2023 IEEE Ural-Siberian Conference on Biomedical Engineering, Radioelectronics and Information Technology (USBEREIT) | 979-8-3503-3605-4/23/$31.00 ©2023 IEEE | DOI: 10.1109/USBEREIT58508.2023.10158880

UWB Reflectometric Method for the Measuring of Vegetation Biometric Parameters and Soil Moisture

Konstantin Muzalevskiy
Laboratory of Radiophysics of the Earth Remote Sensing
Kirensky Institute of Physics Federal Research Center KSC Siberian Branch Russian Academy of Science
Krasnoyarsk, The Russian Federation
email: rsdkm@ksc.krasn.ru

Sergey Fomin
Laboratory of Radiophysics of the Earth Remote Sensing
Kirensky Institute of Physics Federal Research Center KSC Siberian Branch Russian Academy of Science
Krasnoyarsk, The Russian Federation
email: rsd@ksc.krasn.ru

Mikhail Mikhaylov
Laboratory of Radiophysics of the Earth Remote Sensing
Kirensky Institute of Physics Federal Research Center KSC Siberian Branch Russian Academy of Science
Krasnoyarsk, The Russian Federation
email: fractaloff@mail.ru

***Abstract*—In this article, a method for the simultaneous measurement of total biomass, vegetation water content, and soil moisture is developed based on ultra-wideband (UWB) nadir observation of the reflection coefficient in the frequency range from 450 MHz to 6 GHz. The proposed method is based on a simple model of plane wave reflection from a vegetation layer with flat boundaries lying on a smooth soil surface. The model does not take into account the phenomena of wave scattering on the vegetation elements and the soil surface roughness. The dielectric constant of the vegetation canopy and soil were calculated based on Ulaby and Mironov dielectric models, respectively. The proposed method was tested using data from PORTOS-93 (INRA) experiments on measuring: total biomass (up to 3.3 kg/m^2), water content (43%-89%), height (up to 1m) and volumetric content (up to 0.6-0.8%) of wheat plants, moisture (from 5% to 36%), density and clay fraction content (27%) of the soil. As a result, it was shown, the coefficient of determination (R^2) and root-mean-square error (RMSE) appeared to be equal to R^2=0.999 and RMSE=2.2% when comparing the original and retrieved values of volumetric soil moisture. The retrieved values of total biomass (vegetation water content) with the coefficient of determination R^2=0.999 (0.998) and RMSE=16g/m^2 (0.7%) coincide with the original set values. Therewith, the bands from 4 GHz to 6 GHz and from 450 MHz to 1 GHz were used to retrieve the canopy biometric parameters and soil moisture, respectively.**

Keywords—Microwave remote sensing, unmanned aerial vehicle, ultra-wide band remote sensing, reflection coefficient, biomass, vegetation water content, soil moisture.

I. INTRODUCTION

In connection with the development of precision farming systems, the role of remote sensing methods for measuring the biometric parameters of vegetation canopy and soil moisture is increasing. The use of satellite microwave radiometry methods for individual farms is limited by a large spatial resolution (~10-40km). The use of synthetic aperture radars is limited by the mechanism of backscattered wave formation, due to mainly the degree of soil surface roughness, which makes it difficult to develop a common algorithm of soil moisture retrieval. In the future, the appearance of tandems of bistatic radar satellites in P-, L-bands, able to measure the coherent component of the reflection coefficient, will make it possible to offer multi-frequency polarimetric methods for sensing moisture (biometric parameters of vegetation). Currently unmanned aerial vehicles (UAVs), equipped with portable radars and radiometers, are capable to overcome existing limitations.

The investigation supported by the Russian Science Foundation and the Krasnoyarsk Regional Science Foundation, project № 22-17-20042.

Recently, research has been carried out on radar remote sensing of soil moisture [1], soil conductivity [2], soil surface deformations using radar interferometry methods [3], snow cover thickness and density [4], [5], minefield detection [6], arable layer thickness [7], from small UAVs with using of ultra-wideband (UWB) radars and single frequency radiometers [8]. However, the remote sensing problem of vegetation biometric parameters and soil moisture using UWB signals from UAVs has been poorly studied. This paper proposes a method for remote sensing biomass, water content in vegetation and soil moisture, which is suitable for practical use from a light UAV.

II. MODEL OF REFLECTION COEFFICIENT FROM THE VEGETATION CANOPY

Let a plane electromagnetic wave fall perpendicularly down onto the soil covered with a vegetation layer high of h_c. Neglecting the multiple reflections of waves in the canopy, the reflection coefficient, $R(f)$, for the layered structure of canopy-soil can be written in the following form:

$$R(f) = R_{ac} + (1 - R_{ac}^2)R_{cs}exp[4\pi if\sqrt{\varepsilon_c}h_c/c], \quad (1)$$

where R_{ac} and R_{cs} are the Fresnel reflection coefficients between air-canopy and canopy-soil boundaries, respectively, f is the wave frequency, ε_c is the relative complex permittivity (RCP) of vegetation canopy, c is the speed of light in vacuum. Model (1) neglects the phenomena of wave scattering on individual elements of plants, as well as the roughness of the soil surface. The geometry of the problem is shown in Fig. 1. RCP of canopy, we will calculate based on the refractive mixing dielectric model of air and vegetations:

$$n_c(f) = 1 + (n_v(f) - 1)\upsilon_v, \quad (2)$$

$$\kappa_c(f) = \kappa_v(f)\upsilon_v, \quad (3)$$

where $n_{c,v}$ and $\kappa_{c,v}$ are the refractive index and normalized attenuation coefficient of vegetation canopy (c) and separate plants (v), υ_v is the vegetation volumetric fraction (VVF) in the canopy.

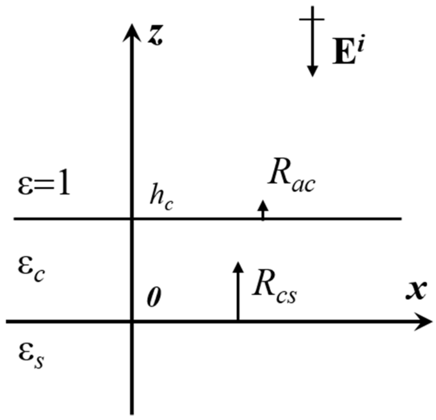

Fig. 1. Geometry of reflection problem.

The RCP is connected to the refractive index and normalized attenuation coefficient through the formula: $\sqrt{\varepsilon_{c,v}}=n_{c,v}+i\,\kappa_{c,v}$. RCP of vegetations $\varepsilon_v=\varepsilon_v(f,\, \boldsymbol{M_v},\, S)$, where S is the salinity of vegetations fluid, can be calculated based on the dielectric model [9]. The volumetric fraction of vegetation in the canopy is given by the equation:

$$\upsilon_v=\frac{V_v}{V}=\frac{M_v}{\rho_v V}, \quad (4)$$

where $\boldsymbol{V_v}$ and $\boldsymbol{V}$ are the volumes of vegetation materials and the test volume of canopy, $\boldsymbol{M_v}$ and ρ_v are the vegetation water content (by weight) and density of wet plants. Gravimetric moisture content is given by $\boldsymbol{M_v}=(\boldsymbol{m_{wet}}-\boldsymbol{m_{dry}})/\,\boldsymbol{m_{wet}}$, $\boldsymbol{m_{wet}}$ and $\boldsymbol{m_{dry}}$ are the weights of wet and dry vegetations. Comparison of the vegetation b-factor measured in radiometric experiments for various plant crops [10] with b-factor calculated based on the refractive model (3) in the plane wave propagation approximation shows satisfactory agreement (see Fig. 2).

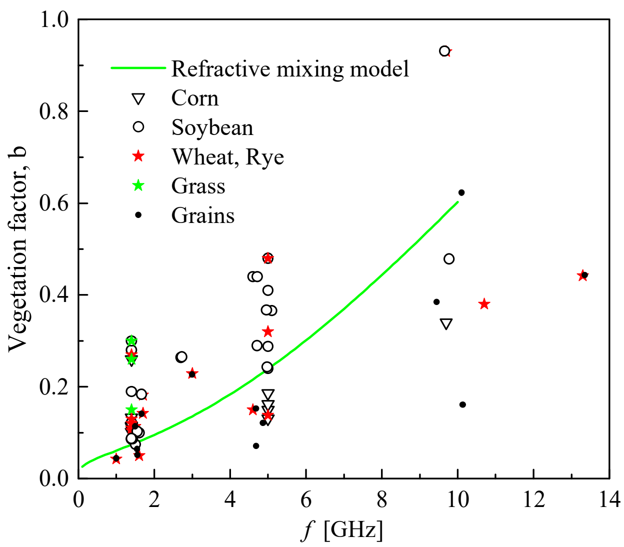

Fig. 2. Dependence vegetation b-factor vs frequency for a different kind of vegetation. Symbols indicate the experimental data of the work [10].

In this case, the optical thickness, τ, and b-factor were calculated from (1) and (3) using the formula: $\tau=bB$, where B is the total biomass [kg/m^2], $b=4\pi f\kappa_v(f)/(cM_v)$. Fig. 2 shows that the dispersion of the b-factor decreases with decreasing frequency, which is a consequence of the predominant wave attenuation over the scattering phenomenon in the vegetation cover. RCP of soil $\varepsilon_s=\varepsilon_s(f,\, W,\, \rho_d,\, M_{clay})$, where W is the volumetric water content, ρ_d is dry bulk density, M_{clay} is clay fraction by weight, was calculated using the Mironov model [11]. Two-relaxation Mironov's dielectric model is created based on RCP data for 6 types of mineral soils measured in the frequency range of 0.04–26.5 GHz. The clay, sand, and silt fractions in these soil samples varied from 7% to 76%, from 0% to 55%, and from 11% to 93%, respectively.

III. Method of Total Biomass, Vegetation Water Content, and Soil Moisture Retrieval

Put the case, that the upper air-vegetation boundary is rough, and has a smooth RCP gradient from 1.0 to ~1.2. As a result, reflections from the air-canopy interface can be completely neglected against the background of the amplitudes of reflected waves from the canopy-soil interface. In this case, model (1) for the module of the reflection coefficient can be further simplified, given the equality $\upsilon_v\boldsymbol{h_c}=\boldsymbol{M_v}/(\rho_v\boldsymbol{A})=\boldsymbol{B}/\rho_v$, where A is some area of the base of the investigated volume of vegetation canopy:

$$|R(f)|=|R_{cs}|exp[-4\pi\frac{f}{c}\kappa_v(f)\frac{B}{\rho_v}]. \quad (5)$$

Further, calculating the ratio $|\boldsymbol{R(f)}|/|\boldsymbol{R(f_1)}|$, where f_1, for example, the initial frequency in the spectrum of sensing waves, and taking the logarithm, we obtain:

$$\frac{c}{4\pi}ln\frac{|R(f)|}{|R(f_1)|}=\frac{B}{\rho_v(f_1\kappa_v(f_1)-f\kappa_v(f))}. \quad (6)$$

Based on equation (6), the minimization problem respect to $\{\boldsymbol{B},\boldsymbol{M_v}\}$ can be solved:

$$\{B,M_v\}=min\sum_{p=1}^{p=N}\left|ln\frac{|R(f_p)|}{|R(f_1)|}-\frac{B}{\rho_v(f_1\kappa_v(f_1)-f\kappa_v(f_p))}\right|, \quad (7)$$

where N is the number of frequencies in the range of spectrum of sensing waves, and $\rho_v\cong\boldsymbol{M_v}$. Finally, volumetric soil moisture, W, is found by solving the inverse problem from the module of the reflection coefficient (5) using the estimated values of $\{\boldsymbol{B},\boldsymbol{M_v}\}$. In this case, biometric parameters of vegetation and soil moisture are supposed to be found from the measured of reflectison coefficients in GHz and MHz frequency range, respectively. Such an approach, in the first case, will minimize the influence of soil RCP; in the second case, reduce wave attenuation and scattering in vegetation canopy and on the soil surface roughness.

IV. Result and Discussion

As a preliminary analysis, let's estimate the module of air-canopy and canopy-soil reflection coefficients based on model (1) and experimental data [12]-[13] of time series: total biomass (B), vegetation water content (VWC), vegetation volume fraction (VVF), vegetation height, volumetric soil moisture W. The measurement of these biometric parameters was carried out in France, INRA (Institut National de Recherches Agronomiques) Avignon test site (43°55 N, 4°53

E) on a field sown with wheat from 78 (March 19, 1993) to 180 day of the year. The soil of test site consists of silty clay loam soil with 62% silt, 11% sand, and 27% clay. For some days, biometric parameters of vegetation and soil are given in Table 1.

TABLE I. CANOPY AND SOIL MODELED PARAMETERS*

DoY	Canopy				Soil
	B [kg/m²]	*VWC [%]*	*h_c [m]*	*VVF [%]*	*W [%]*
119	0.67	89	0.24	0.3	35.6
155	3.27	75	0.94	0.4	13.9
180	2.24	49	0.92	0.5	27.5

*Vegetation fluid salinity, soil dry bulk density and clay fraction were set equal of *S*=9.7‰ [9], 1.2 g/cm³ and 27%, respectively.

As an example, based on the experimental data given in Table 1, the spectra of $\boldsymbol{n_c(f)}$ and $\kappa_c(f)$, and the module of the Fresnel reflection coefficients off the air-canopy and canopy-soil interface were calculated (see Fig. 3 and Fig. 4).

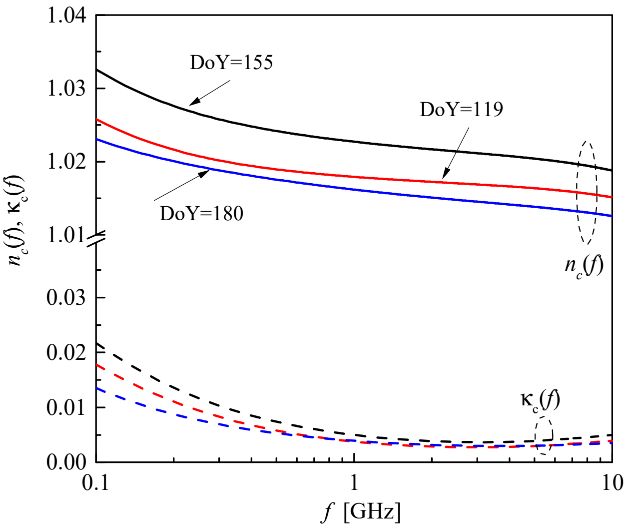

Fig. 3. Refractive index $n_c(f)$ and normalized attenuation coefficient $\kappa_c(f)$ of vegetation canopy for 119th, 155th, and 180th day of year .

In the frequency range from 100 MHz to 10 GHz, the canopy refractive index $\boldsymbol{n_c(f)}$ with a relative error of 2-3% deviates from the values of the air refractive index. From these calculations follows, that it is practically impossible to say anything about vegetation properties based on the measurement of the propagation delay time of an ultrawideband pulse in a canopy. From these calculations follows, that it is practically impossible to say anything about vegetation properties based on the measurement of the propagation delay time of an UWB pulse in a canopy. Close values of $\boldsymbol{n_c(f)}$ to 1.0 explain the very small amplitude from -35dB to -44dB of the reflection coefficient off the air-canopy boundary (see Fig. 4, dash lines). In this case, the contribution of reflection off the air-canopy boundary can be ignored in the total reflection coefficient (see Fig. 4, cyan curves, very weak interference is observed). In the frequency range less than 4 GHz, to identify the reflection from the upper boundary of the vegetation layer against the background of wave reflection from the lower boundary, the dynamic range of the radar system should be better than 30 dB (at the same time, the level of noise and synchronous interference should not exceed -35 dB÷-44 dB).

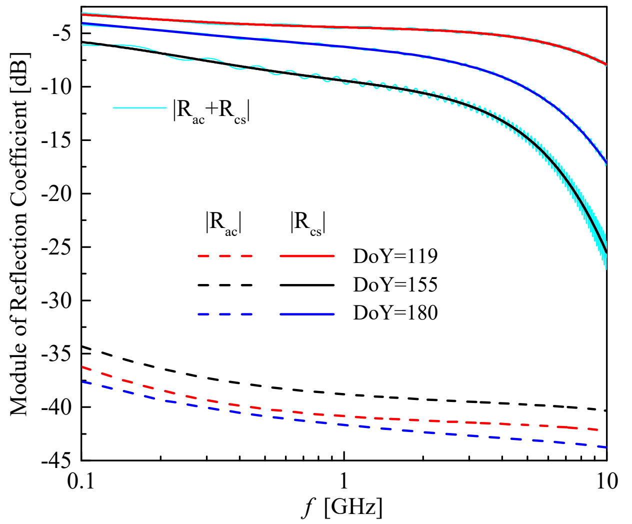

Fig. 4. Module of reflection coefficient off air-canopy $|R_{ac}|$, canopy-soil $|R_{cs}|$ boundary and module of total reflection coefficient $|R_{ac} + R_{cs}|$ for 119th, 155th, and 180th day of 1993 year.

However, this conclusion contradicts the experimental results of the work [14], in which, based on the measurement of time delays between pulses reflected from the upper and lower boundaries of the canopy layer, the vegetation biomass is estimated, see as well [15]. On the other hand, field measurements of the reflection coefficient from corn canopy confirm our estimates [16]. Apparently, this problem has not been studied enough and requires new experimental confirmation of the formation of stable reflections from the upper boundary of the canopy layer, depending on the biometric parameters of vegetation. In the frequency range of 2 GHz ÷ 8-10 GHz, there is a significant decrease in the reflection coefficient of more than 10 dB (see Fig. 4) as the total biomass and VWC increase, which allows to proposing a new spectral method (5)-(7) for measuring these biometric parameters of vegetation canopy.

As initial "measured" values, the normalized reflection coefficient $|\boldsymbol{R(f)}|/|\boldsymbol{R(f_1)}|$ was calculated using the time series of experimental data [12]-[13]: total biomass, VWC, VVF, canopy height, and soil surface moisture (similar to those given in Table 1). In accordance with the proposed method, inverse problems were solved to find the parameters $\{\boldsymbol{B}, \boldsymbol{M_v}\}$ and *W*. The conducted studies have shown that the most optimal frequency range for vegetation canopy biometric parameters retrieval is from 4 GHz to 6 GHz. The range from 450 MHz to 1 GHz was chosen to retrieve of soil moisture. Fig. 5 shows the time series of the retrieved values of $\{\boldsymbol{B}, \boldsymbol{M_v}\}$ and *W* from the "measured" values of the reflection coefficients. A high correlation and small RMSE values between the original and retrieved values can be noted. The coefficient of determination (R^2) and root-mean-square error (RMSE) appeared to be equal to R^2=0.999 and RMSE=2.2% when comparing the original and retrieved values of volumetric soil moisture. The retrieved values of total biomass (vegetation water content) with the coefficient of determination R^2=0.999 (0.998) and RMSE=16g/m² ($6.6\cdot10^{-3}$) coincide with the original set values (see Fig. 5).

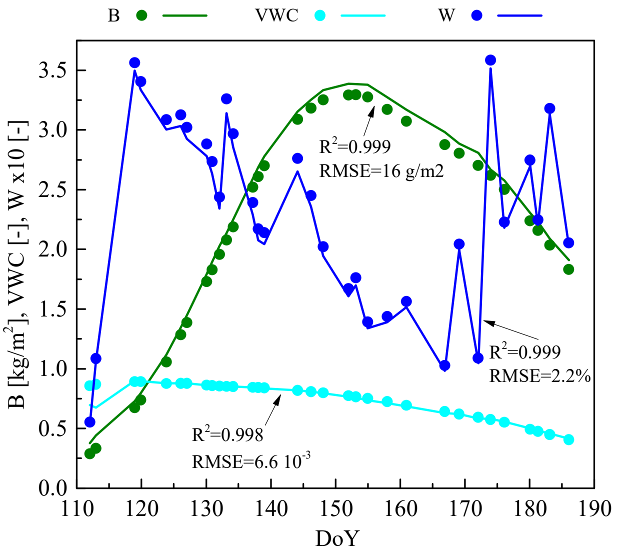

Fig. 5. Time dependence of measured (dots) and calculated (lines) values of total biomass, B (green), vegetation water content, VWC (cyan color) and volumetric soil water, W (blue).

V. CONCLUSION

In this paper, a method for the simultaneous measurement of total biomass, vegetation water content, and soil moisture is developed based on UWB observations of the module of the reflection coefficient in the frequency range from 450 MHz to 6 GHz. The created method does not take into account the scattering waves on the vegetation elements and on the soil surface roughness, which can lead to an underestimation of the retrieved biometric parameters of vegetation and soil moisture when processing real experimental data. The proposed model does not take into account the spherical divergence of the wavefront, as well as the height of the position of the phase center of radiating antenna above the soil surface. However, when the UAV flight height is more than several tens of meters, the wavefront near the soil surface can be approximately considered flat, the spherical divergence of which can be taken into account, for example, according to the method [17]. On the other hand, the proposed method is relative (see formula (6)), there is no need to take into account an exact height value of the antenna phase center above the reflective soil surface. Establishing the optimal frequency range for the spectral reflectometric measurements of vegetation biometrical parameters and soil moisture remains one of the open questions. In this paper, it is shown that to retrieve the vegetation biometric parameters with accuracy suitable for practical use, it is sufficient to use the wave spectral range from 2 GHz to 4 GHz. Since amplitude measurements are subject to significantly greater distortion compared to phase measurements, reliable measurements of the delay times between pulses reflected from the air-canopy and canopy-soil boundary could significantly improve the accuracy of measuring biometric parameters of vegetation. However, the arrival time of a pulse reflected from the air-canopy boundary is determined by the steepness of relative complex permittivity of the transition layer between the air and the middle part of the vegetation canopy, as well as the roughness of this boundary. As a result, the difference in pulse time arrivals between the upper and lower boundaries of the vegetation layer will always be less than the equivalent height of the canopy. In this regard, additional studies using more realistic models and new experimental data are needed.

REFERENCES

[1] K. Wu, G. A. Rodriguez, M. Zajc, E. Jacquemin, M. Clément, A. De Coster, S Lambot, “A new drone-borne GPR for soil moisture mapping,” Remote Sensing of Environment, vol. 235 (111456), p. 1–9, 2019, 10.1016/j.rse.2019.111456.

[2] K. Wu et al., “Low-Frequency Drone-Borne GPR for Soil Conductivity Mapping,” NSG2021 27th European Meeting of Environmental and Engineering Geo-physics, p.1 – 5, 2021. doi:10.3997/2214-4609.202120117

[3] D. Luebeck et al., “Drone-borne Differential SAR Interferometry,” Remote Sensing, V. 12(5), P. 778, 2020. doi:10.3390/rs12050778

[4] R.O.R. Jenssen et al., “Measurement of Snow Water Equivalent Using Drone-Mounted Ultra-Wide-Band Radar,” Remote Sens., v. 13, p. 2610, 2021. doi:10.3390/rs13132610

[5] K.V. Myzalevskiy, ”The remote sensing of snow water equivalent using broadband electromagnetic pulses from an UAV board,” Zhurnal Radioelektroniki [Journal of Radio Electronics], no.8, 2021. doi:10.30898/1684-1719.2021.8.1

[6] D. Šipoš et al., “A Lightweight and Low-Power UAV-Borne Ground Penetrating Radar Design for Landmine Detection,” Sensors, v. 20(8), p. 2234, 2020. doi:10.3390/s20082234

[7] J. Hou et al., “Application of Technology of UAV-Mounted Ground Penetrating Radar in the Study of the Thickness of Soil Plow Layer,” The 7th International Conference on Environmental Science and Civil En-gineering. IOP Conf. Series: Earth and Environmental Science, 2021. doi:10.1088/1755-1315/719/4/042074

[8] E. Dai, A. Venkitasubramony, A. Gasiewski, M. Stachura, and J. Elston, "High Spatial Soil Moisture Mapping Using Small Unmanned Aerial System," IEEE International Geoscience and Remote Sensing Symposium, 2018, pp. 6496-6499.

[9] F. T. Ulaby and M. A. El-rayes, "Microwave Dielectric Spectrum of Vegetation - Part II: Dual-Dispersion Model," IEEE Transactions on Geoscience and Remote Sensing, vol. GE-25, no. 5, pp. 550-557, 1987, doi: 10.1109/TGRS.1987.289833.

[10] A. A. Van de Griend and J.-P. Wigneron, "The b-factor as a function of frequency and canopy type at H-polarization," IEEE Transactions on Geoscience and Remote Sensing, vol. 42, no. 4, pp. 786-794, 2004, doi: 10.1109/TGRS.2003.821889.

[11] V. L. Mironov, P. P. Bobrov, S. V. Fomin, "Dielectric model of moist soils with varying clay content in the 0.04 to 26.5 GHz frequency range," Proceedings of International Siberian Conference on Control and Communications, 2013, p. 1-4.

[12] S.-F. Liu, Y.-A. Liou, W.-J. Wang, J.-P. Wigneron and J.-B. Lee, "Retrieval of crop biomass and soil moisture from measured 1.4 and 10.65 GHz brightness temperatures," IEEE Transactions on Geoscience and Remote Sensing, vol. 40, no. 6, pp. 1260-1268, 2002, doi: 10.1109/TGRS.2002.800277.

[13] J.-P. Wigneron et al., "A composite discrete-continuous approach to model the microwave emission of vegetation," IEEE Transactions on Geoscience and Remote Sensing, vol. 33, no. 1, pp. 201-211, 1995, doi: 10.1109/36.368208.

[14] V.I. Karpukhin, A.N. Peshkov, "Measurement of height and biomass of vegetation canopy by radar method," Proceedings of theory and technology of radar, radio navigation and radio communications in civil aviation, The Riga Institute of Civil Aviation Engineers, p.69-73, 1985.

[15] M. R. Mahmoudzadeh Ardekani, D. C. Jacques and S. Lambot, "A Layered Vegetation Model for GPR Full-Wave Inversion," IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 9, no. 1, pp. 18-28, 2016.

[16] G. Serbin, D. Or, “Ground-penetrating radar measurement of crop and surface water content dynamics,” Remote Sensing of Environment, vol. 96, no. 1, p. 119-134, 2005 ,doi: 10.1016/j.rse.2005.01.018.

[17] K. Muzalevskiy et al., "Synthesizing of Ultra-Wide Band Impulse by means of a Log-Periodic Dipole Antenna. Case Study for a Radar Stand Experiment," IEEE International Multi-Conference on Engineering, Computer and Information Sciences (SIBIRCON), Yekaterinburg, Russian Federation, 2022, pp. 1140-1143.