Effect of standing stubble on radar backscatter from harvested rice fields

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The radar backscatter from standing rice stubble in a harvested rice field is computed numerically using the method of moments with the equivalence principle and impedance sheet theory. The radar backscatter from a bare surface is also computed based on an empirical model, and combined with the numerical results from the standing rice stubble. Based on the analyses of the radar backscatter for various conditions of standing stubble, it is found that the effect of the standing stubble in a typical harvested rice field is negligible when the water content of the stubble is less than about 40%.

Introduction: Rice stubble is left standing and undisturbed for six months in Korea from the grain harvest in October until April of the following year. Therefore, the radar backscatter from a harvested rice field with standing stubble would be helpful in soil moisture remote sensing, synthetic aperture radar (SAR) image classification and calibration, and water resource management of farming regions. The radar backscatter of rice paddies had been widely studied with inclusion of only the first- or second-order multiple scatterings using the first- or second-order radiative transfer model [1]. However, it was shown in [2] that the higher-order multiple scattering is not negligible, especially for cross-polarised radar backscatters. A full-wave analysis should be applied for the radar backscatter computation in order to include all the higher-order multiple scatterings. Moreover, previous studies on the radar backscatter from rice paddies usually employed a flat water surface for their models. Harvested rice fields, however, usually have rough wet soil surfaces. Therefore, the radar backscatter from harvested rice fields with standing stubble should be rigorously calculated with a full-wave analysis for standing stubble clusters and also with an accurate surface scattering model for bare soil surfaces.

In this Letter, the integral equation for the equivalence volume currents induced into standing rice stubble is formulated using the dyadic Green's function for an infinitesimally small current source above an impedance surface [3, 4], and solved using the method of moments. The ensemble-averaged differential Mueller matrix for the radar backscatter from standing stubble is computed from the volume current distribution, and combined with that of the radar backscatter from the rough soil surface [5]. The radar backscatter measurements of a typical harvested rice field at 5.3 GHz agree quite well with the computation results. The effect of the standing rice stubble on total radar backscatter of the harvested rice field is analysed.

Full-wave analysis for rice stubble: A typical arrangement of standing rice stubble is shown in Fig. 1. The equivalent volume current $\boldsymbol{J}$ at a position $\boldsymbol{r}$ is related to the total electric field as in [3]:

$$\boldsymbol{J}(\boldsymbol{r}) = -i\omega\varepsilon_0(\varepsilon_r - 1)[\boldsymbol{E}^i(\boldsymbol{r}) + \boldsymbol{E}^r(\boldsymbol{r}) + \boldsymbol{E}^s(\boldsymbol{r})] \quad (1)$$

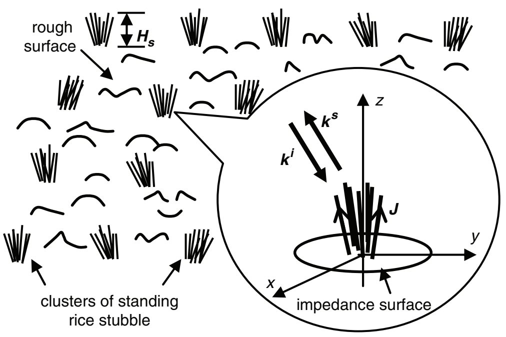

Fig. 1 *Arrangement of standing stubble in typical harvested rice field*

The scattered electric field $\boldsymbol{E}^s$ can be obtained from the current $\boldsymbol{J}$ and the dyadic Green's function $\boldsymbol{G}(\boldsymbol{r}, \boldsymbol{r}')$ using the following relation [4]:

$$\boldsymbol{E}^s(\boldsymbol{r}) = i\omega\mu_0 \int_v \boldsymbol{G}(\boldsymbol{r}, \boldsymbol{r}')\boldsymbol{J}(\boldsymbol{r}')dv' \quad (2)$$

with

$$\boldsymbol{G}(\boldsymbol{r}, \boldsymbol{r}') = \left[\boldsymbol{I} + \frac{\nabla\nabla}{k^2}\right]G(\boldsymbol{r}, \boldsymbol{r}') \quad (3)$$

Since the dyadic Green's function for an infinitesimal current source above a lossy dielectric half-space medium usually has a highly oscillatory form of the Sommerfeld-type integral, the impedance sheet approximation [3] is employed to transform the oscillatory integral to a rapidly converging integral [2].

The integral equation for the volume equivalent current can be cast into a matrix equation by applying the method of moments:

$$\begin{bmatrix} \boldsymbol{Z}_{xx} & \boldsymbol{Z}_{xy} & \boldsymbol{Z}_{xz} \\ \boldsymbol{Z}_{yx} & \boldsymbol{Z}_{yy} & \boldsymbol{Z}_{yz} \\ \boldsymbol{Z}_{zx} & \boldsymbol{Z}_{zy} & \boldsymbol{Z}_{zz} \end{bmatrix} \begin{bmatrix} \boldsymbol{I}_x \\ \boldsymbol{I}_y \\ \boldsymbol{I}_z \end{bmatrix} = \begin{bmatrix} \boldsymbol{V}_x \\ \boldsymbol{V}_y \\ \boldsymbol{V}_z \end{bmatrix} \quad (4)$$

Each sub-matrix $\boldsymbol{Z}_{pq}$ is an $N \times N$ square matrix where N is the total number of cells for a cluster of standing stubble. Solving the above matrix equation, the polarised volume current distribution vector $[\boldsymbol{I}]$ for standing stubble can be obtained. Then, the p-polarised scattered fields are computed from the volume current distribution for the q-polarised incident fields using (2). In this full-wave analysis, of course, all higher-order multiple scattering effects between the soil surface and the rice stubble, as well as those between the rice stubble, are included in the numerical solution. The numerical computation is repeated for 30 independent clusters, which are randomly generated with different sizes, orientations and densities of stubble, to obtain appropriate statistics. Consequently, the differential Mueller matrix can be computed for an arrangement of rice-stubble clusters using the scattering matrix.

Radar backscatter from rice fields: The ensemble-averaged differential Mueller matrix for a randomly rough soil surface is computed using the semi-empirical scattering model given in [5]:

$$\sigma^0_{vh} = 0.11 M_v^{0.7}(\cos\theta)^{2.2}\left[1 - e^{-0.32(ks)^{1.8}}\right] \quad (5)$$

$$p \equiv \frac{\sigma^o_{hh}}{\sigma^o_{vv}} = 1 - \left(\frac{\theta}{90^0}\right)^{0.35M_v^{-0.65}} \times e^{-0.4(ks)^{1.4}} \quad (6)$$

$$q = \frac{\sigma^0_{vh}}{\sigma^0_{vv}} = 0.1(s/l + \sin 1.3\theta)^{1.2}\{1 - e^{-0.9(ks)^{0.8}}\} \quad (7)$$

where M_v is the soil moisture content in cm^3/cm^3, θ is the incidence angle, k is the wave number, s is the RMS (root-mean-square) height, and l is the correlation length of the bare soil surface. The backscattering coefficients for a harvested rice field can be obtained by combining the numerical solution for the stubble clusters and the analytical solution for the bare surface by adding both differential Mueller matrices.

The backscattering coefficients of a typical harvested rice field of Korea were measured at 5.3 GHz in March 2008 using a ground-based scatterometer, which consists of a vector network analyser HP8753D and a C-band polarimetric antenna system. The polarimetric scatterometer was precisely calibrated using the differential-Mueller-matrix calibration technique with the polarimetric measurement of a conduction sphere over the antenna main beam. The field-measured RMS height and correlation length were 1.76 cm and 9.02 cm for the harvested rice field. The field-measured moisture contents of the soil surface and the standing stubble were 0.274 cm^3/cm^3 (volumetric) and 0.05 g/cm^3 (gravimetric). The averaged number of clusters per unit area, averaged number of stems per cluster, averaged length and averaged diameter of the stubble were 30, 13, 8.3 cm, and 0.45 cm, respectively. The measured backscattering coefficients agree quite well with those computed using the proposed technique, as shown in Fig. 2. In this case, the effect of the rice stubble was negligible because the water content of the stubble was only about 5%.

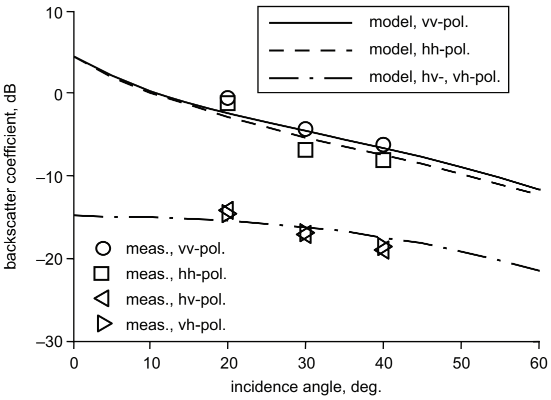

Fig. 2 *Comparison between computed and field-measured radar backscatters for harvested rice field*

Numerical results and discussion: The backscattering coefficients of harvested rice fields for various conditions of stubble clusters and rough surfaces were computed and analysed. In this study the backscattering coefficients of a typical harvested rice field were computed with various moisture conditions of the standing stubble with the other input parameters fixed. Fig. 3 shows a comparison between the contributions of standing stubble and of the soil surface on the total backscattering coefficients for various moisture contents of the standing stubble for $\theta = 50^\circ$ and $f = 5.3$ GHz. In this computation, 30 clusters in 1×1 m, 10–20 standing stubbles per cluster, stem length of 5–10 cm, stem diameter of 0.3–0.6 cm, cluster radius of 3 cm, volumetric soil moisture of 0.3 cm^3/cm^3, RMS surface height of 1 cm, surface correlation length of 10 cm, cluster angle of 0–60° and stem angles of 0–10°, are assumed. The contribution of the standing stubble to the total backscattering coefficient is comparable with that of the soil surface when the stubble has about 75% water content. The contribution of the standing stubble with 65% water content is about 3 dB lower than that of the surface, and about 10 dB lower for the case of 40% water content, as shown in Fig. 3. Similar results were observed for other incidence angles less than 60°. After rain or after harvest, the water content of the stubble can be higher than 70%, and consequently the contribution of the standing stubble on the total radar backscatter will be comparable or even higher than the contribution of the soil surface. However, when the water content of rice stubble is lower than 40%, the effect of the standing rice stubble is negligible.

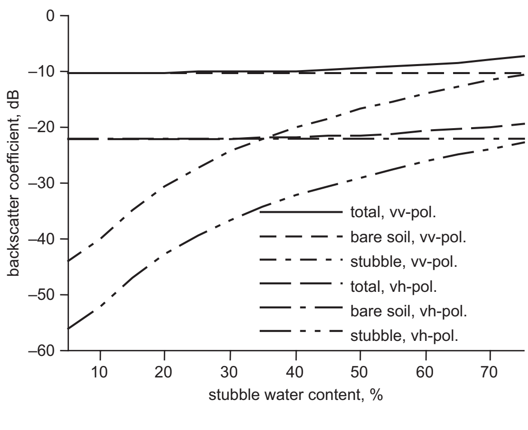

Fig. 3 *Effect of rice standing stubble on radar backscatter for harvested rice field for various water contents of stubble*

Conclusions: The backscattering coefficients of a harvested rice field were computed at 5.3 GHz for vv-, hh-, hv- vh-polarisations by combining the numerical solution for standing stubble and the analytical computation for a rough surface. The computation agreed quite well with experimental data for a typical condition. It was found in this study that the contribution of the standing stubble is comparable with that of the rough surface when the water content of the stubble is higher than 70%. However, the effect of the standing rice stubble is negligible when the water content of the stubble is lower than 40%. This technique will be equally applicable to other harvested fields.

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