119358	SD53	53.4	m	0.39	2.83	plywood
15_2	80119360	ST27	27.0	m	0.19	2.15	metal
15_2	80119360	ST27	27.0	m	0.19	2.15	metal
15_2	80119360	ST27	27.0	m	0.19	2.67	plywood
15_2	80119360	ST27	27.0	m	0.19	2.67	plywood
15_2	80119361	ST32	32.3	m	0.27	2.94	metal
15_2	80119361	ST32	32.3	m	0.27	2.94	metal
15_2	80119367	ST35	34.5	m	0.33	2.59	metal
15_2	80119367	St35	34.6	m	0.33	2.59	metal
15_2	80119368	ST47	46.9	m	0.37	2.32	metal
15_2	80119368	ST47	46.9	m	0.37	2.32	metal
15_2	80119368	ST47	46.9	m	0.37	2.32	metal
15_2	80119369	ST54	53.6	m	0.31	2.66	plywood
15_2	80119369	ST54	53.6	m	0.31	2.66	plywood
15_2	80119370	S51	50.8	m	0.30	2.82	metal
15_2	80119370	S51	50.9	m	0.30	2.82	metal
15_2	80119371	ST 37	37.3	m	0.30	2.49	metal
15_2	80119371	ST 37	37.3	m	0.30	2.49	metal
15_2	80119373	ST38	37.5	m	0.30	2.25	metal
15_2	80119373	ST38	37.5	m	0.30	2.25	metal
18_2	80119452	T69	68.6	55.9	0.59	1.48	metalic
18_2	80119452	T69	68.6	55.9	0.59	1.48	metalic
18_2	80119453	ST37	36.7	37.5	0.24	2.86	plywood
18_2	80119453	ST37	36.7	37.5	0.24	2.86	plywood
18_2	80119454	ST33	33.1	39.7	0.31	2.86	metalic
18_2	80119454	ST33	33.1	39.7	0.31	2.86	metalic
18_2	80119455	G34	33.7	44.6	0.33	2.56	metalic
18_2	80119455	G34	33.7	44.6	0.33	2.56	metalic
18_2	80119457	S48	47.7	43.5	0.31	2.20	metalic
18_2	80119457	S48	47.7	43.5	0.31	2.20	metalic
18_2	80119463	RT58	57.8	38.5	0.30	2.65	plywood
18_2	80119463	RT58	57.9	38.5	0.30	2.65	plywood
18_2	80119464	B61	60.9	50.0	0.44	2.56	plywood
18_2	80119464	B61	60.9	50.0	0.44	2.37	plywood
18_2	80119465	G55	54.5	48.7	0.41	2.61	metalic
18_2	80119465	G55	54.5	48.7	0.41	2.54	metalic
18_2	80119466	B62	61.6	50.5	0.44	2.75	plywood
18_2	80119466	B62	61.6	50.5	0.44	2.75	plywood
21_2	80119612	B40	40.2	39.0	0.27	3.13	plywood
21_2	80119612	B40	40.2	39.0	0.27	3.34	plywood
21_2	80119613	B62	62.4	53.0	0.39	2.60	plywood
21_2	80119613	B62	62.4	53.0	0.39	2.63	plywood
21_2	80119616	ST32	32.0	38.2	0.31	3.33	plywood
21_2	80119616	ST32	32.0	38.2	0.31	3.31	plywood

DATE	Reference number	Sample name	MC ref [%]	NIR [%]	Density [m³/t]	Depth of fuel [m]	Container type
21_2	80119624	ST34	33.6	37.7	0.20	2.74	plywood
21_2	80119624	ST34	33.6	37.7	0.20	2.74	plywood
25_2	80119730	ST60	59.9	50.6	0.32	3.20	plywood
25_2	80119730	ST60	59.9	50.6	0.32	3.20	plywood
25_2	80119731	ST40	40.4	40.9	0.28	2.65	metal
25_2	80119731	ST40	40.4	40.9	0.28	2.65	metal
25_2	8019732	SD53	53.0	50.3	0.39	2.38	plywood
25_2	80119733	ST42	41.6	45.9	0.34	2.67	metal
25_2	80119734	ST39	39.3	41.5	0.23	3.08	plywood
25_2	80119735	ST29	33.6	34.2	0.29	2.42	metal
25_2	80119739	ST34	33.6	37.9	0.23	3.24	plywood
25_2	80119740	B64	63.6	53.3	0.39	2.86	plywood
25_2	80119741	G28	63.6	40.8	0.30	2.53	metal
25_2	80119743	ST62	62.2	40.5	0.38	2.69	plywood
27_2	80119828	ST35	35.4	37.6	0.30	2.02	metal
27_2	80119829	ST39	39.3	43.6	0.28	2.47	plywood
27_2	80119831	RT38	37.5	40.5	0.30	2.94	plywood
27_2	22198	G27	27.2	36.8	0.19	2.28	metal
27_2	80119834	G39	38.9	39.6	0.30	2.37	metal
27_2	80119835	SD53	53.2	51.1	0.35	1.97	plywood
3_3	80119977	SD54	54.0	52.1	0.36	2.63	plywood
3_3	80119978	S42	41.5	0.0	0.30	2.36	metal
3_3	80119979	G 43	42.8	36.8	0.40	2.29	metal
3_3	80119980	SD53	52.8	52.7	0.34	2.58	plywood
3_3	80119983	G62	62.3	46.4	0.38	2.74	plywood
6_3	80120103	RT40	40.4	44.5	0.33	2.66	metal
6_3	80120106	ST50	49.6	51.5	0.35	2.57	metal
6_3	80120108	S50	49.9	45.2	0.29	2.70	metal
6_3	80120109	G34	34.2	35.9	0.25	2.40	metal
6_3	80120110	ST37	36.8	40.3	0.25	3.08	plywood
6_3	80120112	G49	48.9	33.3	0.29	2.91	metal
6_3	80120112	G49	49.0	51.9	0.34	2.66	metal
6_3	80120115	SD52	52.1	56.9	0.35	2.77	plywood
6_3	80120118	ST35	34.7	43.1	0.24	3.11	plywood
6_3	80120120	B63	63.1	60.3	0.45	2.71	plywood
11_3	80120302	S53	53.0	50.3	0.32	2.52	metal
11_3	80120303	B44	44.1	45.1	0.30	2.99	plywood
11_3	80120304	SD53	52.7	47.7	0.39	2.81	plywood
11_3	80120306	RT43	43.4	39.4	0.31	2.75	metal
11_3	80120308	G35	34.6	35.5	0.28	2.51	metal
11_3	80120310	ST42	42.2	38.9	0.31	2.38	metal
11_3	80120311	B64	63.8	36.6	0.40	2.85	plywood
11_3	80120312	SDG28	27.8	32.0	0.30	2.88	plywood
11_3	80120313	G34	33.5	40.3	0.37	2.14	plywood
11_3	80120313	G34	33.5	40.3	0.37	2.24	plywood
18_3	80120573	RT38	37.8	36.1	0.28	3.17	plywood
18_3	80120574	G51	50.9	57.0	0.37	2.33	metal

DATE	Reference number	Sample name	MC ref [%]	NIR [%]	Density [m³/t]	Depth of fuel [m]	Container type
18_3	80120574	G51	50.9	57.0	0.37	2.54	metal
18_3	80120575	ST40	40.2	34.9	0.27	2.75	metal
18_3	80120584	ST35	35.4	38.6	0.26	3.12	plywood
18_3	80120586	RT16	16.2	20.8	0.16	2.98	plywood
18_3	80120586	RT16	16.2	20.8	0.16	2.98	plywood
19_3	80120627	RT35	35.2	36.4	0.27	2.77	metal
19_3	80120627	RT35	35.2	36.4	0.27	2.76	metal
19_3	80120627	RT35	35.2	36.4	0.27	2.76	metal
19_3	80120628	SD29	28.8	38.2	0.26	3.28	plywood
19_3	80120628	SD29	28.8	38.2	0.26	3.28	plywood
19_3	80120630	G47	47.0	47.2	0.36	2.48	metal
19_3	80120632	RT16	16.3	27.2	0.17	2.94	metal
19_3	80120635	G52	52.1	51.2	0.31	2.51	metal
19_3	80120637	B61	60.5	0.0	0.24	2.67	plywood
19_3	80120638	G29	29.4	39.5	0.34	2.49	metal
19_3	80120638	G29	29.4	39.5	0.34	2.69	metal
19_3	80120639	ST27	27.3	40.8	0.21	2.54	metal
19_3	80120649	B64	63.7	52.1	0.38	2.80	metal
19_3	80120650	ST45	44.7	46.1	0.27	3.23	plywood
19_3	80120650	ST45	44.7	46.1	0.27	3.22	plywood

Värmeforsk är ett organ för industrisamverkan inom värmeteknisk forskning och utveckling. Forskningsprogrammet är tillämpningsinriktat och fokuseras på energi- och processindustrins behov och problem.

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- Elforsk
- Svenska Fjärrvärmeföreningen
- Skogsindustrin
- Övrig industri

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