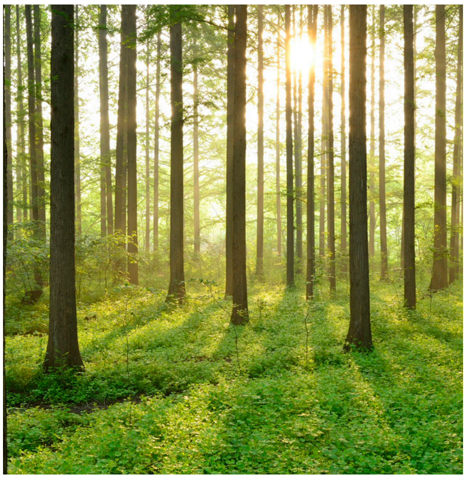
QUICK MOISTURE MEASUREMENT OF WOOD FUEL WITH RADAR TECHNOLOGY

RAPPORT 2015:169



FUEL-BASED ELECTRICITY AND HEAT PRODUCTION

Energiforsk

Quick Moisture Measurement of Wood Fuel with Radar Technology

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Foreword

This report is based on a feasibility study project on moisture measurement of wood fuel with radar technology. The project has been implemented through financial support from the Swedish Energy Agency. The project has been managed by the Energiforsk and a special reference group has been added. Radarbolaget has been the project manager. Gävle Energi and BillerudKorsnäs have been a steering committee, working group and giving other resources available to the project. Their intimate knowledge of rules, laws, research and practical operation at heating power stations has greatly contributed to the project. Radarbolaget and Gävle Energi have done most of the practical work. Gävle University has contributed with knowledge and equipment on frequency analysis.

Costs of the project has been about 1.5 MSEK, of which 448,800 SEK have been financed by the Swedish Energy Agency.

Organizational composition during the project period were:

Reference group

Katja Lindblom/Jakob Thynell, ÅF
Daniel Nordgren, Pöyry
Dag Wiklund, Jämtkraft
Shahriar Badiei, Vattenfall
Sören Hansson, Grontmij

Steering committee

Uno Brinnen, BillerudKorsnäs
Inger Lindbäck, Gävle Energi
Per Carlsson, S-Group Holding

Project group

Patrik Ottoson, Radarbolaget (projektledare)
Daniel Andersson, Radarbolaget
Jahn Johansson, Gävle Energi
Per Ericsson, BillerudKorsnäs

An extended version of this report is available in Swedish as Energiforsk rapport 2015:168 Snabb fukthaltsmätning av trädbränsle med radarteknik,
ISBN 978-91-7673-168-0.

Sammanfattning

Det finns 580 fjärrvärmenät och 125 större biobränsleeldade anläggningar i Sverige. Biobränslet utgörs företrädelsevis av fyra sorters trädbränsle: returträ, GROT (grenar och toppar), bark och cellulosaflis. Fukthalten torde kunna mätas direkt, snabbt och tillförlitligt, och därigenom bestämmas med ett radarsystem inom 60 sekunder. Provtagning torde kunna göras av hela lasten varvid ett representativt medelvärde erhålls. Snabbare och mer tillförlitlig fukthaltsmätning leder till effektivare logistik och bränslehantering, vilket har beräknats ge besparingar på motsvarande 2-4 Mkr per år.

För ofarlig, oförstörande och beröringsfri mätning med hög noggrannhet av fukthalten har en UWB-radar (ultra wideband) använts. Vid frekvensanalys går det att konstatera 0,75 GHz är en lämplig centerfrekvens för mätning på tempererat trädbränsle (>0°C). Även lägre frekvenser kan fungera väl. Huvuddelen av mätningarna inom förstudien har dock gjorts med centerfrekvensen 2 GHz.

Projektet har visat att fukthalten i tempererat trädbränsle (>0°C) kan bestämmas med en noggrannhet på 3 procentenheter. Noggrannheten kan öka ytterligare genom att göra ytterligare kalibreringsmätningar, separat modellering av respektive trädbränsle, modellering med Debyes relaxationsformel, mäta och modellera dämpningen samt mäta och modellera temperaturen och densiteten. Enligt den nya virkesmätningslagen (SKSFS 2014:11) krävs dock en noggrannhet på 2 procentenheter för att bestämning av fukthalten i trädbränsle med en fukthalt under 65% (torrhalt över 35%).

Radarmätningar (dielektricitetskonstanten och dämpningen) av trädbränsle påverkas av fukthalt, temperatur, densitet och frekvensval. Dielektricitetskonstanten och dämpningen är mycket lägre (4-5 gånger) för fryst material och snöklumpar än för temperat fuktigt trädbränsle (>0°C). Det innebär att temperaturen måste mätas och modelleras för att erhålla rätt fukthalt vid frystemperaturer. Mätupplösningen i fukthaltsmätning minskar som en konsekvens av att dielektricitetskonstanten är lägre för fryst material. Mätning på långa avstånd (bredden av en flisbil) torde öka upplösningen och noggrannheten. I princip ska det dubbla avståndet ge dubbel upplösning och noggrannhet. Mätningar på fryst trädbränsle gjordes på en provlåda om 30 cm, vilket innebär cirka 8 gånger högre potentiell noggrannhet på verklig flisbil (240 cm). Även kompletterande modellering av dämpning och densitet torde kunna öka möjligheten till rätt fukthaltsbestämning. Frekvensen påverkar dämpning och dielektricitetskonstant, därför måste lämplig frekvens väljas för fryst material (troligtvis högre än för tempererat trädbränsle (>0°C)).

Projektet har visat att det är möjligt att mäta på långt avstånd (efterliknar mätning på flisbil) på tempererat fuktigt trädbränsle (>0°C) med centerfrekvensen 0,75 GHz. Signalerna är fina och har ett högt signal-till-brus-förhållande (SNR). I testet kunde fukthalten bestämmas med en avvikelse på 1,6 procentenheter.

Under projekttiden har en ny lag om virkesmätning trätt i kraft. Noggrannhetssiffrorna från projektet vittnar om att mätning med radar torde kunna användas, för att matcha de krav som den nya lagen stipulerar, om noggrannheten ökar med 1 procentenhet. Därför skulle ett framtida radio- och radarbaserat mätsystem kunna användas även som en del i ett debiteringssystem för att säkerställa rätt betalning. Inblandade projektparter föreslår med givna resultat att ett prototypprojekt planeras och genomförs. Det är viktigt att inledningsvis visa hur temperatur och densitet ska kunna

modelleras för att nå högre noggrannhet i bestämningen av fukthalten. Det är också viktigt att få fram en stabilare referensmätningsmetod, då nuvarande torkning påverkas stort av den omgivande luftens relativa fukthalt.

Summary

There are 580 district heating networks and 125 larger biomass power plants in Sweden. Biofuel consists mainly of four types of wood fuel: recycled wood, forest residues (branches and tops), bark and wood chips. The moisture content could be measured directly, quickly and reliably, and thereby determined with a radar system within 60 seconds. Measurement can be carried out for the entire load in order to get a representative average value. Faster and more reliable moisture measurement leads to more efficient logistics and fuel management, which have been calculated to save 2-4 million SEK per year.

For safe, non-destructive and non-contact measurement with high accuracy in the moisture content a UWB radar (ultra wideband) has been used. Frequency analysis gives that 0.75 GHz is a suitable centre frequency of measurement at temperate wood fuel (>0° C). Even lower frequencies may work well. Majority of the measurements in the feasibility study have been made with a centre frequency of 2 GHz.

The project has shown that the moisture content of wood fuel temperature (> 0 ° C) can be determined with an accuracy of 3 percentage points. The accuracy may be increased further by making additional calibration measurements, separate modelling of each wood fuel, modelling with Debye's relaxation formula, measure and model the attenuation as well as measure and model temperature and density. According to the new timber measuring act (SKSFS 2014: 11), an accuracy of 2 percentage points is required for determination of the moisture content of wood fuel with a moisture content below 65% (dry content over 35%).

Radar measurements (dielectric constant and attenuation) of wood fuel are affected by moisture, temperature, density and frequency selection. The dielectric constant and the attenuation is much lower (4-5 times) for frozen materials and lumps of snow than temperate moist wood fuel (>0° C). This means that the temperature must be measured and modelled to obtain the correct moisture content at freezing temperatures. On one hand, measurement resolution in moisture measurement decreases as a consequence of dielectric constant is lower for frozen material. On the other hand, measuring at long distance (the width of a wood chip trucks) will increase the resolution and accuracy. In principle, double distance provides double resolution and accuracy. Measurements on frozen wood fuel were made on a sample box of 30 cm, which means about 8 times higher potential accuracy of real wood chip trucks (240 cm). Even additional modelling of attenuation and density will increase the possibility of correct moisture content determination. The frequency and attenuation affects dielectric constant, therefore, the appropriate frequency must be selected for frozen materials (most likely higher than for temperate wood fuel (>0° C)).

The project has shown that it is possible to measure long distances (mimics measurement of wood chip trucks) of temperate moist wood fuel (>0° C) with a centre frequency of 0.75 GHz. The signals are great and have a high signal-to-noise ratio (SNR). In the test, the moisture content was determined with a deviation of 1.6 percentage points.

During the project period, a new timber measuring act has been valid. Accuracy proven in the project suggests that radar measurement match the requirements, which the new law stipulates, if accuracy increases with 1 percentage point. Therefore, a future radio

and radar-based measurement system can also be used as part of a billing system to ensure correct payment. Involved project partners suggest from results given that a prototype project shall be planned and realized. It is important initially to show how temperature and density to be modelled to achieve higher accuracy in determination of moisture content. It is also important to obtain a more robust reference measurement method, because current drying is largely affected by relative humidity of the environmental air.

List of content

1 Energy efficiency of district heating systems

Swedish district heating system is supplied with heat from heating plants or central heating plants (CHP), the latter also produces electricity. Energy conversion is made by incineration or use of other energy source for heating water. Today there are 580 district heating networks in Sweden. Local heating is a kind of heating power plants, which supply a smaller area or property with heat. These types of plants are rapidly growing in number. There are 125 larger biomass power plants. Biofuel consists mainly of four main types of wood fuel: recycled wood, forest residue (branches and tops), bark and wood chips.

Energy efficiency could be increased with 3-5 GWh/year for an average heating plant of 145 GWh if the moisture content of wood fuel is determined directly, quickly and more reliably. The moisture content could be measured directly, quickly and more reliably, and thereby determined with a radar system within 60 seconds. Measurement can be carried out for the entire load in order to get a representative average value. Faster and more reliable moisture measurement leads to more efficient logistics and fuel management, which have been calculated to save 2-4 million SEK per year, if the following steps are made:

1. Measure and decide quickly when wood fuel is unloaded (dry, medium or wet pile)
2. Known moisture allows good mixture in day silo for more uniform moisture of wood fuel to the incinerator, which gives better incineration in heating plant
3. Accurate measurement offer correct billing
4. Measuring more automatic so less staff is needed at the measuring station
5. Avoid mixtures of dry and moist material in long term storage, which may lead to ignition
6. Keep better track of inventory to avoid that you only have wet fuel, which may lead to supplementary purchase of dry wood chips. In incinerator, the wood fuel shall have uniform moisture over time (see point 2), and
7. Have better logistics and more efficient management of fuel.

2 Material and methods

2.1 WOOD FUEL

Four different kinds of wood fuel have been examined. Forest residue (GROT, branches and tops) and bark are the most common wood fuels, while waste wood and cellulose chips are not used so frequently (Table 1). Cellulose chips (C-chips, is chipped heartwood) is a wood fuel that is actually used in pulp production, but the fuel is sometimes used to influence market prices for forest residues. Sometimes, cellulose chips are used at smaller plants and as dry fuel, if the stored fuel is too moist.

Wood fuel that has been used in the project has come from depots in Gävle Energi and BillerudKorsnäs in Gävle. Wood fuel was packaged by the same person to avoid variations in density (see Figure 1a-b). The purpose of this has been not to involve and analyze the density effect on moisture measurement.

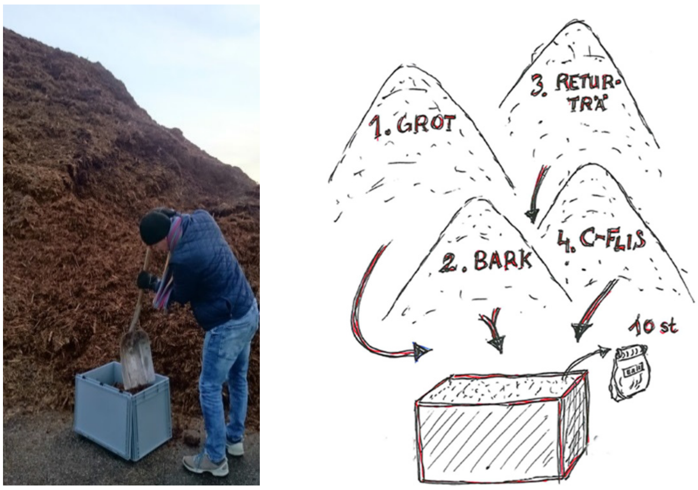

Figure 1. a) Packaging of wood fuel at Gävle Energi. b) Different kinds of fuel have been packaged in the sample boxes and then dried in paper bags or aluminum boxes.

Assortment	Heat, calculated value	Origin
GROT	10 TWh	Product from disforestation
Bark	12 TWh	Product from sawmill and paper mill
C-chips	25-30 TWh, whereof a smaller amount is used in heating plants	Product from sawmill
Waste wood	1.4 TWh	Residueal from recycling centers

Table 1. Estimation of the amount of wood fuel used in Sweden during one year.

2.2 WOOD, WATER, MOISTURE AND DIELECTRIC PROPERTIES

Wood consists mainly of cellulose, lignin, and hemicellulose molecules. Merged molecules form elementary fibers are called microfibrils. These microfibrils form the major structural components of the cell walls and play an important role in wood-humidity conditions (Reeb 2009). Water in timber exists in two forms: free water and bound water (Skaar 1988). Free water in contact with other materials is known as absorbed water (Metaxas and Meredith 1983).Free water is the liquid water and steam in cavities of wood cells. Bound water is part of the cell material and kept bonded between microfibrils by chemical compounds with other molecules or by physical adsorption (binding) to surfaces. Wood is hygroscopic, which means that dry wood and water attracted so strongly to each other that it is impossible to prevent moisture. The moisture content in wood (in form of bound water) tries to reach equilibrium with the relative humidity and temperature of the surrounding air. This means that it takes 0% relative humidity in the air to eliminate all bound water in the wood (Wood database 2015).

The water content is one key component of most biological materials (Komarov V., et al. 2005), (Brodie et al. 2014), (Duarte da Paz 2008). In general, higher water content leads to larger dielectric constant and loss factor. Free water has similar dielectric characteristics to liquid water, while bound water not exhibiting dielectric properties in GHz-area. Dielectric properties of the biomaterials are rapidly reduced with decreasing moisture content to a critical moisture level. Under this moisture level, reduction of the loss factor is only related to bound water and the biological material in itself.

Water affects microwaves (and vice versa) in an important way. Water consists namely of dipole molecules, which orients itself so that adjacent molecules turns their various-loaded sides against each other. The electric dipole in water is trying to continuously orient when exposed to electromagnetic radiation and its oscillating electric fields. Dipole movement is frequency dependent. Permittivity varies with frequency, temperature, orientation, pressure, substance mixtures and molecular structure (Meissner and Wentz 2004), (Chaplin, 2015).

2.3 DIGITAL RADAR

In the project, measurement of the moisture content of wood fuel was made with digital radar. Digital radar generates a unique pseudo code (PRBS code) to be transmitted, correlated and generating a radar signal. Antennas transmit at low power and measures usually within 1-10 meters depending on the measurement object and the surroundings. The radar consists of a transmitter and a receiver. It measures time-of-flight and attenuation. The radar generates a radar wave that either measure the distance to an object or between transmitter and receiver (Figure 2).

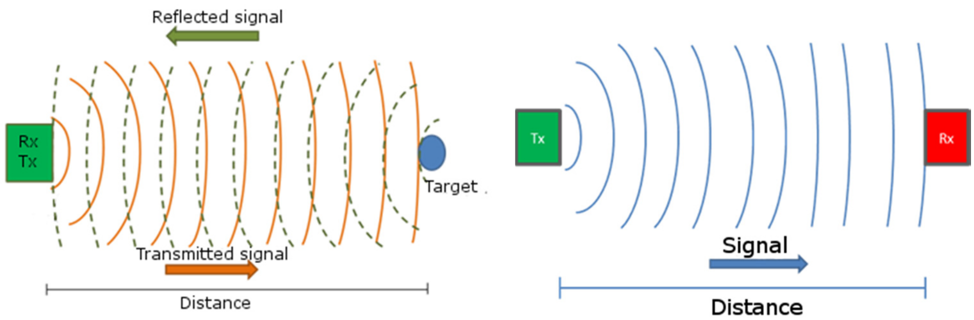

Figure 2. a) Transmitter transmits a wave that is reflected at the target, receiver receives the reflected wave. b) Transmitter transmits a wave that is received by the receiver.

The antennas are so-called Vivaldi antennas, and they are specifically designed to transmit and receive wideband signals. The antennas are designed for a center frequency of 2 GHz, with a frequency range of 1-3 GHz. The radar system has also been modified to operate in 0.75 GHz, with a frequency range of 0.375-1.125 GHz. In experiments, the same antenna has been used for all frequencies.

2.4 DIELECTRIC CONSTANT AND PERMITTIVITY

Permittivity is a quantity that indicatives a medium's ability to polarize under influence of an electric field. This corresponds to the capacitance of a dielectric medium (an electrical insulator that can be polarized by applying an electric field). Relative permittivity of a dielectric material is known as the dielectric constant and is denoted ε_r. Permittivity of a dielectric material (ω) is the permittivity of vacuum (ε_0):

$$\varepsilon_r(\omega) = \frac{\varepsilon(\omega)}{\varepsilon_0} \tag{1}$$

Refractive index (n) is the material property that describes the propagation of electromagnetic waves in a medium, *i.e.* the ratio of the speed of light (c), and the propagation speed in the medium (v). When a wave hits a medium with different refractive index, the speed is changed. This change of speed changes the direction of propagation. There is a relationship between the relative permittivity (ε_r) and refractive index. Relative permeability (μ_r) is the ability of a material to maintain the creation of a magnetic field in itself:

$$n = \frac{c}{v} = \sqrt{\varepsilon_r \mu_r} \tag{2}$$

Non-polar materials are not affected by frequency. However, when the polarization in a material can be changed, frequency must be taken into account when determining of the dielectric constant, permittivity and permeability. Polarization effect occurs when the electric field rotates molecules, ions, atoms and electrons, *i.e.* a physical mass movement. It is not trivial to determine the dielectric constant dependence of frequency. Therefore, a material relaxation time has to be determined. This is the time it takes for an electric field to return to its random equilibrium or the time needed for polarizing.

Loss factor corresponds to the dissipation of electromagnetic energy, such as heat. Besides permittivity and permeability (dielectric loss), the material's conductivity must sometimes be considered. But apart from the conductivity, dielectric constant can be expressed as a real part (ε') subtracted by an imaginary part (ε'', also called loss factor, *Lf*) where the ratio (δ) indicates the "loss":

$$\varepsilon_r = \varepsilon_r' - \varepsilon_r'' \tag{3}$$

$$tan\delta = \frac{\varepsilon_r''}{\varepsilon_r'} \tag{4}$$

Debye's equation explains the relationship between real and imaginary part of the dielectric constant (Equation 5, Figure 3). The equation says that the real part is almost equivalent to the measured dielectric constant at low frequencies (<1 GHz), while the measured dielectric constant decreases as one approaches the material's specific relaxation rate (for example, water is 22 GHz).

$$\varepsilon(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau} \tag{5}$$

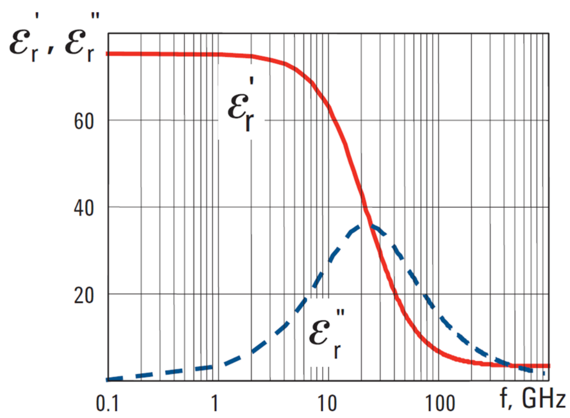

Figure 3. Debye's relaxation for water at +30°C (Chaplin 2015).

2.5 MEASUREMENT OF THE DIELECTRIC CONSTANT

Free space method (measuring through a material or medium) is suitable when measuring the dielectric constant (Figure 4). This works well for a wideband system, for high frequencies and gives high accuracy (Agilent 2014), (Venkatesh and Raghavan 2005). According to Debye's equation, real dielectric constant (ε_r) is higher than the measured (ε_r') , because the loss factor (ε_r'') grows vigorously at high frequencies (> 1 GHz).

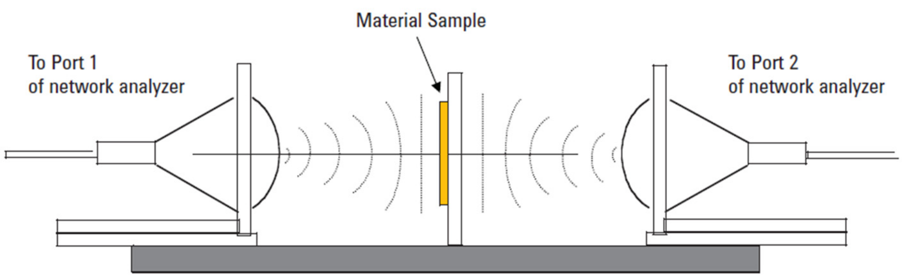

Figure 4. Free space method for determination of the dielectric constant (Agilent 2014).

2.6 RELATION TO GEOSCIENCE

Geoscience uses ground-penetrating radar, which has many similarities with Radarbolaget's radar, which has been used in the project. Ground-penetrating radar is often ultra wideband (UWB) radar, similar to Radarbolaget's radar. Topp-function is often used for the determination of moisture content in soil (Topp et al. 1980). If the dielectric constant is measured and determined, the moisture content can be calculated according to following equation:

$$\Lambda = -5{,}3 \cdot 10^{-2} + 2{,}92 \cdot 10^{-2} \cdot \varepsilon_a - 5{,}5 \cdot 10^{-4} \cdot \varepsilon_a^2 + 4{,}3 \cdot 10^{-6} \cdot \varepsilon_a^3 \qquad (6)$$

2.7 DRYING AND REFERENCE MEASUREMENT

Determination of moisture content in wood fuel is usually done by sampling (statistical sample), *i.e.* parts of the total population (entire load or test box) are investigated.

Reference determination of moisture content is made by drying the wood fuel in a drying cabinet at +103 ± 2 °. The process consists of the following steps:

- Moisture weight is measured
- Drying is done in 1-2 days
- Dry weight is measured
- Compensation is made for the test box/paper bag weight, and
- Calculation of dry and moisture content.

The project has used both sampling and drying of all content. The project has had following requirements:

- Measure and linking moisture to radar measurement
- Analyze frozen material and lumps of snow
- Measure over long distances
- Do frequency analyzes, and
- Measure the different kinds of wood fuel.

3 Results

3.1 TEMPERATE WOOD FUEL

The hypothesis was that wood fuel for measurements at longer distances (2.5 meters) is considered as homogeneous as the material will be distributed stochastically over this distance. Four different wood fuels have been investigated: forest residues (GROT), bark, recycled wood and wood chips. There has not been any separate modeling of these. However, we suspect that a small difference can exist between the various fuels, such as how free water fills the wood cells. Bark consists of another type of cells (cork cells) than the heartwood, which consists of parenchymal cells. The heartwood also consists of extractives such as resin, fats and phenols. It requires, however, more data for verifying whether there are differences between different wood fuels. No account has been taken to the temperature when modeling data.

Radar measurements are made on two kinds of sample boxes: 30 liters/25 cm and 88 liters/40 cm. Initially, the content of whole boxes (16 pieces) was dried for determining the moisture content. Since drying of 88 liter of wood fuel was very time consuming, the project determined that the reference measurements should be carried out as sampling. Samples were taken from the center of the box to correspond to the radar measurement.

A least squares fit of second degree polynomial is made from moisture and dielectric constant determinations (black line, Figure 5). We have also tried to make a logarithmic adaptation of the dielectric constant and moisture content (red line, Figure 5). The differences between a logarithmic formula and a second degree polynomial are small. However, it is easier to adjust minimum and maximum values using a logarithmic formula. A least square fit of the Topp-function is made from measured values (green line, Figure 5). No measurements were made on wood fuels with moisture content over 70%, so the correspondences between the measured values and a modified Topp-function cannot completely be confirmed. Most likely, Topp-function has a steep slope after the saddle point at 60% up to 100% humidity. However, it is unusual to have moisture levels above 70% for wood fuel.

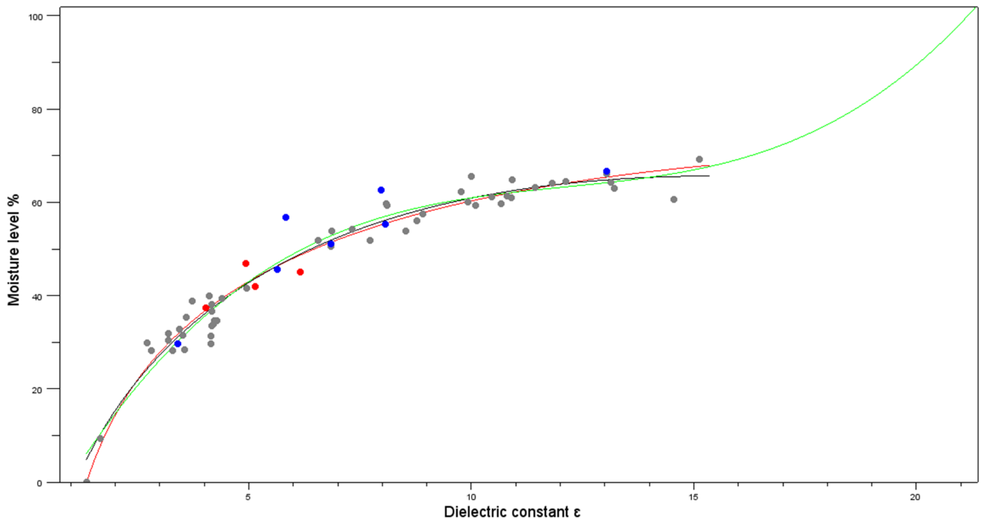

Figure 5. Modelling of dielectric constant and moisture. Red=logarithmic. Black=second degree polynomial. Green=Topp-function.

3.2 FROZEN WOOD FUEL

The hypothesis from the start of the project was that there were no differences between temperate and frozen material. But the differences between temperate and frozen wood fuel was big for the center frequency of 2 GHz at -18°C (compare Figures 5 and 6). Frozen material has a steeper curve than temperate wood fuel. The disadvantage of a steep curve is that the resolution and accuracy decreases. To some extent this can be compensated since the radar signal looks better and is less deformed when penetrating frozen material. A conclusion is that the temperature measurement is required when modeling frozen material; otherwise it can be mixed with dry temperate wood fuel.

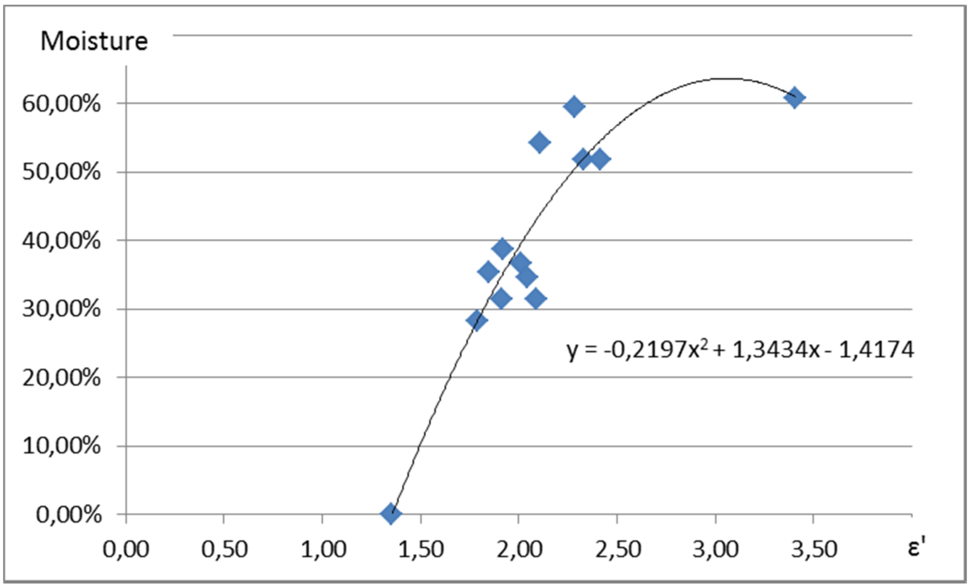

Figure 6. Modeling of dielectric constant and moisture of frozen wood fuel.

Deeper insight and understanding of the differences between temperate and frozen wood fuel was needed. Therefore, simulation of microwaves in ice, snow and water for different temperatures and frequencies were carried out. The modeling showed that there was big differences between 0,75 GHz and 2 GHz in terms of dielectric constant and loss factor for liquid water. For ice and snow, there was no frequency dependence in the GHz-range. Since moist wood fuel probably behaves like water, ice and snow, the project decided to modify the radar system and enable measurements of 0.75 GHz, and to carry out measurements on wood fuel at different temperatures. Two boxes with wood chips of different moisture were equipped with thermometers (Figure 7a). The temperature was variated from +23°C to -18°C. The boxes were scanned with the radar system in 0.75 GHz (Figure 7b).


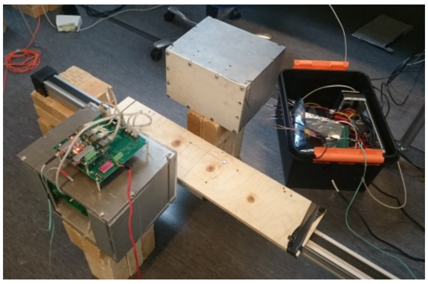

Figure 7. a) Boxes with thermometers. b) Radar scanning of boxes.

Measurements were made of the attenuation (dB) and the dielectric constant with the radar system (Figure 7b). Attenuation measurement was possible due to a modification of the radar system (Figure 8). The "drier" fuel has higher attenuation and dielectric constant than the "moister" at freezing temperatures. The most likely cause is that the density of the wood (exclusively wood) affects the dielectric constant. The dielectric constant was also measured after drying ("drier", ε = 1.31 and "moister ", ε = 1.26), and it shows that the "drier" fuel had a higher density (exclusively wood) than the "drier". The weights were 4 488 grams for the "drier" sample respectively 3 394 grams for the "moister" sample.

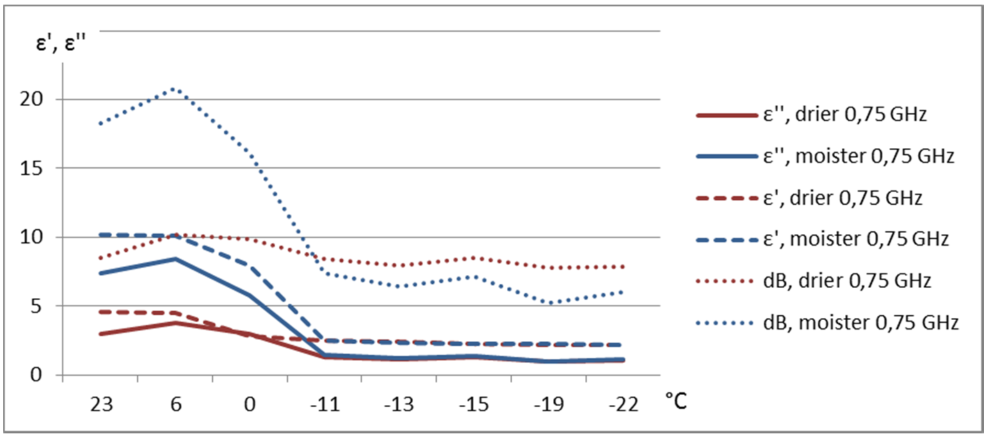

Figure 8. Dielectric constant, attenuation and loss factor at different temperatures and moistures.

3.3 FREQUENCY ANALYSIS

Fast Fourier Transform (FFT) can be used to investigate the frequency domain of radar signals, originally obtained in the time domain. Figure 9a-h shows frequency spectra (0-1.5 GHz) for radar signals that have been the basis for the determination of the dielectric constants in Figure 8. In Figure 9a-c it is possible to see how the high frequencies are heavily attenuated, which causes the loss factor becoming greater for moist wood fuel than for drier wood. At -11 ° C and lower (Figure 9d-h), it is less attenuation in moist wood fuel than in the dry. These figures clearly show that the attenuation of ice and snow has to be almost zero.

At -13° C, measurements with two different frequencies were performed: 0.75 and 2 GHz. These measurements show that the material in the box is affected by the frequency. Only the frozen water should not have made any difference, but moist wood fuel affects microwaves by:

- Dielectric constant: 2.49 (2 GHz), 2.35 (0.75 GHz)
- Loss factor: 0.79 (2 GHz), 1.25 (0.75 GHz), and
- Attenuation: 10.49 dB (2 GHz), 6.41 dB (0.75 GHz).

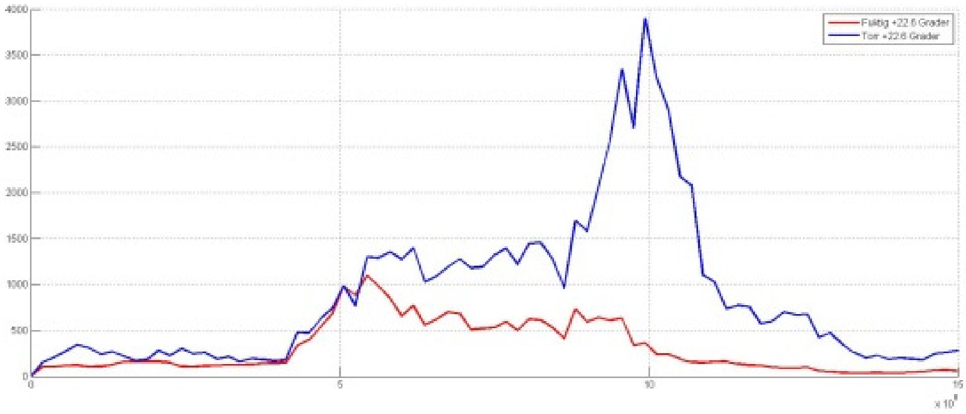

Figure 9. a) Frequency spectrum at +23°C with 0-1.5 GHz.

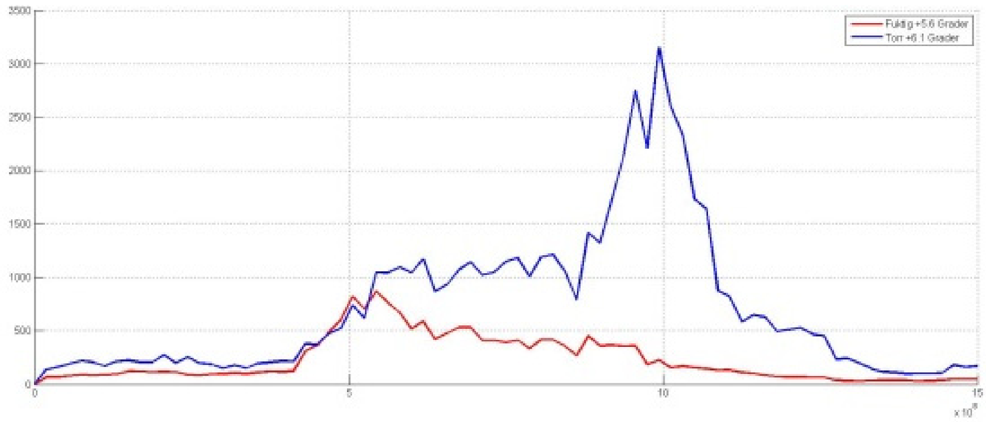

Figure 9. b) Frequency spectrum at +6°C with 0-1.5 GHz.

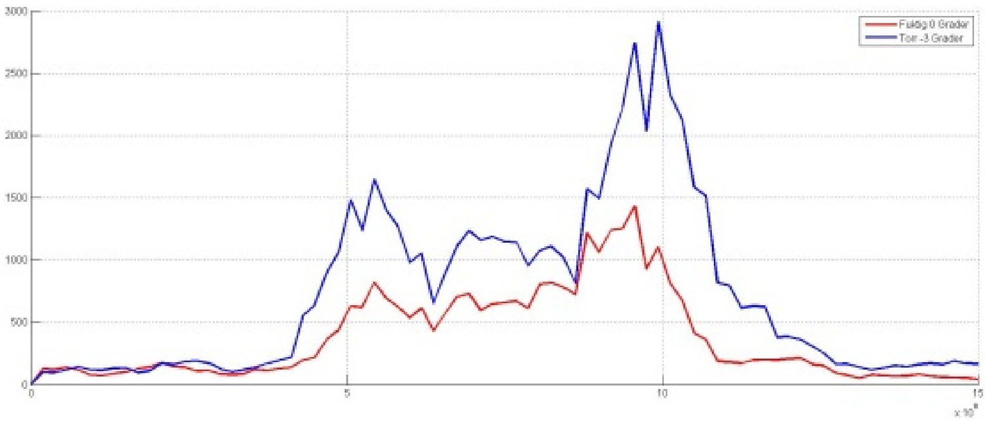

Figure 9. c) Frequency spectrum at 0°C with 0-1.5 GHz.

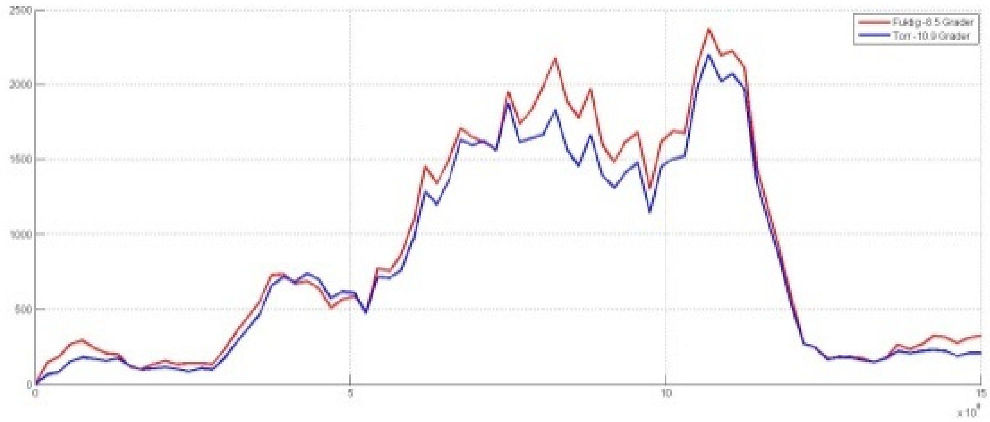

Figure 9. d) Frequency spectrum at -11°C with 0-1.5 GHz.

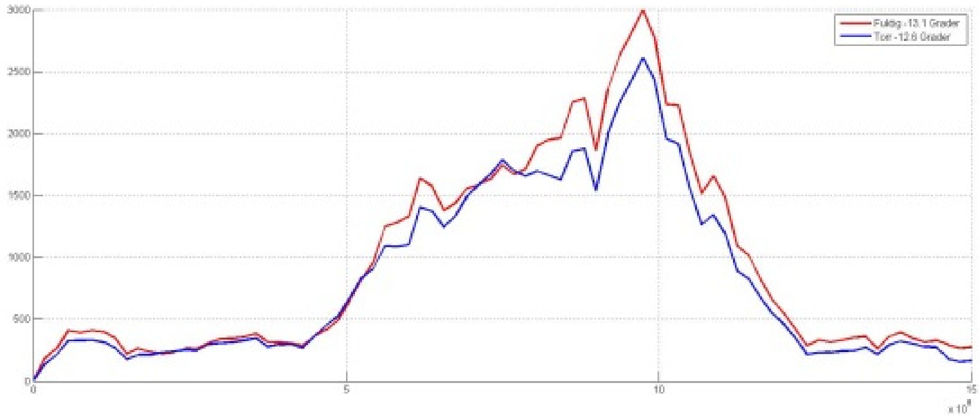

Figure 9. e) Frequency spectrum at -13°C with 0-1.5 GHz.

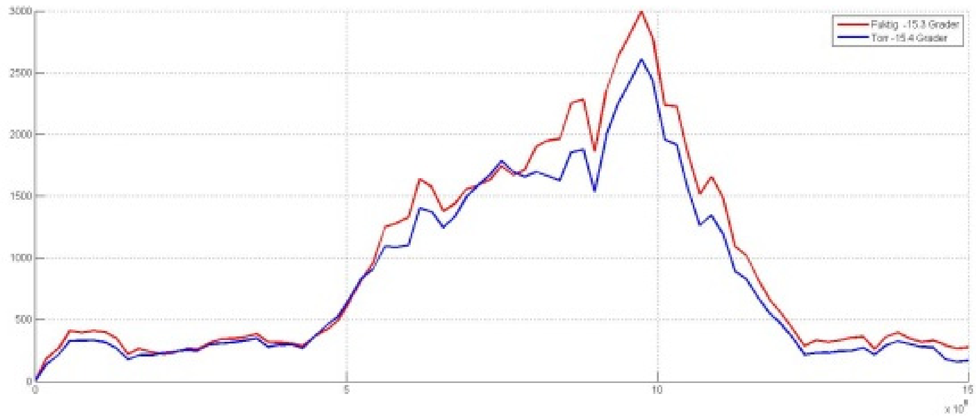

Figure 9. f) Frequency spectrum at -15°C with 0-1.5 GHz.

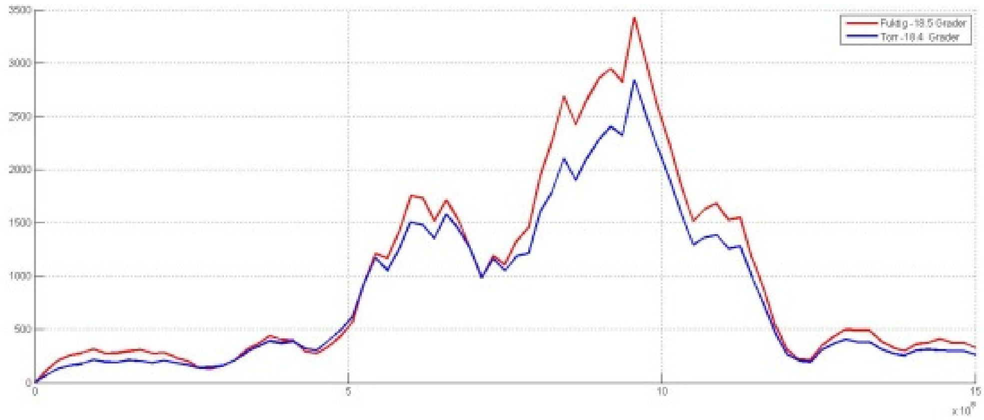

Figure 9. g) Frequency spectrum at -18°C with 0-1.5 GHz.

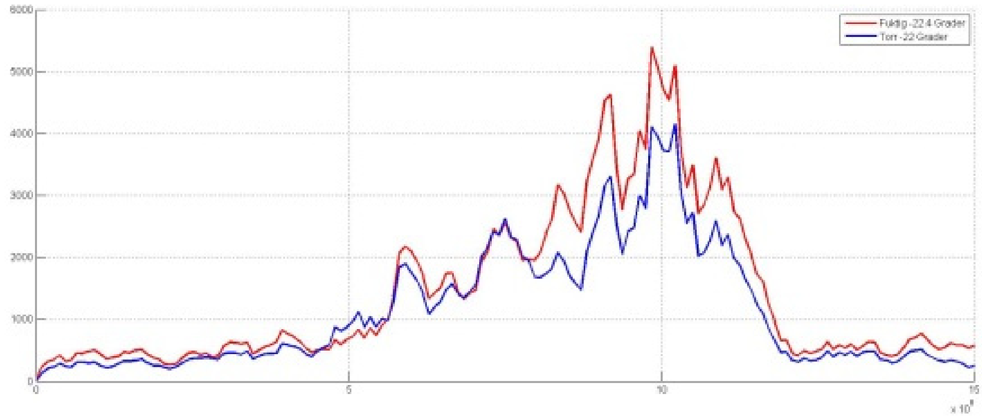

Figure 9. h) Frequency spectrum at -22°C with 0-1.5 GHz.

3.4 LUMP OF SNOW

Wood fuel was frozen down to -18° C. Thereafter, the material was put into a test box together with a lump of snow (Figure 10). Would the lump of snow be seen or affect the measurements? Measurement was carried out by scanning the test box with frozen and temperate moist wood fuel, and temperate dried wood fuel as well (Figure 10). It can be seen that the permittivity varies greatly between frozen and temperate wood fuel, a factor of 4-5. According to simulation, frozen wood fuel has a dielectric constant below 3, which we also measured. The lump of snow is not visible in the frozen state, which was expected. However it is possible to distinguish an increased dielectric constant when the measurement was made at +15° C, which depends on increasing moisture content in one side of the box. The lump of snow has simply melt.

Figure 10. a) Test box with frozen GROT (-18°C) and lump of snow.

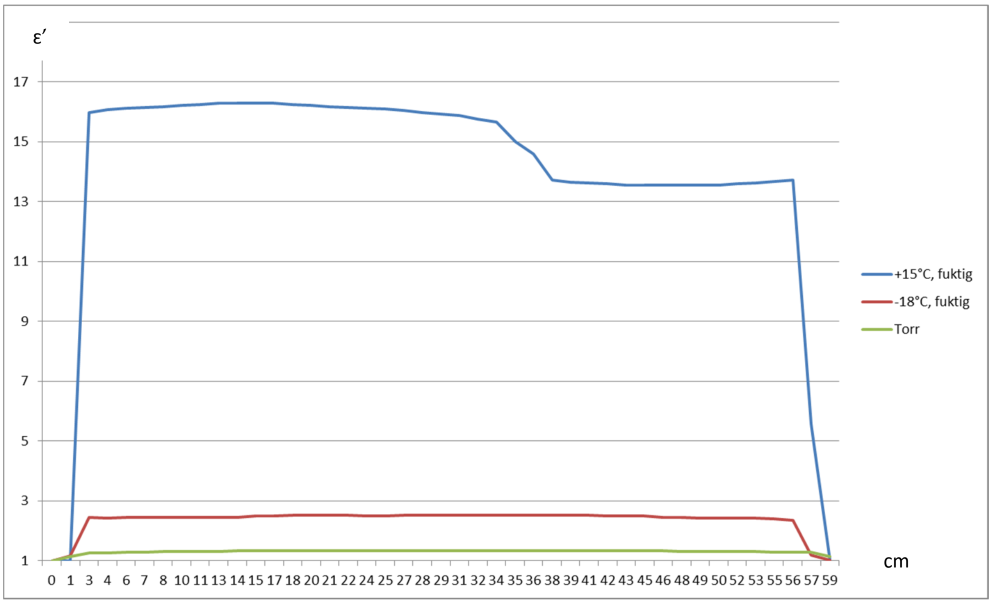

Figure 10. b) Dielectric constants of moist and dried wood fuel at different temperatures with lump of snow. X-axis is scanned area in centimeters.

3.5 LONG DISTANCE

Measurements were made on big test boxes and long distance (Figure 11a). The radar had a center frequency of 0.75 GHz. In this measurement, it was interesting to examine the signal's appearance. Four different distances were measured: 1 m, 1.2 m, 2.2 m and 2.4 m. The challenges in measuring at long distances are to achieve high signal-to-noise ratio (SNR) and low attenuation (high amplitudes). The measured amplitudes were least squared fitted to a polynomial (Figure 11b). It can be seen that SNR is good enough for measurement over long distances. Amplitudes may also be examined for the four signals in Figure 12.

Figure 11. a) Two test boxes of 800 liters and 120x100 cm. Two boxes in a row are 240 cm.

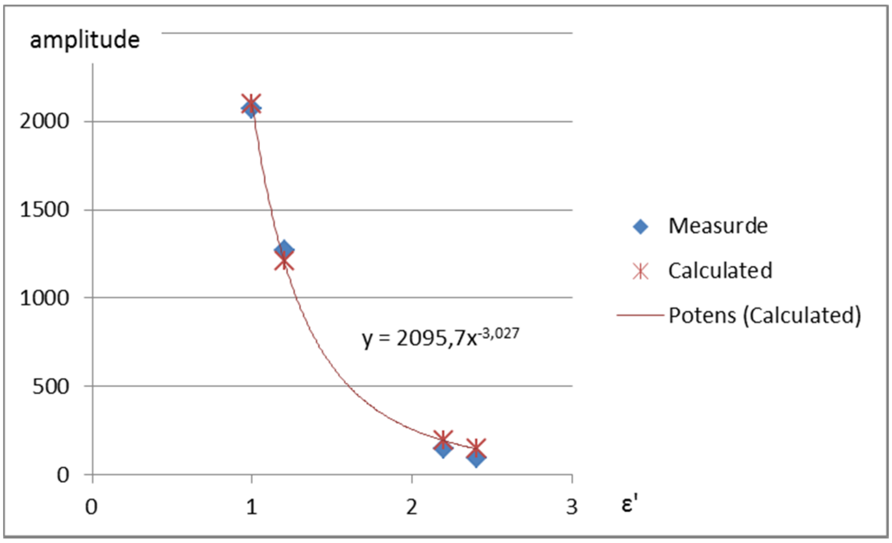

Figure 11. b) Measured amplitudes (blue) and least squared fit amplitudes (red).

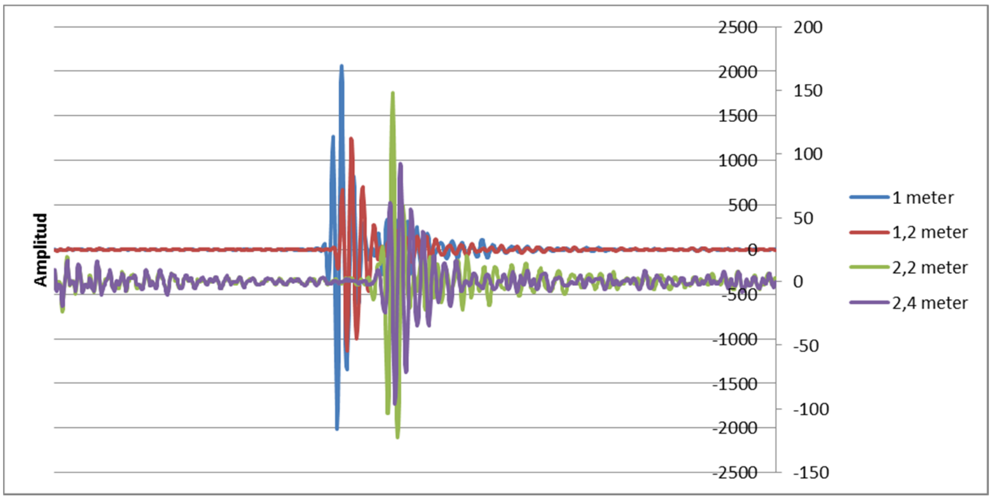

Figure 12. Radar signals for four distances.

4 Conclusions

4.1 REFERENCE METHOD

Reference measurement by drying is an uncertain method (see SIS-CEN / TS 15414-1: 2008 (E)) partly because the dried wood fuel adjust to the relative moisture content in air at every drying occasion. This must be taken into account in future measurements, for example in an upcoming project. Relative humidity of surrounding air may vary by 50 percentage points over one day. The so-called equilibrium moisture (EMC) of wood can be estimated with Hailwood-Horrobin equation in figure 13 (EMC 2015). From the figure, it can be noted that high temperatures (120 ° C) reduces EMC, but under unfavorable conditions (high humidity), EMC can reach 10-15%, which is the remaining moisture in the wood fuel.

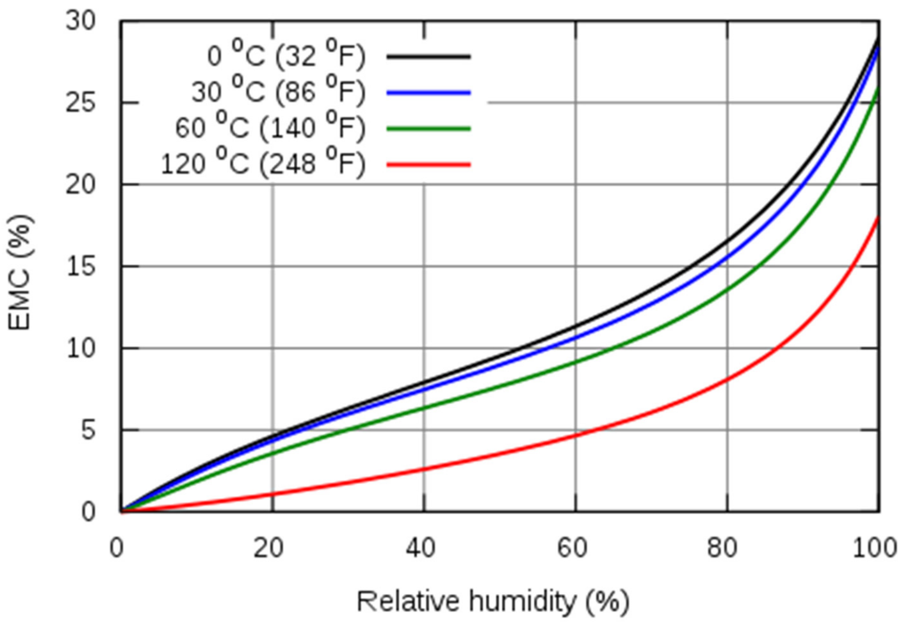

Figure 13. Equilibrium moisture content (EMC) in wood in relation to temperature and humidity.

4.2 FREQUENCY AND TEMPERATE MATERIAL

The project planned to make measurements at different frequencies. Radarbolaget's radar is normally operating with a center frequency of 2 GHz, a frequency that is suitable for the steel industry, where the company normally uses its equipment. Frequency analysis was done with a network analyzer and with FFT. These measurements shown that a center frequency of approximately 0.75 GHz were preferred when measuring moist temperate wood fuel (>0° C). It is always a balancing act to find a suitable frequency. Selected frequency of 0.75 GHz makes it easier to penetrate damp wood fuel with a robust signal and is affected by humidity and water so that dielectric constant and attenuation can be measured with high resolution.

4.3 FROZEN MATERIAL

Frozen wood fuel and microwaves were shown to be a bigger challenge than expected. There shall be no frequency dependence in the measurement of pure ice and snow. Measurements at different frequencies (2 and 0.75 GHz) on wood fuel show differences. It is unclear whether low (0.75 GHz) or high (2 GHz) frequencies is preferable for the measurement of frozen material. Frozen material seems to be more affected at high frequencies.

Dielectric constant and attenuation are much lower (4-5 times) of frozen material than for temperate moist wood fuel (>0° C). This means that the temperature must be measured and modeled to obtain the correct moisture content at freezing temperatures, but it also leads to lower measurement resolution. Measuring at long distance (the width of a wood chip trucks) will increase the resolution and accuracy. In principle, double distance gives double resolution and accuracy. Measurements on frozen wood fuel were made on a test box of 30 cm, which means about 8 times higher potential accuracy of real wood chip trucks (240 cm). Even additional modeling of attenuation and density will increase the possibility of correct moisture content determination.

4.4 ACCURACY

The accuracy of the modeling of moist temperate wood fuel can be made with $\sigma \approx 3$ percentage points. Thus, the project goal has been achieved. This accuracy will be even higher if:

- Reference measurement shall be done in a better way (consideration must be taken to relative moisture content in air and how it affects the moisture content of wood fuel)
- Measurement is performed at long distances (increases accuracy)
- Additional calibration measurements are made
- Separate modeling and wood fuel are made
- Debye’s relaxation formula can be formulated and modeled
- Attenuation is measured and included
- Temperature can be measured and modeled, and
- Density can be measured and modeled.

In addition, it should also be noted that high levels of ash (salts) may affect the measurements and accuracy. However, it is doubtful whether it is possible to do something about the variations of the ash content.

4.5 HOW CLOSE TO OBJECTIVES?

The overall objective was to measure the moisture content of wood fuel directly on a truck with a 2-3 percentage point accuracy, which is achieved by the project. Current laws stipulate, however, higher accuracy. To reach these legal requirements, the required accuracy must be 1 percentage point higher, which should be possible in accordance with the above accuracy action points. Measurements of the dielectric constant gives the moisture content also for frozen material (which is not possible with attenuation measurements), but it is a challenge to determine the moisture content according to legal requirements. Advanced data mining and data modeling is a possible way to achieve high accuracy for frozen wood fuel. Long distance measurements (whole truck's width) work well and will also increase the accuracy of measurements.

5 Discussion and future

5.1 OTHER SCIENTIFIC WORK

Jenny Nyström (Nyström 2006) and Ana Paz (Paz 2010) are two of few who thoroughly researched water, moisture and wood fuel. Their results are broadly consistent with the results of Radarbolaget, even if the methods are not entirely the same. Nyström uses a network analyzer and reflective measurement in a container for determining the dielectric constant. Radarbolaget used transmission measurement on test boxes to mimic intended direct measurements on wood chip trucks. Nyström has shown that it is possible to achieve an accuracy of 2.7 percentage points and Radarbolaget 3 percentage points, which is relatively comparable.

The great challenge is to find a method that can be implemented on real heating plants, which Nyström also has raised. This has been Radarbolaget's focus throughout the project. The only conflict between Nyström and Radarbolaget is measurements in different temperatures. Nyström mentions that the temperature and density is affected by radio waves, which is quite true, but even so her measurements were not affected by the temperature. After a telephone conversation with Nyström, it was exposed that she had not focused on frozen material, and therefore she did not do detailed analysis. Nyström has measured on frozen material when it was delivered, but it was done in a small test chamber (why the material can be melted), with lower frequencies and reflective measurements.

Radarbolaget has clearly demonstrated that temperature affects permittivity and attenuation. This must definitely be taken into consideration since a large amount of wood fuel is supplied in frozen form during the winter. Radarbolaget has taken Nyström work further but also addressed implementation issues and challenges that are linked to this particular research area (long distance, measured directly on the wood chip trucks, frozen materials and lumps of snow).

5.2 FUTURE VISION

The project's objective has been to develop the relationship between the dielectric constant and moisture content of the temperate wood fuel. It has emerged that the temperature and density must be measured and included in the models to determine the moisture content with high accuracy. In the current state, wood fuel trucks are measured at weighbridges (before and after unloading). It would be simple to roll off the tarpaulin at the top of the lorry. It can be done from inside the cab (Figure 14). Thereafter the temperature can be measured by infrared meter while the radar system measures height, width, dielectric constant and attenuation (Figure 14b). Data mining (analysis of the amount of data) that can be made are:

- Height and width gives volume
- Volume and weight gives the density and the indication of the moisture content, which simplifies decision analysis of frozen materials
- Width measurement improves the determination of the permittivity and attenuation, and

- Measurement of dielectric constant and attenuation at different heights, and sideways gives better average moisture and density determination.

Figure 14. a) Unrolled tarpaulin for Eksjövagnen. b) Vision for measurement and data mining

5.3 PROPOSAL OF FORTHCOMING PROJECT

This project was a feasibility study with a goal to identifying opportunities, challenges and "showstoppers" related to nondestructive measurement of wood fuel by radar. The project has not found any "showstoppers". The great challenge is to model the moisture content of wood fuel at different temperatures, especially in freezing temperatures. This project has run in parallel with other projects and further development of Radarbolaget's radar. Therefore, non-destructive measurement of wood fuel by radar offered the possibility to complement the measurements of the dielectric constant measurement with attenuation and a system with higher dynamics, and thereby improving radar signals and provide greater accuracy.

Involved project partners suggest the results given that a prototype projects are planned and started. During the project period, a new law on timber measurement has been valid. If accuracy figures will be improved with 1 percentage point, radar can be used to match the requirements of the new law. Frozen material has to be separately considered. Therefore, a future radio and radar-based measurement system can be used, in addition to better logistics and incineration, as part of a billing system to ensure the correct payment.

A prototype project outcome would contribute to greater efficiency in the wood fuel heaters with 0,2-0,3% by reliable moisture determination of wood fuel, and contribute to more efficient logistics and fuel management. The project would aim to develop a prototype for fast and accurate determination of the moisture content of the wood fuel (wood chips and bark). The objectives of the project would be to the measurement method:

- is harmless, non-destructive and non-contact
- working outdoors and be able to measure by a truck filled with wood fuel
- determines moisture content of wood fuel with <2 percentage points accuracy, and
- works on wood fuel from -10° C to +50° C.

Projects can be broken down into the following project components:

- Ensure a reference method that gives reliable reference measures

- Development of a model and carry out additional measurements including attenuation measurements using wood fuel for frozen material, and different temperatures and densities
- Designing and manufacturing a measuring device that measures the dielectric constant, attenuation, volume and temperature in real environment
- Connect the measurement data (weight, temperature, dielectric constant, attenuation, wood fuel type, volume, etc.), calculate and store data
- Conducting actual tests on wood chip trucks, data analysis and improvement, and
- Project management, project, final report and reporting.

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QUICK MOISTURE MEASUREMENT OF WOOD FUEL WITH RADAR TECHNOLOGY

Today, determination of moisture content by drying wood fuel in dryer cabinets is tedious, costly and time-consuming, which leads to that wood fuels with different moisture content are mixed. Alternative methods of infrared and X-rays are not extensively used for wood fuel deliveries by truck. The three existing methods are based on sampling, which is time consuming and can cause poor accuracy in the determination of moisture content.

Radio and radar measurement technology is a non-contact, non-destructive and harmless measurement method that can be used directly by averaging measurement of incoming trucks. The measurement can be done through trucks with fiberglass sides or reflecting on trucks with steel bottom.

The benefit of direct measurement is that wood fuel can be directly ordered by moisture, which leads to improved logistics, fair billing, and more optimized incineration, and reduce the risk of spontaneous ignition of the fuel piles as well.

Another step forward in Swedish energy research

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