Scattering Parameters Measurements with the Microwave Transmittance Technique Using a Microstrip Patch Antennas as Non-Invasive Tool for Determination of Soil Moisture

Paulo Sergio de Paula Herrmann
Embrapa Instrumentation
São Carlos (SP), Brazil
e-mail: paulo.herrmann@embrapa.br

Felipe Nieves Marques Porto
Maastricht University
Maastricht, Netherlands
e-mail: porto.felipe94@gmail.com

Viktor Sydoruk
Forschungszentrum Jülich / IBG-2: Plant Sciences
Jülich, Germany
e-mail: v.sydoruk@fz-juelich.de

Abstract— **Interactions of soil moisture with plant's root system are very important for plant growth. For non-invasive determination of volumetric soil moisture in a Rhizobox a microwave system based on transmittance of electromagnetic waves in the microwave frequency range was developed using microstrip patch antennas. A Vector Network Analyzer (VNA) was used to measure the S-parameters at frequency range close to 5 GHz. A transmission system with microstrip patch antennas was developed. The result of this attenuation is in the frequency domain. The antennae were designed resonant microstrip antennae. The antennas were placed on both sides of a rhizobox, which allows measuring non-invasively soil moisture in the box. The attenuation (S12(dB)) was used to measure the effect of temperature in different kinds of soils. Sensitivity, reproducibility and repeatability were evaluated as well. This works presents quantitative results of soil moisture in rhizobox. The microwave technique, using microstrip patch antennas, is a reliable and accurate system, and showed very promising potential applications for rhizobox-based investigations of root performance.**

Keywords- microwave technique;, transmittance; soil moisture; microstrip patch antennas; rhizobox.

I. INTRODUCTION

New tools or approaches are considered important to investigate and evaluate soil-water-plant interactions in the plant phenotyping investigations [1]. A central parameter determining root system response to water availability is that water is usually not homogeneously distributed in the soil and the heterogeneity significantly increases when drought stress occurs. Thus, the development of non-invasive instruments and sensors to measure soil moisture distribution would open up new approaches to investigate plant strategies to deal with low water content or, in particular, heterogeneities in water availability of soils during periods of drought cycles.

Electromagnetic soil water content sensors are now widely accepted for soil water content determination because these sensors allow continuous, fast, stable, and nondestructive sensing of the spatial-temporal dynamics of soil water content at the lab and field scale [2].

From the electromagnetic point of view, the soil-plant-water set is considered a mixture of four dielectric compositions consisting of air, soil volume, bound water, and free water and roots. A water molecule attached to the soil interacts with an incident electromagnetic wave different from the free water molecule, thereby exhibiting a dielectric dispersion spectrum which is very different from free water. The dielectric constants in the complex form of free and bound water are functions of the electromagnetic frequency (f), the physical temperature (T) and the salinity (S).

The dielectric properties of the wet soil are characterized by frequency dependence as a function of dielectric constant response.

In a soil-plant-water system, the ε_r values for the soil are typically between 3 and 5. In water, the values are around 80 and, for the roots of a plant, they oscillate between 42 and 56. The volumetric water contents of the root samples vary linearly with the volume. The ε_r of the air is equal to 1. In this way, relatively small amounts of free water in the soil will greatly affect its electromagnetic properties [3][4].

For non-invasive determination of volumetric soil moisture (θ_V) a microwave system based on transmittance of electromagnetic waves in the frequency range close to 5.0 GHz was developed using microstrip patch antennas. The antennas were placed on both sides of a rhizobox. The evaluation is made using scattering parameters (known as S-parameters) describing dispersion and dielectric properties of a soil-water. In the figure 1(a) is showing the basic principle of the electromagnetic wave (EM) interactions with the matter. A block diagram of the system that was developed to conduct this experiment can be seen in the Figure 1(b).

Copyright (c) IARIA, 2018. ISBN: 978-1-61208-621-7

Calibration curves for four porous media are presented for two soils, the Nullerde - Einheitserde Typ 0 - Einheitserde- und Humuswerke, and a peat-sand-pumice substrate - Dachstaudensubstrat SoMi 513 (Kaktus soil), and Cerrado soil (tropical soil); and one for glass beads. The results presented in this work show a potential of using microwave transmittance technique and microstrip patch antenna for development of a new non-invasive determination of volumetric soil moisture (θ_V) which will be possible to be applied for better understanding of roots growth.

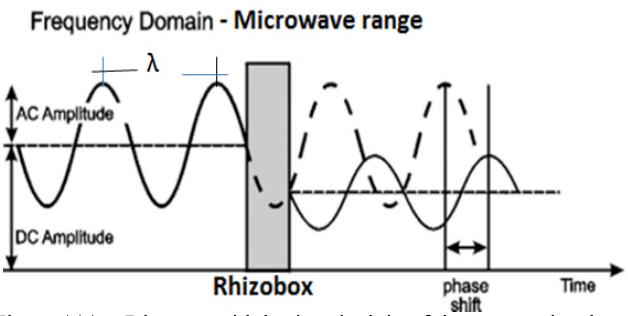

Figure 1(a). Diagram with basic principle of the system developed to this investigation. (Attenuation and phase shift) (Modified from [5]).

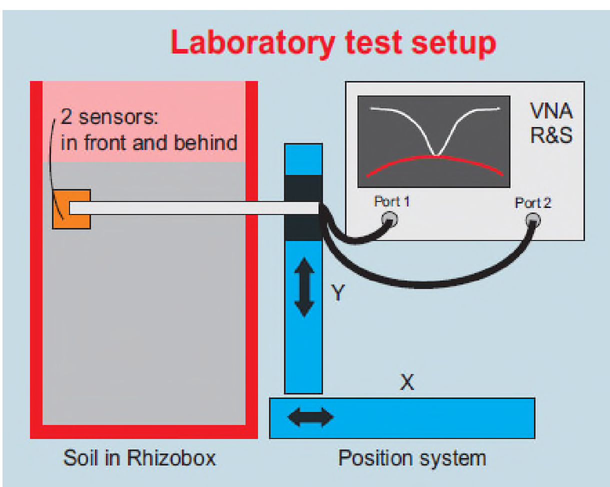

Figure 1(b). The block diagram of the system developed to measure S21 (dB) of the soil moisture in the rhizobox, using Vector Network Analyzer, in the microwave range (4.6 GHz to 5.0 GHz).

II. MATERIALS AND METHODS

A. *Vector Network Analyzer (VNA)*

The antennas are connected to Vector Network Analyzer (VNA) (ZNB 8, Rohde & Schwarz) which is generally used to generate and measure radio frequency/microwave signal. Some features about the equipment used: Frequency range from 9 kHz up to 40 GHz; Wide dynamic range of up to 140 dB and High temperature stability 0.01 dB/°C. Using VNA, we measured scattering parameters (S-parameters (S21 (dB)) in a frequency range from 4.6 GHz to 5.0 GHz to characterize transmission of microwaves through a soil with a resolution of 6 x 10^{-3} dB.

B. *Design of Microstrip Patch Antenna*

The antennas were designed as λ/2-resonant microstrip antennas [6] and executed on a circuit board with a 1.5 mm thickness and a dielectric constant ($\varepsilon_{r,sub}$ of 4.4). Each antenna was 15.7 mm wide and 15.4 mm long. The total size is 25.0 x 25.0 x 1.5 mm^3. Such a design allows working at frequencies close to 4.8 GHz. Figure 2 is presents the picture of the microstrip antenna design to microwave range.

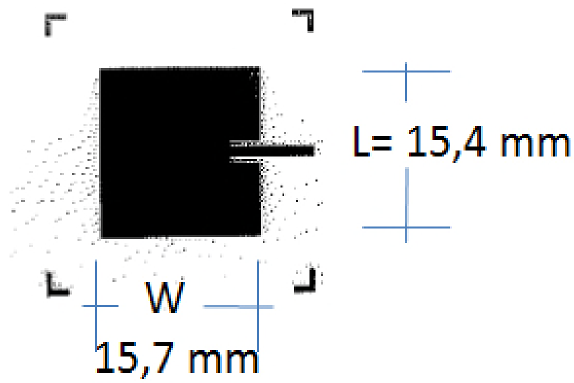

Figure 2. The mask used to develop the microstrip antenna on to circuit board

C. *Rhizobox*

The rhizobox were made out of PVC and Plexiglas (εr ~ 2.6) and PVC (εr ~ 2.9) with walls of about 5.0 mm in thickness, a length of 315.0 mm and a width of 200.0 mm. The internal space for the porous media samples is 20.0 mm.

D. *Measurement of reproducibility and repeatability (Dielectric Constant vs Attenuation)*

The two chemical solutions used were 1,4-Dioxane (C4H8O2) and 2-Isopropoxyethanol ((CH3)2CHOCH2CH2OH), abbreviated as i-C3E1. The objective was to make an "ideal solution" by combining water (ε_w= 79 (1.2 GHz)) and another liquid fully miscible in water. Dioxane is a strong solvent with a low flash point and a high volatility.

The mixtures, values and relative complex dielectric permittivity parameters are derived from [7]. The real and imaginary part of the complex dielectric permittivity of the reference liquids were described by the Cole-Cole model [8]. The model can be seen in the equation (1):

$$\varepsilon = \varepsilon_\infty + \frac{(\varepsilon_s - \varepsilon_\infty)}{1 + (j\omega\tau)^{1-\alpha}} - j\frac{\sigma}{\omega\varepsilon_0} \qquad (1)$$

The ε represents the complex dielectric permittivity, while ε_s [-] and ε_∞ [-] are the permittivity at frequencies f much lower and much higher than the relaxation frequency f_{rel} [Hz], respectively, α [-] is the dispersion factor for the relaxation time (0<α<1), σ [S m^{-1}] is the electrical conductivity and ε_0 is the free space permittivity.

The concentrations of the liquids were created as is shown in Table I.

TABLE 1: THE VOLUME FRACTION OF THE LIQUIDS, THE DIELECTRIC CONSTANT AND A RELATION WITH SOIL MOISTURE

Reference Liquid	Medium	Volume Fraction		$\varepsilon_s \approx \varepsilon_{ref}$	θ_{eq}
		Dioxane / i-C_3E_1	Deionized Water		
		[-]	[-]	[-]	[m^3 m^{-3}]
M1	Dioxane	0.90	0.10	6.65	0.117
M2	i-C_3E_1	1.00	0.00	11.95	0.228
M3	i-C_3E_1	0.92	0.08	18.14	0.331
M4	i-C_3E_1	0.86	0.14	22.15	0.388
M5	i-C_3E_1	0.80	0.20	26.26	0.441
M6	i-C_3E_1	0.73	0.27	31.38	0.502
M7	i-C_3E_1	0.68	0.32	34.82	0.540

E. Calibration Curve

Each sample was prepared to have the same bulk density (ρb) of a dry soil and its different volumetric soil moisture, θV(%). We used three different porous media (PM): Nullerde (Einheitserde Typ 0, Einheitserde- und Humuswerke Gebr. Patzer GmbH & Co. KG), peat-sand-pumice substrate (Dachstaudensubstrat SoMi 513, Hawita GmbH, Vechta, Germany) and glass beads (particles size ~ 0.5 mm). The soil used in these experiments was the dystrophic Red Latosol/Oxisol (Cerrado - Brazil (ρ_b = 1.19 g/cm^3)). The ρb, during the experiments were about 0.28 g/cm^3, 0.59 g/cm^3 and 1.40 g/cm^3, respectively. The experiments were made under laboratory conditions at temperature of about 25.0 ± 0.5 °C and relative humidity of ~30.0%. Additionally, we measured influences of temperature for Nullerde soil under climate controlled environment at temperature range from 13.0 ± 0.5 °C to 39.0 ± 0.5 °C.

The equation 2 can be used to calculated the volumetric soil moisture (θV(%)):

$$\theta V(\%) = \left(\left(\frac{V_{H_2O}}{M_{ds}} \right) x \rho_{ss} \right) x\ 100 \tag{2}$$

where: V_{H2O} is the volume of the water (cm^3); M_{ds} is the weight of the dry soil (g); ρ_{ss} is the dry soil density (g*cm^{-3})

III. RESULTS AND DISCUSSION

A. Evaluation of reproducibility and repeatability of the system developed

The aim of this experiment was to correlate attenuation values received from the rhizobox with the concentration of chemical organic solution placed for analysis. This experiment aimed to correlated the dielectric permittivity constant of certain concentrations of organic chemical solutions (in this case mainly 2-isopropoxyalcohol) with the microwave attenuation values. The results clearly show a relation between the two variables – mainly which as the dielectric permittivity increases, so does the attenuation. The graph demonstrating the percentage of reliability of reproducibility and repeatability shows that this same experiment should theoretically be possible to perform in any circumstance, resulting in the same values.

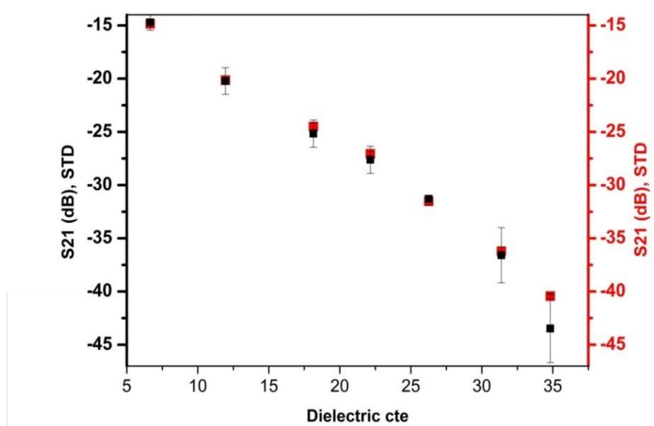

Figure 3. The repeatability and reproducibility of the system developed were calculated. The measurement was carrying out three times to each dot (n=3). The red dots represent the reproducibility (98.9%) averages and the black dots represent the repeatability (93.0%) averages.

B. The influence of temperature during the measurement of volumetric soil moisture (θV(%)).

The influence of temperature (°C) is an important parameter in the measurement of soil moisture. In the figure 4 has been shown the influence of temperature during the measurement of volumetric soil moisture of the Null Erde sample. The situation is dramatically changed when PM has high amount of water. The ΔT (°C) was equal 26.0 ± 0.5 °C and the maximum variation of S21(dB) was 35.3% to θV (%) = 45.0%.

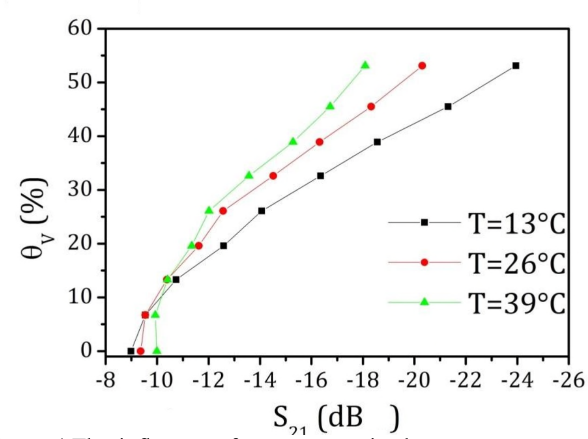

Figure 4.The influence of temperature in the measurement of θV (%) using the attenuation (S21 (dB)). The porous media used was Null Erde and the temperature set up to this experiment was between 13.0 ± 0.5 °C to 39.0 ± 0.5 °C.

C Influence of salty water in the measurement.

Dissolving of salts leads to increasing of conductivity which has a major effect to the attenuation of the transmitted signal. To take into account and separate influence of water and salts/nutrients in a soil it is necessary to measure the resonance frequency shift of the antennas together with attenuation.

D The calibration curve and modeling of volumetric soil moisture (θV(%)) in function of S21(dB).

Therefore, different calibration curves are needed for different PM. Calibration curves were obtained by measuring S21-parameter (dB), which reflects transmission of EM waves. Measuring the attenuation of transmitted signal we obtained clear dependence of θV (%) on S21 (dB). The dependence tends to be comparable for different PM when it is relatively dry, below 20.0 % of θV(%), and has a small dependence of bulk density, as well the soil physical and chemical properties of each PM, mainly the typical tropical soil (Cerrado soil).

The curve obtained to four (04) samples (Cerrado Soil, Null Erde, Kaktus Soil and Glass Beads) is shown in the figure 6 and the equation the table (2):

Figure 7 is shows the preliminary results of the measurement of S21(dB) attenuation of volumetric soil moisture in the rhizobox, during the time (16 days:21hr:17 min). The sample is a Katus soil with maize. The experiment was organized to obseve the attenuation of soil moisture during the time of the roots growth. The measurement was taken in the lab conditions (T=24,3 ± 1,1 C and RU=62,8 ± 5,0 %) during the morning, the afternoon and the night to measure the behaviour of the water.

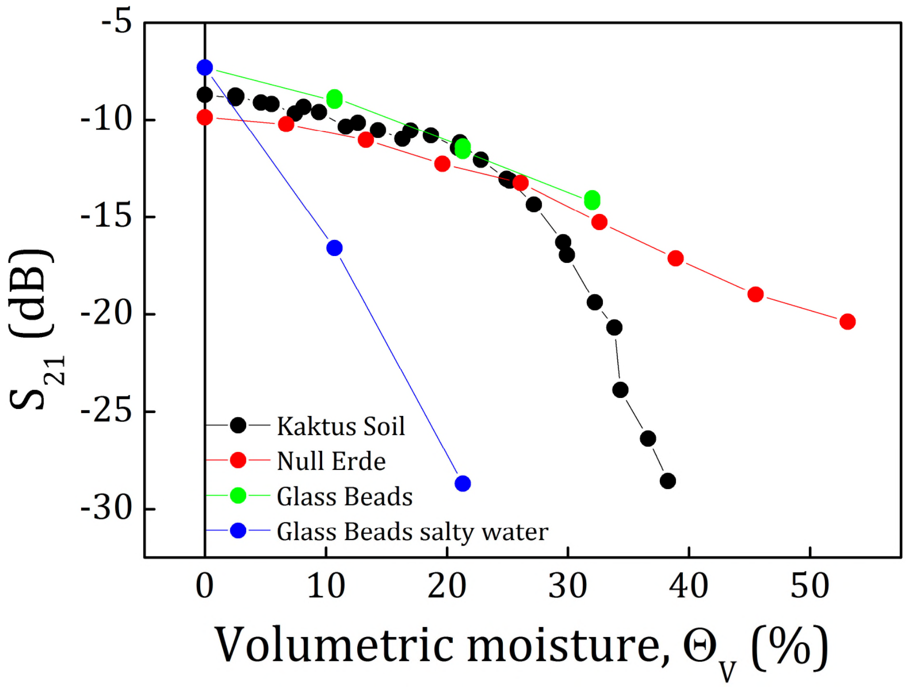

Figure 5. Calibration curves for different types of soil and glass beads with and without salt. The graphic is showing dependencies on salinity, moisture and properties (such as bulk density, dielectric constant etc.) of soil.

TABLE II: EQUATIONS USED TO MODEL THE CALIBRATION FOR EACH SAMPLE

Samples	**Equation**	R^2
Cerrado Soil ρ_{ss}=1,19 g*cm^{-3}	$\Theta_v(\%) = -0{,}00258*S_{21}(dB)^3+0{,}07924*S_{21}(dB)^2+0{,}27515*S_{21}(dB)-4{,}72555$	0,9834
Null Erde ρ_{ss}=0,28 g*cm^{-3}	$\Theta_v(\%)= -0{,}18679*S_{21}(dB)^3 -7{,}79899*S_{21}(dB)^2-112{,}0218*S_{21}(dB) -524{,}374$	0,9804
Kaktus Soil ρ_{ss}=0,59 g*cm^{-3}	$\Theta_v(\%)= 0{,}1555*S_{21}(dB)^3+4{,}16601*S_{21}(dB)^2+29{,}24777*S_{21}(dB)+42{,}96299$	0,9725
Glass Beads ρ_{ss}=1,54 g*cm^{-3}	$\Theta_v(\%)= -0{,}19723*S_{21}(dB)^2-8{,}78181*S_{21}(dB) -52{,}87515$	0,9923

Copyright (c) IARIA, 2018. ISBN: 978-1-61208-621-7

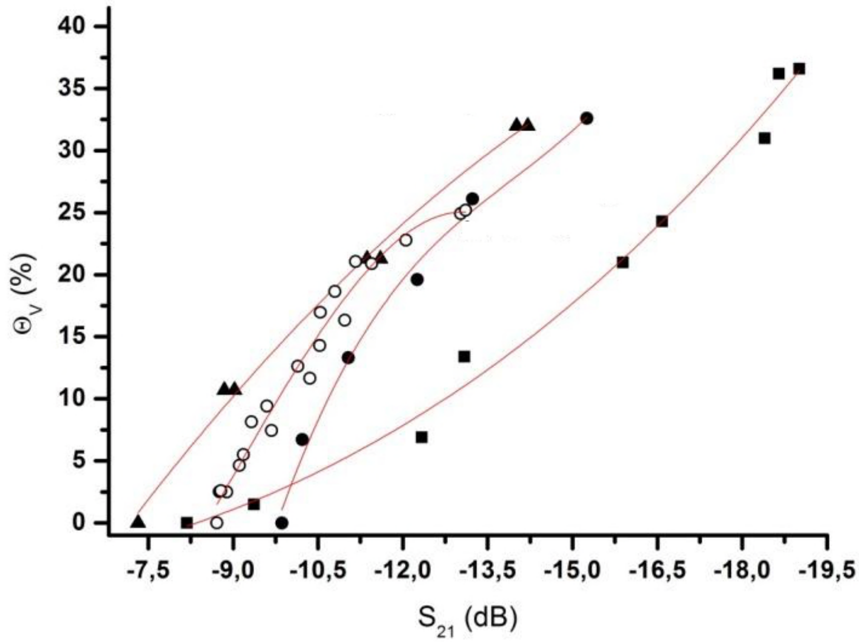

Figure 6. Relation between the S21 (dB) measured with the system developed and the volumetric soil moisture (θV(%)) determined and calculated by second and third order polynomial equation. The equations were presented in the table 2. The four (04) samples used are: Cerrado Soil (■), Null Erde (●), Kaktus Soil (○) and Glass Beads (▲).

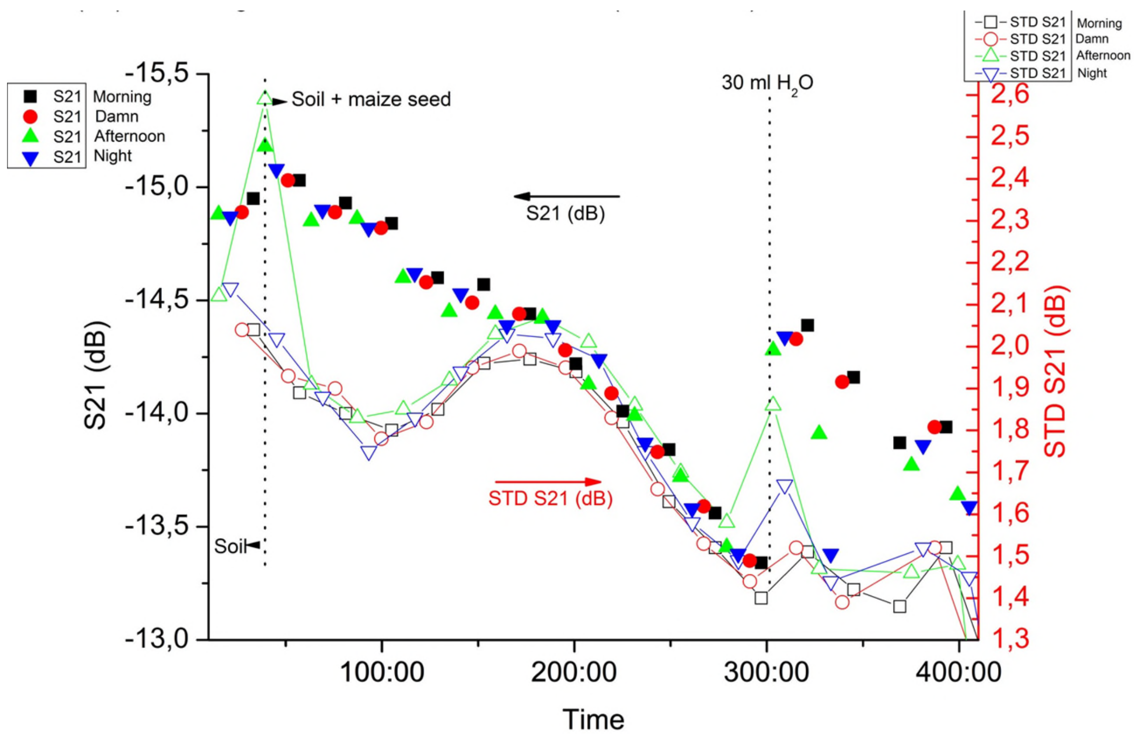

Figure 7. Results of the measurement of S21(dB) attenuation of volumetric soil moisture in the rhizobox, during the time (16 days:21hr:17 min) and a calculation of standard deviation (STD S21(dB)). The sample is a Katus soil with maize. The experiment was organized to measure the attenuation of soil moisture during the time of the roots growth. The measurement was taken in the lab conditions (T=24,3 ± 1,1 C and RU=62,8 ± 5,0 %) during the morning, the afternoon and the night.

IV. CONCLUSION

From the measured results, it is possible to conclude that the developed non-invasive microwave method, using microstrip antennas, is an innovative sensing method to measure the water status in rhizobox filled with soil. This can be used to investigate the growth of plant roots together with soil physics properties. This kind of approach gives an opportunity to apply it to study and monitor non-invasive volumetric soil moisture θV (%) distribution, using rhizobox.

ACKNOWLEDGMENTS

The Forschungszentrum Jülich (FZJ/Jülich) / IBG-2: Plant Science to the support and facilities, the Jülich Plant Phenotyping Center (JPPC), as well the Enabling Technologies group to good discussion and use of the laboratories. This research was financially supported by Embrapa Labex Europe Program, Agropolis, Montpellier, France, number DZ002947.

REFERENCES

[1] F. Fiorani and U. Schurr,. “Future Scenarios for Plant Phenotyping,” Annual Review of Plant Biology, vol.64, pp.267 – 291, 2013.

[2] W. Qu, H. R. Bogena, J. A. Huisman and H. Vereecken, “Calibration of a Novel Low-Cost Soil Water Content Sensor Based on a Ring Oscillator,” Vadose Zone Journal, vol. 12, Iss.: 2, 2012

[3] T. J. Schmugge and T. J. Jackson, “Survey of methods for soil moisture determination,” Water Resources Research, vol. 16, n. 6, pp. 961 – 979, 1980

[4] M. A. Mojid and H. Cho, “Evaluation of the time-domain reflectometry (TDR)-measured composite dielectric constant of root-mixed soils for estimating soil-water content and root density,” Journal of Hydrology, vol. 295, pp. 263–275, 2004

[5] A. Pellicer and M. D. C. Bravo, “Near-infrared spectroscopy: a methodology-focused review,” Seminars in fetal & neonatal medicine, vol. 16, Iss.: 1, pp. 42-49, 1744-165X, 2011

[6] A. Cataldo, G. Monti, E. De Benedetto, G. Cannazza and L. Tarricone, “A noninvasive resonance-based method for moisture content evaluation through microstrip antennas,” IEEE Transactions on Instrumentation and Measurement, vol. 58, Iss.: 5, pp. 1420-1426, 2009,

[7] U. Rosenbaum, J. A. Huisman, J. Vrba, H. Vereecken and H. R. Bogena, “Correction of Temperature and Electrical Conductivity Effects on Dielectric Permittivity Measurements with ECH2O Sensors,” Vadose Zone Journal, vol. 10, Iss.: 2, pp. 582-593, 2011

[8] K. S. Cole, R. H. Cole, "Dispersion and Absorption in Dielectrics - I Alternating Current Characteristics", J. Chem. Phys., vol. 9, pp. 341–352, 1941.

Copyright (c) IARIA, 2018. ISBN: 978-1-61208-621-7