A Soil Moisture Algorithm Using Tilted Bragg Approximation

Yunjin Kim and Jakob van Zyl
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109-8099
Tel: (818) 354-9500
Fax: (818) 393-3379
E-mail: yunjin.kim@jpl.nasa.gov

Jiancheng Shi
Institute for Computational Earth System Science
University of California
Santa Barbara, CA 93106

ABSTRACT

A successful soil moisture algorithm using radar data must identify the soil moisture effect and the surface roughness dependence explicitly since rough surface scattering depends on both the roughness and the dielectric constant of an imaged surface. For bare surfaces, several algorithms have been developed to estimate soil moisture using polarimetric radar data. These algorithms were empirically derived from either experimental data or numerical data instead of starting from rough surface scattering theories. In this paper, we present a soil moisture algorithm theoretically derived using the tilted Bragg approximation. With appropriate approximations using the tilted Bragg theory, we have derived both co- and cross- polarization ratios. Then, a soil moisture algorithm is developed based on these two ratios. This new algorithm is compared with the existing empirical methods using input data from the IEM (Integral Equation Method) and experimental radar data. We also briefly discuss the effect of vegetation on this soil moisture algorithm.

I. INTRODUCTION

Knowledge of the land hydrosphere state is a key to understanding the global water and energy cycle. The global hydrologic cycle is an endless process linking water in the atmosphere, on the continents, and in the oceans. More than 50% of the water that falls on land returns to the atmosphere, and the remaining water runs off on the surface through streams and lakes or infiltrates into the ground. Soil moisture plays an important role in the interactions between the land surface and the atmosphere and the partitioning of precipitation into runoff and ground water storage. Therefore, soil moisture is the critical information needed in numerous Earth science areas and has significant applications in the weather prediction and agriculture.

Even though soil moisture is a key parameter, it is not widely used due to the difficulty in measuring soil moisture accurately in a large area with sufficient spatial resolution. A space-borne mission, like HYDROS, will revolutionize the global soil moisture measurement. For SAR measurements, several successful algorithms have been reported using polarimetric radar data to estimate soil moisture [1,2,3]. These algorithms were developed based on experimental data or numerical scattering data. The experimental data were collected using ground scatterometers and the numerical data were generated using the IEM. Since rough surface scattering depends on the surface roughness and the dielectric constant of a rough surface, it is necessary to have more than one input measurement. Therefore, SAR data from a single polarization radar are not suitable for estimating soil moisture even though the relative soil moisture variation can be monitored using time series, single polarization data. In order to understand the polarimetric scattering characteristics, we have developed a theoretically derived algorithm that is valid beyond the SPM (Small Perturbation method) limit. For example, there is no cross polarization component predicted under the SPM. Based on the SPM, the linear co-polarization ratio does not depend on surface roughness. The existing experimental data clearly have demonstrated that this ratio depends on surface roughness. We show in this paper that this surface roughness dependence can be explained using the tilted Bragg approximation.

In this paper, we first derive a soil moisture algorithm under the tilted Bragg approximation. Then, the accuracy of the algorithm is compared with that of the existing algorithms. The noise sensitivity and the vegetation effect

of the proposed algorithm is briefly discussed. Finally, we conclude this paper by summarizing the results of our study.

II. A SOIL MOISTURE ESTIMATION ALGORITHM USING THE TILTED BRAGG APPROXIMATION

In order to improve the SPM, the tilted Bragg approximation can be implemented. Under this approximation, both co- and cross-polarization ratios can be derived as

$$\frac{\sigma_{hhhh}}{\sigma_{vvvv}} \approx \frac{\left[1-\frac{2\langle h_y^2\rangle}{\sin^2\theta}\right]|\alpha_{hh}|^2+\frac{2\langle h_y^2\rangle}{\sin^2\theta}|\alpha_{hh}||\alpha_{vv}|}{\left[1-\frac{2\langle h_y^2\rangle}{\sin^2\theta}\right]|\alpha_{vv}|^2+\frac{2\langle h_y^2\rangle}{\sin^2\theta}|\alpha_{hh}||\alpha_{vv}|} \tag{1}$$

$$\frac{\sigma_{hvhv}}{\sigma_{vvvv}} \approx \frac{\frac{\langle h_y^2\rangle}{\sin^2\theta}\left[|\alpha_{hh}|-|\alpha_{vv}|\right]^2}{\left[1-\frac{2\langle h_y^2\rangle}{\sin^2\theta}\right]|\alpha_{vv}|^2+\frac{2\langle h_y^2\rangle}{\sin^2\theta}|\alpha_{hh}||\alpha_{vv}|} \tag{2}$$

where

$$|\alpha_{hh}| = \left|\frac{1-\varepsilon}{\left(\cos\theta+\sqrt{\varepsilon-\sin^2\theta}\right)^2}\right| \tag{3}$$

$$|\alpha_{vv}| = \left|(\varepsilon-1)\frac{\left[\sin^2\theta-\varepsilon\left(1+\sin^2\theta\right)\right]}{\left(\varepsilon\cos\theta+\sqrt{\varepsilon-\sin^2\theta}\right)^2}\right| \tag{4}$$

Here, ε is the dielectric constant, θ is the incidence angle, and h_y is the azimuth slope. The ground azimuth slope causes the polarization rotation as shown in equation (1). Unlike the SPM, the cross polarization component can be obtained using the tilted Bragg approximation as expressed in (2). The range direction slope that causes the incidence angle change was ignored since the surface power spectrum modification is independent of polarization. The frequency dependence is implicitly included in the azimuth slope $\langle h_y^2\rangle$. In order to estimate soil moisture, the dielectric constant must satisfy equation (5) for a given incidence angle.

$$\frac{R_x|\alpha_{vv}|^2}{\left(|\alpha_{hh}|-|\alpha_{vv}|\right)^2+2R_x|\alpha_{vv}|^2-2R_x|\alpha_{hh}||\alpha_{vv}|} = \left(\frac{1}{2}\right)\frac{|\alpha_{hh}|^2-R_c|\alpha_{vv}|^2}{|\alpha_{hh}|^2-R_c|\alpha_{vv}|^2+R_c|\alpha_{hh}||\alpha_{vv}|-|\alpha_{hh}||\alpha_{vv}|} \tag{5}$$

where

$$R_c = \frac{\sigma_{hhhh}}{\sigma_{vvvv}} \tag{6}$$

$$R_x = \frac{\sigma_{hvhv}}{\sigma_{vvvv}} \tag{7}$$

Notice that equation (5) is independent of the radar frequency.

III. COMPARISON WITH EXISTING SOIL MOISTURE ALGORITHMS

Oh *et al.* [1] developed an empirical model based on polarimetric radar measurements and the scattering behavior in limiting cases. Another empirical algorithm for estimating soil moisture was derived by Dubois *et al.* using scatterometer data [2]. This algorithm does not require weaker cross polarization measurements to be less sensitive to the radar systematic noise and the presence of vegetation. Shi *et al.* developed a soil moisture algorithm based on a fit of numerical data generated by the single scattering IEM [3]. We compare these three algorithms with the tilted Bragg solution shown in equation (5). An estimation using the SPM was also compared to understand the improvement achieved by the tilted Bragg algorithm. At the incidence angles between 35 deg. and 55 deg., the tilted Bragg solution is more accurate than all other algorithms under the volumetric soil moisture less than 30% when we used the numerical data from the IEM. In addition, the soil moisture estimation difference between the SPM algorithm and the tilted Bragg algorithm is a good indicator of surface roughness. However, the tilted Bragg solution is not as accurate as the empirical

algorithms when we used the experimental scatterometer data. Notice that both algorithms in [1] and [2] were derived from the same experimental data. It is difficult to characterize the surface condition accurately for the experimental data. It is also not easy to reduce the speckle noise significantly since it is difficult to find the statistically independent surfaces with the same statistics. We must understand the validity of the experimental data and the limitation of the tilted Bragg approximation in order to verify the accuracy and the sensitivity of the proposed algorithm.

III. VEGETATION EFFECTS

When the surface is covered by vegetation, an algorithm based on surface scattering may not be accurate enough to provide reliable soil moisture. This is the main reason that a longer wavelength radar is preferable for soil moisture measurements since the vegetation effect can be reduced. At L-band, it is reasonable to assume that the dominant vegetation scattering mechanism is randomly oriented dipole scattering. Under this condition, equations (1) and (2) can be written as

$$\frac{\sigma_{hhhh}}{\sigma_{vvvv}} \approx \frac{\left[1-\frac{2\langle h_y^2\rangle}{\sin^2\theta}\right]|\alpha_{hh}|^2+\frac{2\langle h_y^2\rangle}{\sin^2\theta}|\alpha_{hh}||\alpha_{vv}|+V}{\left[1-\frac{2\langle h_y^2\rangle}{\sin^2\theta}\right]|\alpha_{vv}|^2+\frac{2\langle h_y^2\rangle}{\sin^2\theta}|\alpha_{hh}||\alpha_{vv}|+V} \tag{8}$$

$$\frac{\sigma_{hvhv}}{\sigma_{vvvv}} \approx \frac{\frac{\langle h_y^2\rangle}{\sin^2\theta}\left[|\alpha_{hh}|-|\alpha_{vv}|\right]^2+\frac{1}{3}V}{\left[1-\frac{2\langle h_y^2\rangle}{\sin^2\theta}\right]|\alpha_{vv}|^2+\frac{2\langle h_y^2\rangle}{\sin^2\theta}|\alpha_{hh}||\alpha_{vv}|+V} \tag{9}$$

where the vegetation backscattering cross section is denoted by V assuming that the vegetation scattering is statistically independent of the surface scattering. When V becomes larger, the co-polarization ratio becomes unity and the cross polarization ratio becomes larger. Therefore, the estimated soil moisture will be lower than the actual value.

IV. CONCLUSIONS

In this paper, we presented a soil moisture algorithm using the tilted Bragg approximation. This algorithm was compared with the existing soil moisture algorithms. Even though the proposed algorithm shows excellent results using the IEM data, it did not perform well using the experimental data. We conjecture that this algorithm is more sensitive to the system noise and the presence of vegetation. More study is needed to modify the algorithm to reduce the system noise contamination and the vegetation effect.

ACKNOWLEDGMENT

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

[1] Y. Oh, K. Sarabandi, F. T. Ulaby, "An empirical model and an inversion technique for radar scattering from bare soil surfaces," IEEE Trans. Geosci. Remote Sens., Vol. 30, No. 2, pp. 370-381, 1992.

[2] P. C. Dubois, J. van Zyl, and T. Engman, "Measuring soil moisture with imaging radars," IEEE Trans. Geosci. Remote Sens., Vol. 33, No. 4, pp. 915-926, 1995.

[3] J. Shi, J. Wang, A. Y. Hsu, P. E. O'Neill, E. T. Engman, "Estimation of bare surface soil moisture and surface roughness parameter using L-band SAR image data," IEEE Trans. Geosci. Remote Sens., Vol. 35, No. 5, pp. 1254-1266, 1997.