TRANSMISSION LINE THEORY BASED TWO LAYER MODEL FOR DETERMINING SOIL MOISTURE

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ABSTRACT:

Present paper deals with the task of estimating soil moisture under vegetation cover by using transmission line theory based two layer model. The two layer model measures the impedance of both the layers namely, soil and vegetation. This impedance is the function of dielectric constant and thickness of both the layers. For known dielectric constant and height of vegetation layer, dielectric constant of soil was determined for certain thickness of soil layer using genetic algorithm (GA). The soil moisture value was retrieved from dielectric constant of soil by using Topp et al.,(1980) relationship. Retrieved soil moisture values were in good agreement with observed values.

1. INTRODUCTION

Soil moisture estimation has gained much attention due to its importance in various applications, such as hydrology (Schmugge et al., 2002), agriculture (McNairn et al., 2004), etc. In past several methods have been developed for estimating soil moisture over bare soil surface (Oh et al., 1992; Dubois et al., 1995) at microwave bands. Application of these algorithms over vegetated surfaces causes under-estimation of soil moisture (Shi et al., 1997). These methods also show some limitation in estimating soil moisture under vegetated surface because vegetated surface represent multiple scattering effect *i.e.,* diffuse scattering from vegetation and surface scattering from underlying soil. In other terms, for vegetation covered soil, the emission of bare soil surface is very much influenced by the canopy layer which attenuates the soil emission and adds its own emission (Jackson et al., 1982).The separation of scattering contribution of both the media (vegetation and soil) using backscattering coefficient is still a very challenging task. Therefore, in this paper two layer model has been proposed and applied for estimating soil moisture under vegetation cover. Earlier this method has been used by several researchers for different applications, like, estimation of thickness of burnt coal seam (Tetuko et al., 2003a; Tetuko et al., 2003b), and topsoil of semiarid area (Al-Bilbisi et al., 2004). Mishra et al., (2012) have used the capability of this method in estimation of the thickness as well as moisture of two different layers of soil.

By using the concept of transmission line theory, series impedance of any media can be obtained as a function of dielectric constant and width (thickness) of that media. Therefore in this paper two layer model has been constructed assuming first layer as vegetation having thickness t_v and complex dielectric constant ε_1 and second layer as soil layer having thickness t_s and dielectric constant ε_2. For known dielectric constant and height of vegetation layer calculated during field survey, dielectric constant of soil was determined for certain thickness of soil layer using genetic algorithm (GA). The soil moisture value was retrieved from real part of complex dielectric constant of soil by using well-known polynomial relation proposed by Topp et al.

The present approach has been successfully evaluated on C-band radarsat-2 quad-pol data. The retrieved soil moisture values show the good agreement with the observed values of soil moisture.

2. STUDY AREA AND DATA SET

2.1 Study area

Present study has been performed over Roorkee region of India. The proposed approach has been evaluated on C-band (5.405 GHz) Radarsat-2 quad polarimetric data acquired on 31st May, 2011.

Ground truth survey was carried out over the study area on same date of image acquisition and two fields of sugarcane were selected as the test area. A total of 10 samples were collected from test area and fresh weight of samples, plant height, leaf area index, leaf thickness, etc., were also measured.

3. METHODOLOGY

The two layer model has been developed for modelling the scattered wave from two layers namely, vegetation and soil using the concept of transmission line theory. The whole procedure and physical significance of the model has been discussed below:

3.1 Two layer model

Two layer model was developed by assuming that media is composed of two layers namely, vegetation and soil having thickness t_v and t_s, respectively. There is infinite length of air above vegetation layer. The two-dimensional diagram for this model is shown in Fig.1. The analysis of two-layer model was performed by using the concept of transmission line theory. By taking the advantage of transmission line theory, impedance of each layer can be calculated as a function of dielectric constant and thickness of those layers. The equivalent circuit of this two-layer model is shown in Fig.2, where Z_{C1} and Z_{C2} symbolize effective series impedance of vegetation and soil layer, respectively, respectively while Z_{L1} and Z_{L2} symbolize parallel impedance of vegetation and soil layer, respectively. Z_T is the total input impedance. For simplicity, the parallel impedances of vegetation and soil layer *i.e.,* Z_{L1} and Z_{L2}, respectively are considered as zero in the analysis (Tetuko et al., 2003a; Tetuko et al.,2003b; Al-Bilbisi et al., 2004; Mishra et al., 2012).

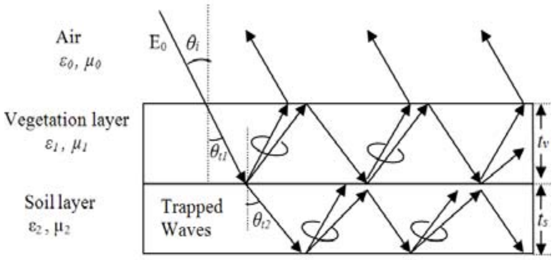

Fig.1. Two-dimensional diagram for two-layer modelling approach (Al-Bilbisi et al., 2004)

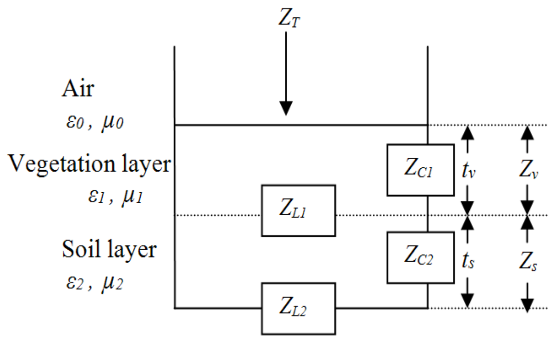

Fig.2. Equivalent circuit of two-layer model (Al-Bilbisi et al., 2004)

Using the concept of transmission line theory, impedances of vegetation and soil layers *i.e.*, Z_v and Z_s, respectively, were determined as,

$$Z_v = Z_{C1}\frac{Z_{L1} + Z_{C1}\tanh\gamma_{C1}t_v}{Z_{C1} + Z_{L1}\tanh\gamma_{C1}t_v} \quad (1)$$

$$Z_s = Z_{C2}\frac{Z_{L2} + Z_{C2}\tanh\gamma_{C2}t_s}{Z_{C2} + Z_{L2}\tanh\gamma_{C2}t_s} \quad (2)$$

where γ_{C1} and γ_{C2} are propagation constants of vegetation and soil layer, respectively.

The total input impedance Z_T seen looking towards vegetation and soil layers was determined by,

$$Z_T = Z_v + Z_s \quad (3)$$

After applying Snell's law, at the boundary between the air and vegetation layer, following relationship was obtained,

$$\sin\theta_i = \sqrt{\varepsilon_1\mu_1}\,\sin\theta_{t1} \quad (4)$$

where ε_1, μ_1 and θ_{t1} are complex dielectric constant, complex specific permeability and transmission angle of vegetation layer, as shown in Fig.1.

The incident wave E_0 was assumed to be a plane wave with incidence angle θ_i. Considering incidence of plane wave E_0 from air to vegetation layer, the propagation constant was derived as,

$$\gamma_{C1} = j\frac{2\pi}{\lambda}\sqrt{\varepsilon_1\mu_1 - \sin^2\theta_i} \quad (5)$$

The effective series impedance of vegetation layer was obtained as

$$Z_{C1} = Z_0\sqrt{\frac{\mu_1}{\varepsilon_1}}\cos\theta_{t1} \quad (6)$$

where Z_0 is intrinsic wave impedance of free space (*i.e.,* 120π ohms). Now, equation (1) can be written as

$$Z_v = \frac{Z_0}{\varepsilon_1}\sqrt{\varepsilon_1\mu_1 - \sin^2\theta_i}\,\tanh\left(j\frac{2\pi t_v}{\lambda}\sqrt{\varepsilon_1\mu_1 - \sin^2\theta_i}\right) \quad (7)$$

Similarly *Zs* can be calculated. After obtaining impedances of both the layer, total input impedance Z_T was calculated. The reflection coefficient is then determined by,

$$\Gamma = \frac{Z_T - Z_0\cos\theta_i}{Z_T + Z_0\cos\theta_i} \quad (8)$$

3.2 Retrieval of effective dielectric constant of vegetation layer

The complex dielectric constant of vegetation can be determined using Debye-Cole dual dispersion model (Ulaby et al., 1987).

$$\varepsilon_{veg} = \varepsilon_r + v_{fw}\varepsilon_{fw} + v_b\varepsilon_b \quad (9)$$

where ε_r, ε_{fw}, ε_b, v_{fw} and v_b are non-dispersive residual component, dielectric constant of free water, dielectric constant of bulk vegetation-bound water mixture, volume fraction of free water and volume fraction of bulk vegetation-bound water mixture, respectively. They can be calculated as,

$$\varepsilon_r = 1.7 - 0.74m_g + 6.16{m_g}^2 \quad (10)$$

$$\varepsilon_{fw} = 4.9 + \frac{75}{1 + jf/18} - j\frac{18\sigma}{f} \quad (11)$$

$$\varepsilon_b = 2.9 + \frac{55}{1 + (jf/0.18)^{0.5}} \quad (12)$$

$$v_{fw} = m_g(0.55m_g - 0.076) \quad (13)$$

$$v_b = 4.64\frac{{m_g}^2}{1 + 7.36{m_g}^2} \quad (14)$$

where m_g is gravimetric moisture of vegetation which can be calculated as, (Ulaby et al., 1984);

$$m_g = \frac{\text{wet weight of vegetation - dry weight of vegetation}}{\text{wet weight of vegetation}} \quad (15)$$

In equations (11)-(12), f is frequency in GHz and σ is ionic conductivity in Siemens per meter. The value of σ is taken as 1.27 Siemens/m (Ulaby et al., 1987).

The effective dielectric constant of canopy (*i.e.,* ε_1) (Ulaby et al., 1986) can be calculated as,

$$\varepsilon_1 = [1 + vf({\varepsilon_{veg}}^{\beta} - 1)]^{\beta} \quad (16)$$

where vf is volume fraction of canopy filled with vegetation and β is the indicator of used dielectric mixing. In the present analysis refractive model (β=0.5) has been used because it fits well for longer wavelengths (λ>5cm) (Schmugge et al.,1992).

3.3 Implementation of two layer model on SAR data

After pre-processing radarsat-2 data using SARscape software, complex reflection coefficient was retrieved for *VV* polarization over the test area representing sugarcane field. This reflection coefficient was used to obtain total impedance Z_T from equation (8), with θ_i equals to 34.42°, for radarsat-2 data.

In order to calculate impedance of vegetation layer *apriori* knowledge of effective dielectric constant ε_1 and width t_v of vegetation layer was required. Therefore, a total of 10 samples were collected from two sugarcane fields. The samples were dried in oven at 80°C for 12 hours and gravimetric moisture (m_g) was calculated by using equation (15). During survey height of vegetation layer (sugarcane) t_v was obtained as 130cm. Volume fraction of canopy was obtained as 0.0012. Now impedance of vegetation layer Z_v was obtained from equation (7) for calculated dielectric constant ε_1 and plant height t_v. The series impedance of soil layer *say,* $Z_{s(OBSERVED)}$ was obtained by subtracting Z_v from Z_T.

3.4 Use of Genetic algorithm (GA) for retrieving dielectric constant of soil

It was observed that impedance of soil layer *say*, $Z_{s(CALCULATED)}$ was nonlinear function of dielectric constant ε_2 and soil thickness t_s. Since we are interested in measuring soil moisture in first few centimetres of soil surface, therefore t_s was assumed to be 5cm in the present analysis. Now in order to retrieve complex dielectric constant ε_2 genetic algorithm approach has been used. Genetic algorithm is optimization based approach which is used to determine maximum or minimum of any arbitrary function, depending upon the nature of problem (Tseng et al., 2008). The most critical step of genetic algorithm is proper selection of fitness function for accurate determination of solution close to optimal results (Mishra et al., 2012).The fitness function for the current problem is defined as,

$$Fitness\ fn = \left| Z_{s(CALCULATED)} - Z_{s(OBSERVED)} \right| \quad (17)$$

where $Z_{s(OBSERVED)}$ is the impedance of soil layer obtained from equation (3) after subtraction of Z_v from Z_T , and $Z_{s(CALCULATED)}$ is impedance of soil layer which can be represented as follows:

$$Z_s = \frac{Z_0}{\varepsilon_2}\sqrt{\varepsilon_2\mu_2 - \sin^2\theta_i}\ \tanh\left(j\frac{2\pi t_s}{\lambda}\sqrt{\varepsilon_2\mu_2 - \sin^2\theta_i} \right) \quad (18)$$

The complex dielectric constant of soil is given by,

$$\varepsilon_2 = \varepsilon_2' - j\varepsilon_2'' \quad (19)$$

where real part ε_2' is the permittivity of soil whereas imaginary part ε_2'' is the dielectric loss factor of soil After applying genetic algorithm on fitness function, complex dielectric constant ε_2 was retrieved.

3.5 Retrieval of soil moisture

The soil moisture is retrieved by using Topp et al.,(1980) relationship. This polynomial relates real part of complex dielectric constant of soil to volumetric soil moisture value m_v. It is given by,

$$m_v = -5.3\times10^{-2} + 2.92\times10^{-2}\varepsilon_2' - 5.5\times10^{-4}\varepsilon_2'^2 + 4.3\times10^{-6}\varepsilon_2'^3 \quad (20)$$

4. RESULTS AND DISCUSSION

Genetic algorithm was applied over the fitness function given in equation (17) and complex dielectric constant of soil was retrieved for 5cm thickness of soil surface. The constraint boundaries for real and imaginary part of dielectric constant ε_2 were taken as (3-50) and (0.01 -10), respectively.

Table-I- Soil parameters retrived from two-layer model

	Average soil moisture		Average permittivity of soil (ε_2')
	Measured through GA	Ground truth values	
Field 1	0.35539	0.369	23.77
Field 2	0.417668	0.434	27.22

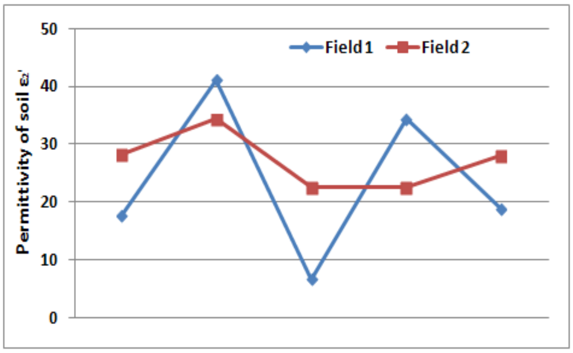

Fig.3 Permittivity of soil retrieved after application of genetic algorithm for the collected samples in two fields of sugarcane (5 samples were collected in each field).

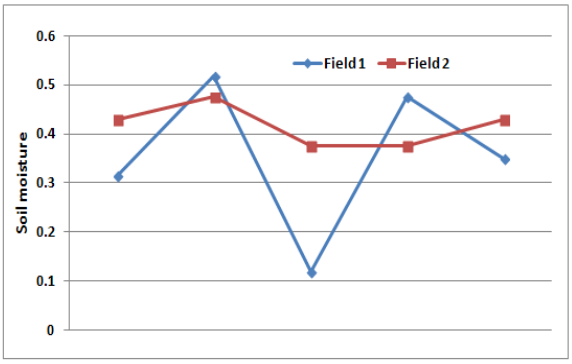

Fig.4. Soil moisture in first 5cm layer of soil surface in two fields of sugarcane for the collected samples in two fields of sugarcane.

Fig. 3 shows the values of permittivity of soil *i.e.,* ε_2' for both fields of sugarcane. These values were used to retrieve soil moisture values using equation (20). Fig 4 shows soil moisture in first 5cm layer for two fields of sugarcane.

Table-1 shows the average value of permittivity and soil moisture retrieved by optimization using genetic algorithm (GA). Average value of soil moisture measured during ground truth survey is also shown in this table. It can be observed from the table that average soil moisture value is in good agreement with the measured ground truth-values of soil moisture in both the fields of sugarcane.

5. CONCLUSION

In the present paper transmission line theory based two layer model has been developed for estimating soil moisture under vegetation cover. For this purpose C-band radarsat-2 data has been used. The proposed approach has been evaluated on *VV* polarization of radarsat-2 data. In order to retrieve soil moisture under vegetation cover, two fields of sugarcane were selected in the study area. The developed two- layer model gives quite good results for retrieval of soil moisture. Retrieved soil moisture values are in good agreement with the observed ground truth values of soil moisture.

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