Profile Soil Moisture Estimation Using the Modified IEM

Jeffrey P. Walker[1], Peter A. Troch[2], Marco Mancini[3], Garry R. Willgoose[1] and Jetse D. Kalma[1]
[1]*Department of Civil, Surveying and Environmental Engineering, The University of Newcastle, Callaghan, 2308, AUSTRALIA*
[2]*Laboratory of Hydrology and Water Management, University of Gent, Coupure Links 653, 9000 Gent, BELGIUM*
[3]*Polimi, Dipartimento di Ingegneria Idraulica, Ambientale e del Rilevamento Piazzo Leonardo da Vinci 32, I-20133 Milano, ITALY*
Tel: +61 49 216073, Fax: +61 49 216991, email: cejpw@cc.newcastle.edu.au

Abstract - A variable transition rate factor is proposed for the modified IEM, such that it uses a variable dielectric profile down to the radar observation depth. A theoretical observation depth model is also proposed. It is shown that radar observation depth calculated by this model agrees with values noted in literature, and that backscattering simulations using the variable transition rate factor compare well with data collected in the European Microwave Signature Laboratory (EMSL) experiments.

INTRODUCTION

Soil moisture in the root zone is a key parameter in meteorology, hydrology and agriculture. The significance of soil moisture is its role in the partitioning of energy at the ground surface into sensible and latent heat exchange with the atmosphere, and the partitioning of precipitation into infiltration and runoff [1, 2]. As remote sensing observations only respond to the soil moisture in a thin surface layer, observations of surface soil moisture must be related to the complete soil moisture profile in the unsaturated zone, to be of use for climatic, hydrologic and agricultural studies [3].

The problem of relating surface soil moisture to that of the profile has been studied for the past two decades. Four approaches have been adopted: regression, knowledge-based, inversion, and combinations of remotely sensed data with soil water balance models [4].

A recent attempt to relate passive microwave observations of surface soil moisture to that of the profile has been made, where a radio-brightness temperature model and coupled soil heat and moisture transfer model have been combined in the context of a Kalman filter [1]. In order to extend this approach to radar observations, the backscattering equations must be related to the complete soil moisture profile. Using a series of separate regression relationships between soil moisture and backscattering coefficient for different depths of soil, an empirical method of relating a single backscattering observation to the soil moisture profile in the top 10 cm layer has been presented [5]. Apart from this, all empirical and semi-empirical backscattering models have been related to a single soil moisture value in the top 2-5 cm. Furthermore, until recently all theoretical backscattering models have been formulated as a function of the dielectric constant of the soil at the air-soil interface, and have not accounted for the effects of volume scattering in the soil.

A modification to the theoretical backscattering IEM (Integral Equation Model) was proposed by [6], to account for volume scattering from a drying profile. This modification was made by replacing the Fresnel reflection coefficients with a modified set of reflection coefficients, which incorporate a dielectric profile. In so doing, an exponential dielectric profile model was used, in which the relative dielectric constant (ε_r) as a function of depth (z) is given by:

$$\varepsilon_r(z) = 1 + \left(\varepsilon_{r_\infty} - 1\right)\frac{\exp(mz)}{1 + \exp(mz)} \quad (1).$$

The inputs to this dielectric model are the transition rate factor m (which controls the rate of change of ε_r with depth) and the dielectric constant at depth $z=\infty$ (ε_{r_∞}). By (1), the relative dielectric constant starts from 1 in air and gradually changes to ε_{r_∞} at the rate m. It has been suggested that a value for m equal to about 12 cm^{-1} is appropriate, and this was shown to be an improvement in the simulation of backscattering when compared to the IEM [6].

However, a value of m=12 cm^{-1} suggests that the modified IEM may only be used to relate backscattering observations over a profile depth of around 3 mm. This limits application of the model, as a variable dielectric profile over a depth of 3 mm does not provide any additional information on the soil moisture profile than the surface scattering models. Furthermore, various authors have noted that radar observation depth is of the order of a few tenths of a wavelength [2], and varies as a function of soil conditions and radar configuration.

This paper presents a variation on the modified IEM, such that it uses a variable dielectric profile down to the radar observation depth, by using a variable transition rate factor. In order to estimate the radar observation depth, an observation depth model is required.

A radar penetration depth relationship has been proposed by [7]. This relationship defines penetration depth, as the depth at which the transmitted power in the soil has diminished to the proportion 1/*e* (ie. 37%). However, if the transmitted wave has lost 63% of its power to penetrate to this depth, it is unlikely to provide a detectable contribution to backscattering upon return to the surface from this depth.

0-7803-3839-1/97 $10.00(c) IEEE

Hence, this relationship does not correspond with the observation depth of the radar. Therefore a theoretical radar observation depth model which accounts for soil moisture, observation frequency, incidence angle and wave polarisation is proposed.

VARIABLE TRANSITION RATE FACTOR

As m governs the depth over which a varying dielectric profile is imposed on the theoretical backscattering model, through the modified reflection coefficients, it is proposed that m should be a function of the observation depth. The proposed method for specifying m and ε_{r_∞} in the modified IEM is as follows. (i) Estimate the observation depth d for the given observation conditions; (ii) Evaluate from (1) an appropriate value of m such that $\varepsilon_r(z) = \varepsilon_{r_\infty}$ at $z = d$; (iii) As the radar can only "see" as deep as the observation depth, the value given to ε_{r_∞} in the model should be the value at depth d.

OBSERVATION DEPTH RELATIONSHIP

As no quantitative relationships for radar observation depth which account for soil moisture could be found in literature, we propose a theoretical amplitude attenuation model. This model compares the amplitude of the volume scattered wave with that of the surface scattered wave, as illustrated in Fig 1. The theoretical basis for this model is that when the amplitude of the volume scattered wave (E_{vol}) falls below some proportion of the surface scattered wave amplitude (E_{sur}), it is no longer making a detectable contribution to the total backscattering from the dielectric medium. Hence, the maximum depth from which a volume scattered wave is returned to the surface such that it just satisfies an imposed limit of E_{vol}/E_{sur}, may be considered as the observation depth (d).

The model treats the soil as consisting of two dielectric layers, with the intermediate boundary representing a dielectric discontinuity in the soil. Using the Fresnel reflection (R) and transmission (T) coefficients (functions of soil dielectric constant, incidence angle and wave polarisation) and the incident wave amplitude (E_i), the reflected (E_{sur}) and transmitted (E_t) wave amplitudes are evaluated at the soil surface. The amplitude of the transmitted wave is then attenuated by an amplitude attenuation factor (a) [8], as it passes through the surface layer to the dielectric discontinuity. Upon reaching this discontinuity, the attenuated wave (E_t') is reflected. The reflected wave (E_r) arrives back at the surface with further attenuated amplitude (E_r'), where it again undergoes transmission and reflection. The amplitude of this transmitted wave (E_{vol}) is then compared with that for the surface reflected wave (E_{sur}), and the layer thickness altered

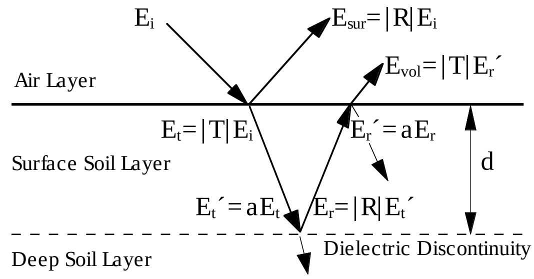

Fig. 1: Diagrammatic illustration of observation depth model.

until the imposed ratio between the surface scattered and volume scattered waves is achieved.

A major weakness of the above model is the assumption of a homogeneous specular reflecting surface at the layer interfaces. However, the volume scattered waves may be expected equally in all directions, as volume scattering is caused by dielectric discontinuities whose spatial locations are random [7]. Therefore, if the soil surface is lambertian, evaluation of the observation depth using the specular model will yield the same results.

A difficulty associated with evaluating this observation depth model is the specification of an appropriate limit on the ratio of volume scattered wave amplitude to surface scattered wave amplitude. This problem is addressed through an error analysis of the backscattering equation [9]

$$\frac{E_{vol}}{E_{sur}} = \partial\sigma^{\circ}\frac{\ln 10}{20} \qquad (2),$$

by considering the sensitivity of the backscattering coefficient ($\partial\sigma^{\circ}$) to soil moisture and calibration accuracy of the sensor. In the first case, for a 2% change in soil moisture, there can be between 0.15 to 1 dB change in backscattering coefficient [10]. For the latter case, the literature suggests an absolute radiometric calibration accuracy between 1 and 2 dB [11]. Therefore, calibration accuracy appears to govern the observable influence of volume scattering at the present time. Hence a backscattering sensitivity of about 1.5 dB is appropriate, yielding a ratio of volume to surface scattering of 0.17.

APPLICATION OF THE MODELS

Both the observation depth model and variable transition rate factor have been tested using data collected in the European Microwave Signature Laboratory (EMSL) experiments [3]. Simulations for the modified IEM with variable transition factor are also compared with the IEM and modified IEM for m=12 cm^{-1}.

Fig. 2 indicates that the proposed observation depth model gives values which correspond with those suggested in literature, while Fig. 3 indicates that the modified IEM with a

0-7803-3839-1/97 $10.00(c) IEEE

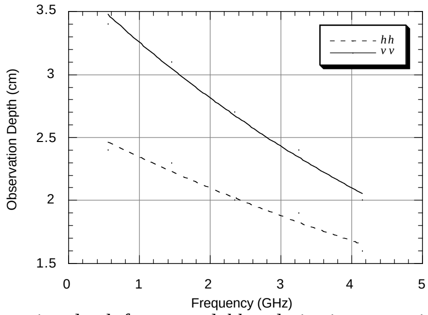

Fig. 2: Observation depth for *vv* and *hh* polarisation at an incidence angle of 23° and average volumetric soil moisture of 9%.

variable transition rate factor yields good results when compared to EMSL data. Furthermore, the simulations of backscattering coefficient at low frequencies are an improvement on those from the IEM and the modified IEM with m=12 cm^{-1}, for this particular data set.

CONCLUSIONS

The comparisons of backscattering simulations using the modified IEM with a variable transition rate factor show good agreement with the EMSL data. We conclude that by using the modified IEM with a variable transition rate factor, soil moisture profiles to a depth of 3.5 cm may be determined at low frequencies. Furthermore, the theoretical model presented for estimating radar observation depth gives comparable results to those suggested in literature.

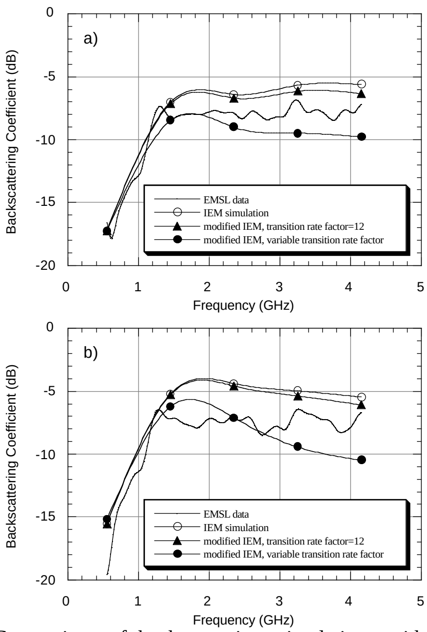

Fig. 3: Comparison of backscattering simulations with EMSL data for correlation length of 60 mm, rms roughness height of 25 mm, incidence angle of 23° and; a) *hh* polarisation, b) *vv* polarisation.

ACKNOWLEDGMENTS

Comments made by Zhongbo Su and Rudi Hoeben (University of Gent) are gratefully acknowledged.

REFERENCES

[1] D. Entekhabi, H. Nakamura, and E. G. Njoku, “Solving the inverse problem for soil moisture and temperature profiles by sequential assimilation of multifrequency remotely sensed observations,” *IEEE Trans. Geosci. Remote Sensing*, vol. 32, pp. 438-448, 1994.

[2] T. J. Jackson, T. J. Schmugge, and E. T. Engman, “Remote sensing applications to hydrology: soil moisture,” *J. Hydrol. Sci.*, vol. 41, pp. 517-530, 1996.

[3] M. Mancini, F. Vandersteene, P. A. Troch, O. Bolognani, G. Terzaghi, G. D'Urso, et al., “Experimental setup at the EMSL for retrieval of soil moisture profiles using multifrequency polarimetric data,” presented at International Geoscience and Remote Sensing Symposium, Firenze, Italy, 1995.

[4] K. G. Kostov and T. J. Jackson, “Estimating profile soil moisture from surface layer measurements - A review,” presented at The International Society for Optical Engineering, Orlando, Florida, 1993.

[5] L. Bruckler, H. Witono, and P. Stengel, “Near surface soil moisture estimation from microwave measurements,” *Remote Sens. Environ.*, vol. 26, pp. 101-121, 1988.

[6] A. K. Fung, M. S. Dawson, K. S. Chen, A. Y. Hsu, E. T. Engman, P. O. O'Neill, et al., “A modified IEM model for scattering from soil surfaces with application to soil moisture sensing,” presented at International Geoscience and Remote Sensing Symposium, Nebraska, USA, 1996.

[7] F. T. Ulaby, R. K. Moore, and A. K. Fung, *Microwave remote sensing, active and passive, Volume II: Radar remote sensing and surface scattering and emission theory*. Norwood, MA: Atech House, Inc., 1982.

[8] F. T. Ulaby, R. K. Moore, and A. K. Fung, *Microwave remote sensing, active and passive, Volume I: Microwave remote sensing fundamentals and radiometry*. Norwood, MA: Artech House, Inc., 1981.

[9] A. K. Fung, *Microwave scattering and emission models and their applications*. London: Artech House, 1994.

[10] E. Altese, O. Bolognani, M. Mancini, and P. A. Troch, “Retrieving soil moisture over bare soil from ERS 1 synthetic aperture radar data: Sensitivity analysis based on a theoretical surface scattering model and field data,” *Water Resour. Res.*, vol. 32, pp. 653-661, 1996.

[11] M. Zink, P. Olivier, and A. Freeman, “Cross-calibration between airborne SAR sensors,” *IEEE Trans. Geosci. Remote Sensing*, vol. 31, pp. 237-245, 1993.

0-7803-3839-1/97 $10.00(c) IEEE