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Modeling the electromagnetic wave propagation through crop material in harvesters

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To lay out an ultra-wide band (uwb) microwave sensor system for inline determination of moisture and feed rate in forage harvesters during harvest process, engineers need to identify the optimal specification and configuration of the system, e.g. regarding spectral range and spectral resolution. For a better understanding of the complex interactions of electromagnetic wave propagation in the crop channel of harvesters, a simplified model for estimating the permittivity of the crop material was derived from literature capable to model the effects of disturbing parameters like density and temperature, mainly affected by water. Utilizing the transfer-matrix method, the sensor system was modeled in a transmission configuration and validated based on lab test data. A sufficient match of the results is demonstrated. That enables to investigate, understand, and consider sensor setups and influences of varied main parameters with that model.

Keywords
Forage, microwave, moisture content, dry matter content, feed rate, harvester, permittivity of plant material, volumetric mixture model, transfer matrix method

One of the main quality parameters of fresh harvested crop is its moisture content (mc), here in agricultural context, the percentage of weight of water in the plant material or the reciprocal: the dry matter content (dmc), which describes the value giving material fraction of the crop,

$$mc = \frac{m_w}{m_w + m_{dm}} \cdot 100\ \% \qquad \text{(Eq. 1)}$$

$$dmc = \frac{m_{dm}}{m_w + m_{dm}} \cdot 1000\ g\ kg^{-1} \qquad \text{(Eq. 2)}$$

calculated out of the mass of water m_w and the mass of dry matter m_{dm} in a material sample (other moisture definitions utilize the volumetric proportion, like in soil sciences or the moisture is based on dry material, like in the timber branch).

Because of the strong non-polar structure of the water molecule and the special features of the hydrogen bond between the molecules in fluid water, water shows extravagant characteristics in the entire electromagnetic spectrum (Hübner and Kaatze 2016).

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Especially fresh forage processed by a forage harvester is challenging for determining moisture because of the wide spread of total amount of water not only for electromagnetic measuring principles. Nevertheless, electromagnetic signals are affected additionally by the variance of the dielectric properties of crop and also its variable particle size and shape. Because of high moisture content, the total mass or feed rate of the crop can’t be evaluated without the knowledge of its moisture. That is why operators and farm managers are interested in both: moisture and mass (feed rate).

Current moisture sensors at (self-propelled) forage harvesters (SPFH) do not fulfil all requirements regarding accuracy, as if conductance sensors or costs. The currently employed near-infrared spectrometers are expensive (and will remain, because of the requirement of precise optical components in the sensor) and are maintenance-intensive (because of the permanent calibration process).

Mass-flow rate sensing systems in SPFH base on measuring the volume intake of material (Ehlert 2002). An exact value for the density is required to calculate the mass from volume measurements. However, depending on changing conditions and compaction characteristics of the material and its amount the density in the intake system varies permanently. This system requires frequent calibration, which increases costs while disrupting the harvesting process or requiring expensive automated systems with weighing trailers. Other principles were not transferred into production because of missing accuracy within all conditions and crops.

Because of the wave propagation is not only affected by water but by dry matter too. Electromagnetic waves transferred through and/or reflected by crop material contain information regarding the total amount of harvested crop and its total water content.

The ultra-wide-band regulations (uwb) and new cost-efficient electronic components for higher frequencies offer the possibility to establish a sensor system based on multi-parameter measurement at a wide spread of frequencies to overcome current drawbacks of electrical moisture sensors for forage harvesters, to extract information regarding mc and total amount of crop while eliminate disturbing effects.

For developing a sensor, the physical system needs to be circumscribed first to identify optimal technical parameters for best measuring results with acceptable costs. Therefore, in this paper a simple approach is utilized, describing plan wave propagation through a mixture of crop matrix material, air and water in the spout of a forage harvester.

Mixing Model

Dielectrical properties: permittivity

Dielectrical constant ε' and dielectrical loss ε'' form the complex permittivity, that describes the propagation of an electromagnetic wave through a nonmagnetic material continuum (Nyfors 2000, Sihvola 2000).

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r'' \quad \text{(Eq. 3)}$$

The relative permittivity ε_r is related to absolute permittivity by the permittivity of vacuum ε0:

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} \quad \text{(Eq. 4)}$$

Dielectric constant ε_r' comprises the energy storage, *j* is the square root of -1, and ε_r'' is the imaginary part, or loss factor, describing the energy dissipation (Ulaby and Jedlicka 1984). According to literature, in the following ε_r is replaced by ε and stands for relative permittivity in the paper.

Plant material

The most important two crops processed by forage harvesters are whole plant maize (corn silage) and wilted grass. The maize plant is cut in the field in a vital stadium; the grass dries several hours at the grassland before it is chopped and conveyed onto a transport vehicle by the harvester. Plant material consists of countless different organic molecules that can be assigned to the main groups: carbohydrate, proteins, cellulose (hemicellulose) and fat, inorganic material like minerals and water (Figure 1). Water is the non-organic constituent, mc varies most: from 15 % (and below) for storable crops like straw and hay up to 85 % for fresh grass.

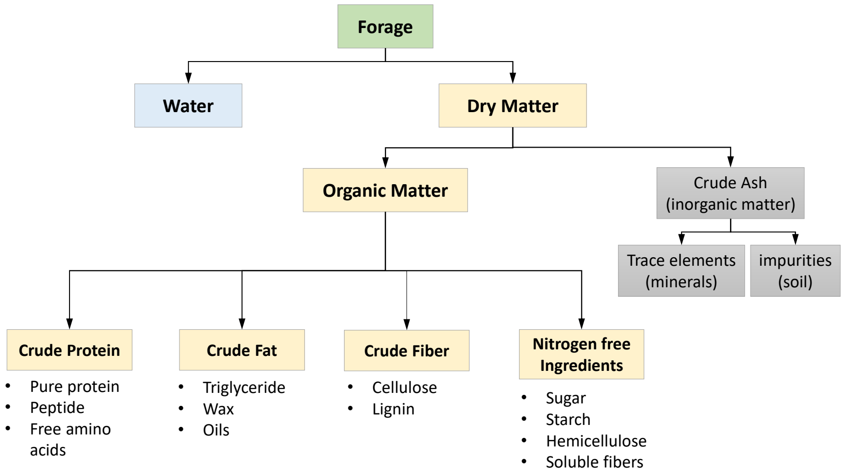

Figure 1: Composition of forage material

Table 1 shows the typical quantitative variability of composition for the main crops harvested by SPFH.

Table 1: Constituents of plant material for silage production at the time of harvest (Bernhardt et al. 2006)

Constituent	Maize plant	Wilted grass
Water (% on wet base)	45 .. 75	30 .. 75
Starch/sugar (% in dm)	23.5 .. 41.6 (starch)	3 .. 8 (sugar)
Crude protein (% in dm)	5.9 .. 8.5	<17
Fibers (% in dm)	17 .. 20	22 .. 25
Crude fat/oil (% in dm)	2.7 .. 4.4	-
Ash (% in dm)	2.6 .. 4.8	< 10

dm = dry matter

The relative dielectric permittivity of bulk vegetation material, (containing no water) rarely exceeds 5 and typically is around 1.5 to 3, depending on the amount of air contained in the material (Ulaby and Jedlicka 1984). Carlson (1967) determined dielectrical constants ε' from ca. 4 to 20 and loss ε'' from ca. 1 to 5 for moisture content from 10 to 60 % respectively for cut corn leafs and comparable numbers for grass leafs utilizing waveguide resonator at 8.5 GHz. He introduced a linear regression model for relative permittivity ε_{mix} of vegetation bulk material as a mixture of plant material, water and air:

$$\varepsilon_{mix} = 1.5 + (\varepsilon'_w - j\varepsilon''_w) \cdot mc \qquad \text{(Eq. 5)}$$

where $\varepsilon'_w - j\varepsilon''_w$ is the permittivity of water.

Tan (1981) published consistent values for 9.5 GHz for casuarina, rubber leaf, rubber wood and tested several mixing formulas to regress his data. Because all these values depend on experimental design respectively, especially on the volume fraction of crop in the crop-air-mixture resulting from compaction and because they do not span the expected range of temperature and mc, we have planned to predict the dielectric properties of the crop material in a forage harvester from a mixture of individual constituents.

There were less data for dielectrical constant, and loss found in literature for pure constituents (absolute dry) for all of the components mentioned. Data of constituents in Table 2, containing a remaining fraction of water, show small variation in contrast to water. The influence of the variance in permittivity of plant matrix material can be neglected at the current stage of system modeling. Later it can be considered as a disturbing parameter for variance analysis by stochastically variation.

Table 2: Dielectrical constant *ε'* and dielectrical *ε''* loss of plant materials (averaged values from literature)

Plant material	ε'	ε''
Dry vegetation material[1)]	3 (8 GHz)	0
Dry vegetation material[2)]	1.5 .. 2.0 (0.5 .. 20 GHz)	≤ 0.1
Wood cellulose at 20 °C[3)] perpendicular with fiber	3.8 (1 GHz) .. 3,6 (10 GHz)	0.19 (1 GHz) .. 0.169 (10 GHz)
Wood cellulose at 20 °C[3)] parallel with fiber	4.1 (1 GHz) .. 3,9 (10 GHz)	-
Cellulose-based paper[4)]	3.3 (1 GHz) .. 2.9 (7.5 GHz)	0.165 (1 GHz) .. 0.183 (7.5 GHz)
Cell wall substance at 20 °C[3)]	3.5 (1 GHz) .. 3,3 (10 GHz)	0.175 (1 GHz) .. 0.142 (10 GHz)
Starch at 30 °C[6)]	1.25 .. 2,81 (2.45 GHz)	0.0 .. 0.43 (2.45 GHz)
Vegetable oils at 30 °C[6)]	3.1 (0.4 GHz)	

[1)] (Ulaby and Jedlicka 1984) [2)] (El-Rayes and Ulaby 1987) [3)] (Torgovnikov 1993) [4)] (Kim et al. 2018) [5)] (Ndife 1998)
[6)] (Pecovska-Gjorgjevich et al. 2012)

Electromagnetic waves propagate in space, that means in the volume of the respective material. For known composition of crop samples, the volume occupied by the pure material can be calculated using the density of pure materials.

For rough design of the sensor system, a mean value of 1,500 kg/m³ was assumed for pure density of typical plant material as an acceptable average (examples for materials see Table 3). A mean dry matter bulk density of 80 kg/m³ was obtained during tests runs for chopped material.

Table 3: Pure density of plant materials

Material	pure density ρ in kg/m³
Corn seeds[1)]	1,300
Short wheat straw[1)]	1,351
Wheat chaff[1)]	1,535
Hard wood[2)]	1,460 .. 1,548
Cell wall cellulose[3)]	1,550

[1)] (Freye 1980) [2)] (Stamm 1929) [3)](Bosshard 2013)

Water

Since the permittivity of plant material is strongly influenced by the dielectric constant of its water component, and since the dielectric constant of water is temperature and frequency dependent, the dielectric constant of the mixture is likely to be dependent also.

Salinity

Generally, a medium is said to be a good (lossless or perfect) dielectric if the loss tangent is very small. This means $\sigma \ll \omega\varepsilon$ (where σ is the conductivity). On the other hand, the material is considered as a good conductor if the loss tangent value is very large ($\sigma \gg \omega\varepsilon$), (Zahedi et al. 2011). Increasing salinity improves the conductivity of the water-salt-solution because of existence of more free charge carrier.

Most of the dielectric loss is within the lower microwave range of electromagnetic radiation. Extracted fluid from corn stalks and leaves was tested to an equivalent NaCL-salinity of 9.7 ‰ (ca. 14,900 µS/cm at 20 °C in water), which can have a significant effect on the dielectric loss at frequencies below 5 GHz (Ulaby and Jedlicka 1984).

Temperature

As the temperature increases, the strength and extent of the hydrogen-bonding both decreases. This lowers dielectric permittivity, lessens the difficulty for the movement dipole and so allows the water molecule to oscillate at higher frequencies, and reduces the drag to the rotation of the water molecules, so reducing the friction and hence the dielectric loss. Note that ε_∞ (dielectric permittivity at short wavelengths) does not change significantly with temperature based on Debye Equation (Debye 1929).

Bound and free water

Additionally, water in biomass mixtures with a solid phase can either be found in free form or bound to the solids (Paz et al. 2011). When water is tightly bound to the host material its dielectric behavior is similar to that of ice, while free water is believed to exhibit the same dispersion properties as liquid water (Ulaby and Jedlicka 1984).

The amount of bound water in organic matter is discussed in literature controversy. Uhlaby (1987) e.g. introduced a dual dispersion model for the dielectric characteristics of free and bound water in vegetation material and validated the results with corn leaves. Bound water is not a part of the current model in this study, but a feature comprising bound water can be added if needed.

Water model

The analytical procedure of Hernandez-Walls (2010) considers all mentioned parameters: frequency, temperature and salinity. It was applied for computing the permittivity of water in the present paper (Figure 2). It bases on Debye's equations (Debye 1929). The results agree with other publications (Buchner et al. 1999, Hasted 1972, Kaatze and Hübner 2010, Nelson 2015, Somaraju and Trumpf 2006). The salinity is set to 10 ‰ in the following as a mean for measurements according to Ulaby (Ulaby and Jedlicka 1984).

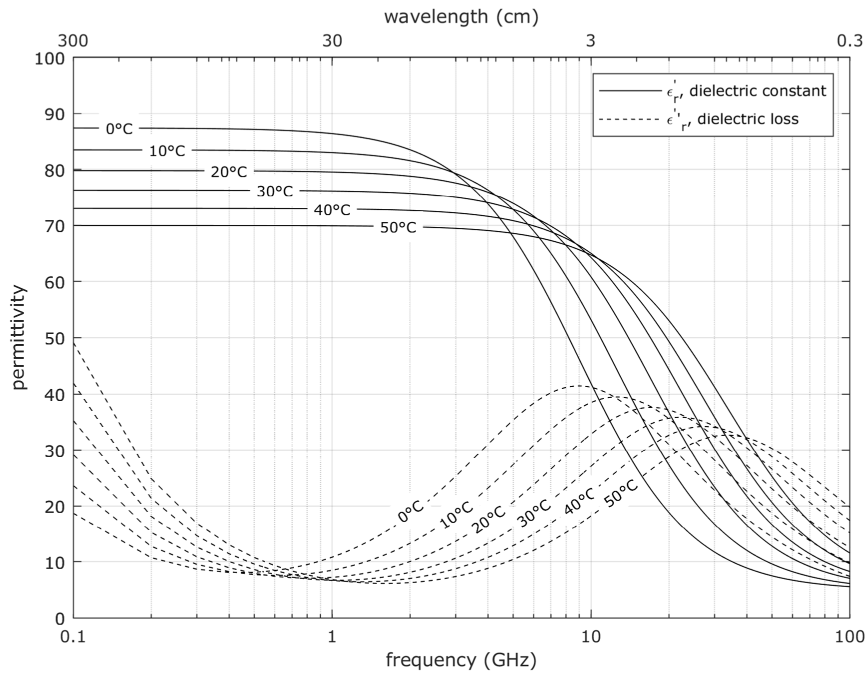

Figure 2: Permittivity water versus frequency at different temperatures for salinity 10 ‰

Dielectrical mixtures

In this study, the chopped and conveyed crop is considered to be a mixture of three phases: water, biological matrix and air. Different mixing formulas, predicting the effective permittivity of a mixtures, consider the geometric shape of the inserted particles (Loor 1968, Nelson and You 1990, Paz et al. 2011, Sihvola 2000, Ulaby and Jedlicka 1984). The often utilized (complex refractive) two-phase mixing models for agricultural products describe a bulk of particles and air (Kraszewski and Nelson 1989). Ulaby and Jedlicka (1984) noted the two-phase mixing models in following form for the case of air as a mixture component with $\varepsilon_a = 1$:

$$\sqrt{\varepsilon_{mix}} = v_m\sqrt{\varepsilon_m} + (1 - v_m) \qquad \text{(Eq. 6)}$$

where v is the volumetric fraction of material, is the relative permittivity of the mixture, the index m stands for pure plant material.

The frequently cited equation from Landau and Lifshits, Looyenga (Looyenga 1965) was derived for heterogeneous mixtures of two components (subscripts stand for, m – plant matrix, w – water, a – air):

$$(\varepsilon_{mix})^{1/3} = v_m(\varepsilon_m)^{1/3} + v_a(\varepsilon_a)^{1/3} \qquad \text{(Eq. 7)}$$

Application of (6) or (7) fails because of the lack in knowledge of the permittivity of the crop material, which is influenced by mc. The idea to mix dry matrix material and air as one component with water fails also, because data of permittivity for different degrees of compaction of matrix material are not available.

Polder and van Santen (Polder and van Santen 1946) developed an equation for ellipsoid particles (or empty holes) randomly distributed in a matrix obtained from Böttcher's method (Böttcher 1938). That particle model is as follows

$$\varepsilon_{mix} = \varepsilon_m + \frac{v_w}{3}(\varepsilon_w - \varepsilon_m) \cdot 3 \cdot \sum_{i=1}^{3}\left[1 + A_i \cdot \left(\frac{\varepsilon_w}{\varepsilon^*}\right)\right] \qquad \text{(Eq. 8)}$$

According to Tan (1981), A_i are the depolarized factors along the major axes of the ellipsoids (here in the present case, we have isotropic material with same polarization for all directions in space, $A_i = 1/3$) and ε^* is an internal effective dielectric constant accounting for the effects of interactions and special distributions of the granules. The quantity of ε^* is unknown. It lies between $\varepsilon^* = \varepsilon_{mix}$ and $\varepsilon^* = \varepsilon_m$ (Loor 1968).

Tan (1981) investigated the mentioned approaches for modeling the permittivity of vegetation samples and concluded: a general two-component dielectric mixture model appears to be an oversimplification. In the simple power law model for three mixture components (9), geometry effects are taken into account by an empirical constant, the geometric factor β that compensates for the shape of the components (Figure 3) and their orientation relative to the applied electric field (Ferré and Topp 2000). The model is based on the simple principle of averaging a power of permittivity by the volumetric fractions v of the constituents of the mixture (Paz et al. 2011).

$$\varepsilon_{mix} = (v_m \cdot \varepsilon_m^{\beta} + v_w \cdot \varepsilon_w^{\beta} + v_a \cdot \varepsilon_a^{\beta})^{1/\beta} \qquad \text{(Eq. 9)}$$

Equation 9 includes two-component refraction models, if one summand is rejected and β is set to ½, to meet the Complex Refractive Index or β is set to ⅓, to meet the Landau and Lifshitz, Looyenga Equation. Additionally, Figure 3 shows the effect of several assumptions for β and the influence of salinity on conductivity processes that lead to higher loss at frequencies below 1 GHz.

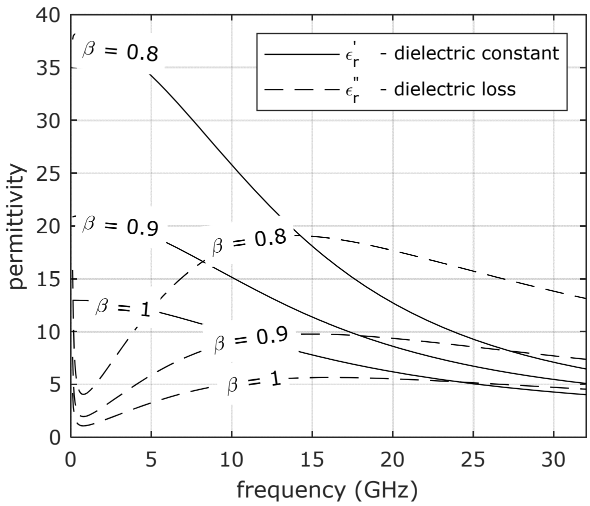

Figure 3: Influence of geometrical constant β on permittivity: results of power law equation (9)

El-Rayes and Ulaby (1987) developed an additive model (Equation 10 to 13) assuming the water distributed homogeneously in vegetation. The parameters of that dual dispersion model were determined utilizing sucrose water solution and validated at corn leaves. The equation and the coefficients were confirmed at a frequency of 8.13, 9.12 and 10 GHz at single leafs of rubber and oil palm leaves by Chuah et al. (1995) with following equations

$$\varepsilon_{resid} + v_{fw}\left[4.9 + \frac{75}{1+\frac{jf_{GHz}}{18}} + \mathrm{j}\frac{18\sigma}{f_{GHz}}\right] + v_{bulk}\left[2.9 + \frac{55.0}{1+\left(\frac{jf_{GHz}}{0.18}\right)^{0.5}}\right] \qquad \text{(Eq. 10)}$$

where

$$\varepsilon_{resid} = 1.7 - 0.74mc + 6.16mc^2 \qquad \text{(Eq. 11)}$$

$$v_{fw} = mc(0.55mc - 0.076) \qquad \text{(Eq. 12)}$$

$$v_{bulk} = \frac{4.64mc^2}{(1+7.36mc^2)} \qquad \text{(Eq. 13)}$$

where ε_{resid} is a non-dispersive residual component, v_{fw} is the volume fraction of free water depending on the moisture content mc at wet base in %, f_{GHz} is the frequency in GHz, σ is the conductivity: 1.27 S/m and v_{bulk} is the volume fraction of bulk vegetation including bound water (Chuah et al. 1995).

Results of mixing model

Figure 4 gives an overview of the permittivity of cop material with dmc of 370 g/kg calculated with preselected approaches: power law model (9); additive model ((10) to (13)) and particle-model (8) (for $\varepsilon^* = \varepsilon_{mix}$ and $\varepsilon^* = \varepsilon_m$), compared in the microwave frequency range up to 30 GHz. In opposite to expectation, the additive model gives no lower permittivity despite reduction of free water.

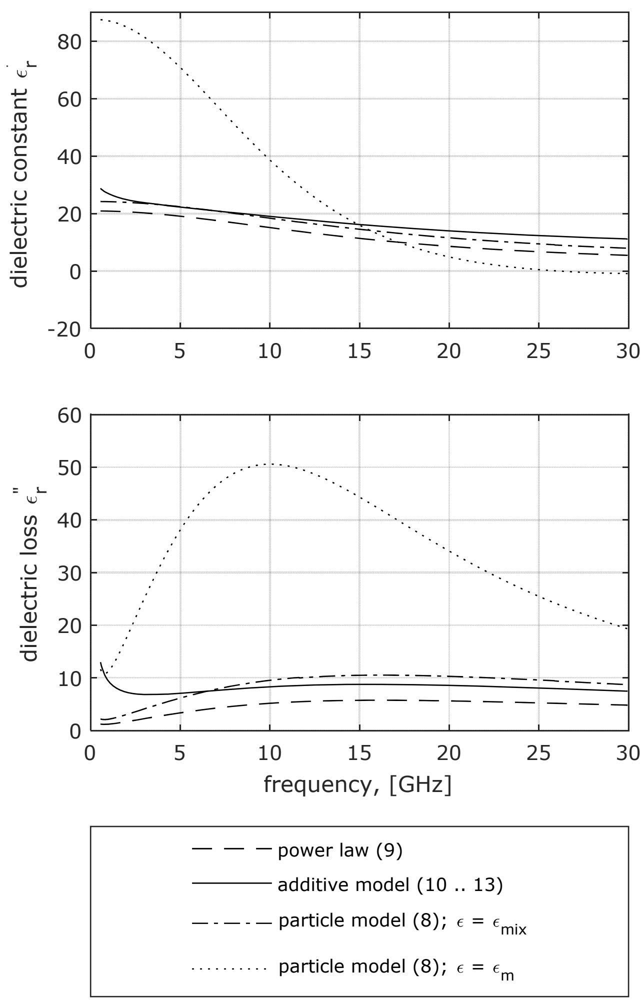

Figure 4: Comparison of permittivity models at dry matter content of 370 g/kg (*mc* = 63 %), power law model (9) for β = 0.9; additive model (10) to (13) and particle-model (8) for $\varepsilon^* = \varepsilon_{mix}$ and $\varepsilon^* = \varepsilon_m$

For particle model (8), the two extreme values for ε^* are presented. For $\varepsilon^* = \varepsilon_{mix}$, the permittivity approximates power law and additive model. In opposite to Tan (1981), who found A = [0,0,1], $\varepsilon^* = \varepsilon_m$ giving best results. Excepting lower frequencies, the trend of additive (dual dispersion) model, volumetric mixing model and particle model ($\varepsilon^* = \varepsilon_{mix}$) are corresponding. Differences in absolute values could be reduced by adapting factor β for power law model. The characteristics of the different approaches regarding mc is presented in Figure 5 at a frequency of 8.5 GHz.

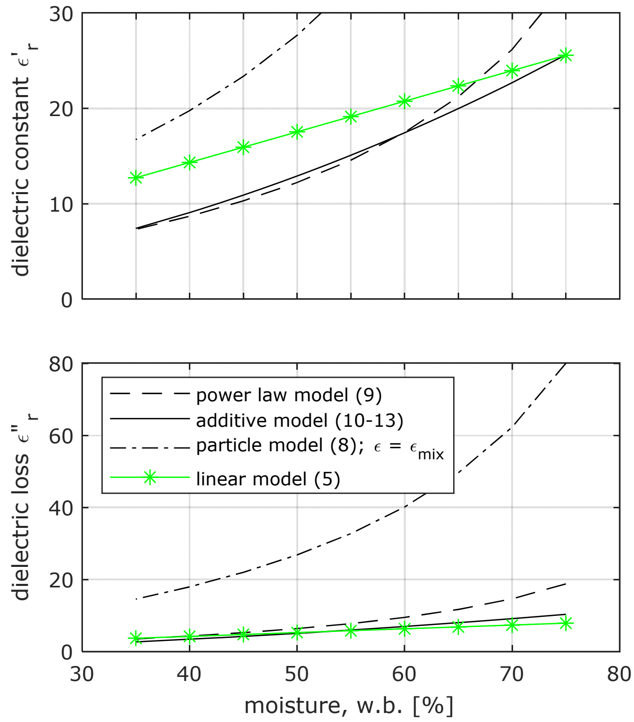

Figure 5: Comparison of permittivity models: (9), where β = 0.85, (8) and (5) respective to legend at 8.5 GHz

Describing matrix material more detailed as a mixture of cellulose, cell wall material (fiber), protein and starch or sugar is possible, but the message of that study would not be improved.

The effective permittivity is a macroscopic parameter, which relates the "average" electric field in the medium to the average flux density. In this sense, we are implying that the physical size of the mixture constituents is small (main fraction in maize silage: 4 to 10 mm), compared to the wavelength (4 GHz to 18 GHz correspond 75 to 17 mm) they are shaped irregularly, homogeneous (but randomly in detail) distributed and compacted more closely than in ball filling or a loose bulk. The power law model for three mixture components (9) gives most confidence and flexibility and is utilized in the following. Reflection and scattering effects at refraction transitions (dielectric boundaries) between crop particles have small impact on the global wave propagation in the crop material

Modeling Wave Propagation

System configuration

First, the installation conditions for the sensor system, we are designing, in the forage harvester and the planned sensor configuration are described, since the simulation model must mimic the design. Along the material flow in a forage harvester, most homogeneous and compact material is found in the spout after 1/3 length. Based on experiences of other gained with sensor systems in forage harvesters (Bernhardt et al. 2006), that location is preferred. Figure 6 shows the scheme for a transmission configuration of a sensor system at the spout with a vector network analyzer (VNA) for measuring scattering parameters S11 and S21 of the system consisting of antennas, microwave sensors, crop material and remaining air gap.

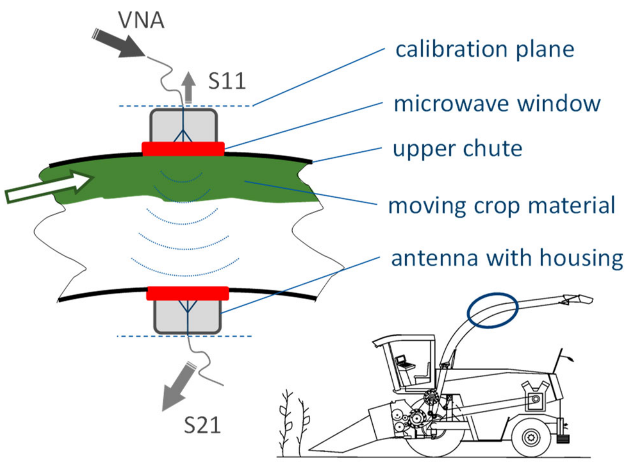

Figure 6: Scheme of sensor system with antennas in transmission configuration at the spout of a forage harvester

The crop is pressed to the upper chute by radial acceleration of 4 to 6 g.
High-density polyethylene (HDP) is utilized as material for the microwave windows for the first sensor buildup to protect the antennas. Its electromagnetic properties are deeply investigated and well known.

As well as the permittivity of polyethylene changes with temperature, that effect is less than 3 % in the typical harvesting range from 0 to 40 °C. Dielectrical constant ε' decreases from 2.4 to 2.35 (Riddle et al. 2003)we present complex permittivity data at microwave frequencies (approximately 10 GHz. In the present study, a fix value of ε = 2.4 – j0.0036 is applied for HDPE.

The strongest simplification for modeling the system is to assume plane wave propagation although the antennas are mounted directly at the microwave window.

Transfer-Matrix-Method

If all parameters are known, the reflection and transmission coefficients of a multilayer dielectric stack for one dimension can be calculated by a fast recursive method, as described in (Balanis 1989). Thereby each layer has to be plane, smooth, and infinite (Zwick et al. 2002). This is an acceptable simplification for the layers in the sensor system.

Transfer-Matrix-Method (TMM) is the most widely used method for the mathematical study of wave transmission in one-dimensional structures (Xifré Pérez et al. 2007). This approach assumes a stack of layers that are uniform in the longitudinal direction. Scattering matrices are calculated for each layer and are combined into a single overall scattering matrix that describes propagation through the entire system. Free space gaps with zero thickness are inserted between the layers virtually and the scattering matrices are made to relate fields which exist outside of the layers, but directly on their boundaries (Rumpf 2011). Alternative approaches are reported by Sanadiki and Mostafavi (1991) and Tan (2006).

Multilayer Model

We consider two polarization components, called Transverse Electric (TE) and Transverse Magnetic (TM). All plane waves can be treated as the sum of TE and TM components. TE waves are those in which the electric field is directed perpendicular to the plane of incidence, the plane formed by the incident ray and the surface normal. TE waves are also called perpendicularly-polarized (Pascoe 2001)

TMM was adapted and expanded to scattering matrices for more computational stability by Rumpf (2011). The Matlab® code from Rumpf and his team from University of Texas and at EMpossible (CEM 2018) was applied in this study to compute the layer stack described in Figure 7 with hints regarding utilized permittivity.

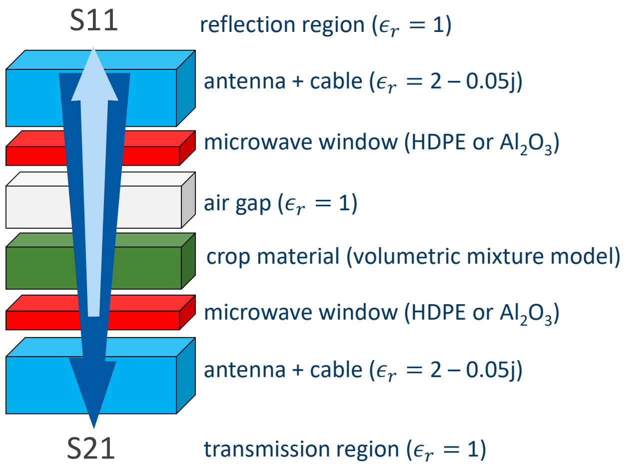

Figure 7: Construction of the global layer system

For validation purposes, additionally a layer for the antenna and the cable to the antenna is to consider, because of the calibration plane for the VNA is at the end of the cables to the connectors at the housing of the antennas (see Figure 8 for setup of validation setup in laboratory).

The model does not consider contribution of multipath propagation occurred by reflections at metallic spout. Especially at lower feed rates and moisture content, when less crop material with low permittivity attenuates the signals, the contribution of multipath effects to the received signal will cover information from crop.

Validation method

The model of permittivity of crop and of wave propagation in the system is to be validated utilizing a stationary test stand. During stationary test runs, the crop material cannot be pressed to the upper boundary of a channel by active forces. Therefore, the order of the layers for the remaining air gap and the crop material was changed between Figure 7 and Figure 8.

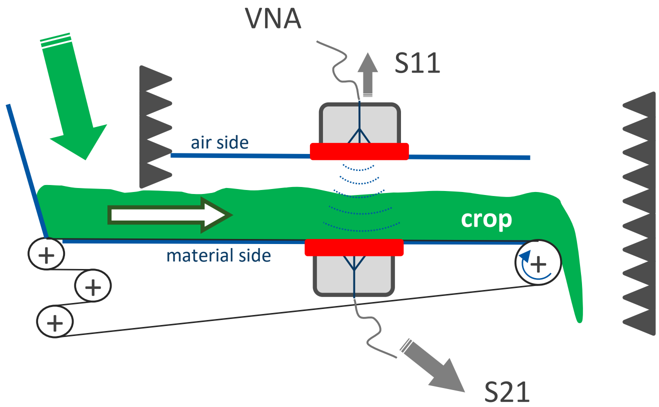

Figure 8: Schematic of test arrangement in the laboratory

The test stand consists of a metallic rectangular channel with length of 1 m plus refilling funnel section, horizontally aligned and with the same cross section like the spout at a SPFH. A very thin conveyor belt out of PVC and cotton textile (d < 1 mm) at the bottom of the channel transfers the crop material slowly across the antenna section (belt speed = 6 mm/s). Intention of that method is not to mimic the material flow in the harvester. The crop velocity in the spout can be neglected compared to speed of electromagnetic wave fronts in the system. We wanted to present crop material with similar chemical properties with different physical packaging, alignment of individual particles, different structure of layer surface and small variation in compaction. So many repeated measurements were conducted with low physical work in short time. The system is filled initially and starts to empty during data collection. One time per run, material was refilled through the filling funnel to keep the boundary conditions in the background constant. The test run was stopped before that refilled crop crossed the antenna section to keep the entire measuring channel filled consistently.

The openings at material inlet and outlet were covered with microwave absorbers behind. Variable amounts of crop material were put on the floor of the channel from two types of crops: grass or maize. The grass from grassland wilted different long periods before it was cut with a laboratory cutting machine according to typical SPFH settings (cutting length: 12 mm). The chopped maize came fresh from the field, processed by SPFH.

The S-parameters were measured with a 2-port VNA (Anritsu MS46122 A) from 3 to 18 GHz (1001 steps) with intermediate frequency of 10 kHz and 100 sweep repetitions to average the stochastic variation of density and particle orientation of material between the antennas caused by manual filling. With the resulting sweep frequency, a distance of ca. 600 mm of crop was scanned during conveying.

Results and Discussion

Both main parts of the simulation model, the volumetric mixing model (power law) and the TMM propagation model were implemented in the Matlab® environment. The tool calculates the scattering parameters for a predefined frequency range and enables variation of properties of crop material: temperature, sample weight, dry matter content. Implicit the particle geometry and structure in the layer including compaction can be adapted. Different materials and thickness of microwave windows are selectable. The real dimensions of the spout are applied.

Validation of simulation model

Data from lab tests with grass and maize differ (Figure 9), probably caused by the particle size and shape and the resulting density. These effects were considered by adapting the factor β in the volumetric mixture equation (7): β(grass) = 0.85, β(maize) = 0.95. A good match for frequencies below 8 GHz is achieved. At higher frequencies the dynamic range and resolution capacity of the VNA is reached. Below -90 dB noise detected covers the small signals. It is suspected that the accuracy and resolution of an economically priced production sensor cannot not deliver the same precision like the recently applied laboratory device. Therefore, the first lesson learned from the model is: frequencies higher 8 GHz don't contribute information regarding the crop material, when a transmission arrangement is utilized.

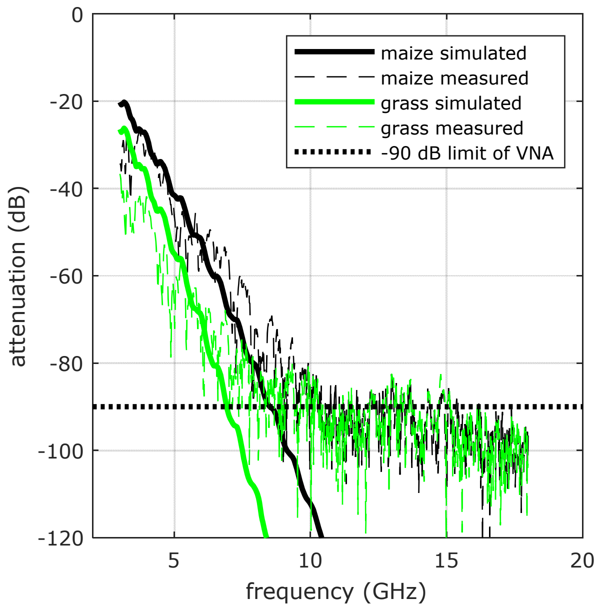

Figure 9: Comparison of simulated and measured signal attenuation for samples of grass (*dmc* = 378 g/kg) and maize (*dmc* = 368 g/kg) at 18 °C at 3.000 g/m sample mass

The remaining deviation results from the characteristics of the antennas and their interaction with the metallic housings and the metallic channel besides the microwave windows. Frequency drops occur because of interferences in metallic spout channel, which is not modeled yet.

Modern powerful SPFH are specified for feed rates above 400 t/h fresh crop. This leads to a mass per distance of more than 5.5 kg/m in the spout at crop speed of 20 m/s. During grass harvest, approximately 50 % of throughput of maize is practical. This range of values was tested in the laboratory (Figure 10).

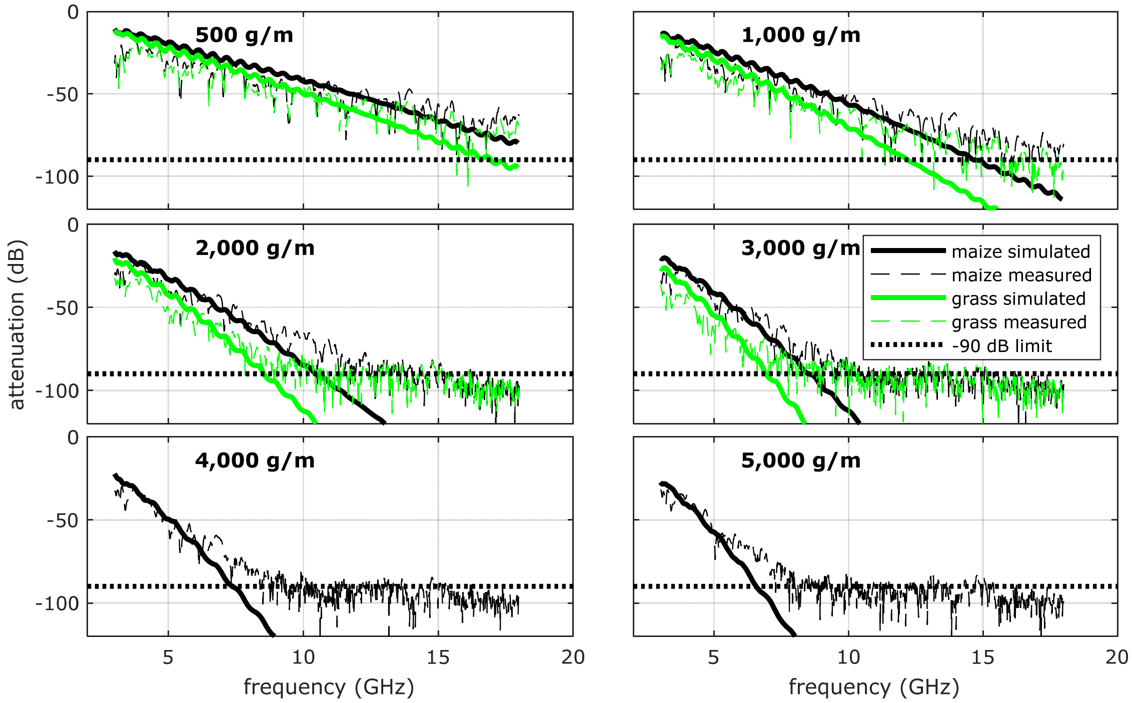

Figure 10: Overview of simulated and measured attenuation of signals from grass and maize for a sample weight range from 500 to 5,000 g/m (temperature ≈ 18 °C, *dmc* ≈ 370 g/kg)

The reflected signals agree sufficiently to extract trends from the model (in the example in Figure 11 at 11 GHz). At lower frequencies, the in-house developed Vivaldi-antenna and its nearfield are not modeled adequately. Not modeled reflections from surrounding parts of the antenna assembly dominate at higher frequencies.

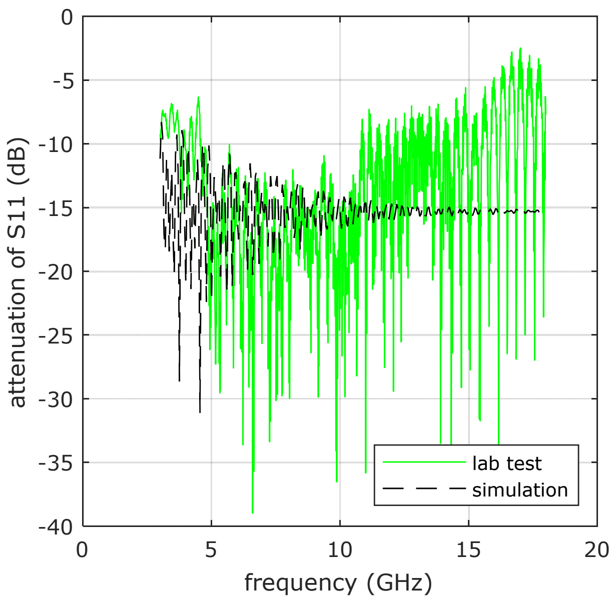

Figure 11: Amplitude of reflected signals for lab test and simulation (sample mass = 5000 g/m, temperature ≈ 18 °C, *dmc* ≈ 370 g/kg)

Examples for effects to be investigated with the model

In addition to the data presented so far in frequency domain, many moisture detecting microwave sensors work in the time domain. To get similar results a length of 0.4 m for the antenna plus cable was assumed for the model.

In the time domain, the simulated data demonstrate the effect of changing group velocity of the wave front and decreasing amplitude of the main path of propagation more clearly than the measured data (Figure 12), because of the phase signal is more stable and less affected by unwanted disturbances.

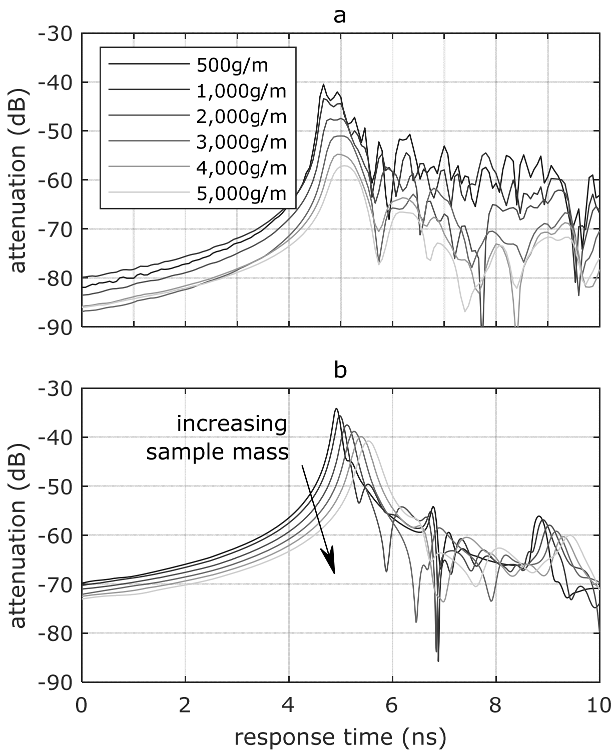

Figure 12: Response time for different amounts of crop; a – measured data from lab tests, b – simulated data, (temperature ≈ 18°C, *dmc* ≈ 370 g/kg)

Depending on the configuration of the antennas at the spout of the harvester, material that is more wear resistant is required, especially at the upper chute location. Therefore, ceramics is proven, is not conductive and has constant and repeatable dielectrical properties with acceptable loss. The dielectric constant ε' of aluminum oxide ceramics is 9.78 at 20 °C, the dielectric loss *ε''* is 0.489 (dielectric loss tan(δ) = 0.5) (Park et al. 2007).

The more lossy ceramic (Al_2O_3) would cost between 5 to 10 dB in the spectral range up to 10 GHz compared to a window made of polyethylene (Figure 13). The effect of material thickness of polyethylene is small, that means, that also wear does not affect the results. For the ceramic, more thick windows cost money and signal.

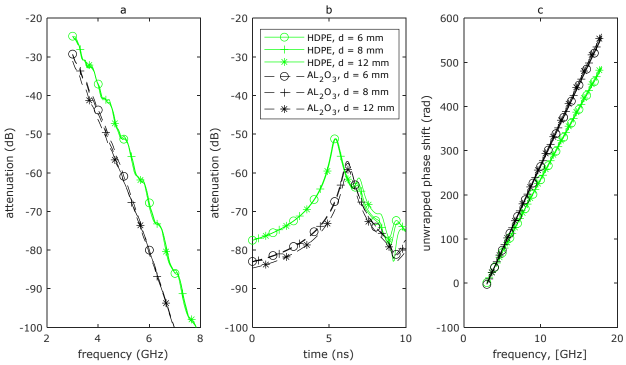

Figure 13: Influence of different materials for microwave windows (HDPE and Al2O3) and different thickness
c – phase shift (unwrapped), b – time response, a – amplitude, (temperature ≈ 18 °C, dmc ≈ 370 g/kg)

Conclusions

The effects of electromagnetic wave propagation in a channel partially filled with crop can be approximated based on parameters from literature for general specification of a dielectric sensor system. A simplified volumetric mixture model to estimate the permittivity of the crop material depending on material temperature, density and mc matches published values with sufficient precision. The transfer-matrix method is appropriate to model the setup of a sensor system in a harvester.

The capability of the present approach was validated at an example, applying a transmission sensor configuration with a test arrangement mimicking the spout of a forage harvester. As can be seen in Figure 10, the model works for the completely feed rate range. Influences of design variants can be investigated and an optimal sensor design regarding physical basements can be specified.

Other parameters to be variated in upcoming project work will be:

- Dry matter content
- Temperature
- Further materials for microwave windows
- Test of calibration approaches.

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