Soil Moisture Measurement of Bare and Vegetated Surfaces by X-band Radars

Yisok Oh · Soon-Gu Kwon · Ji-Hwan Hwang

Abstract

The radar backscatter from various earth surfaces is sensitive to the frequency of the incident wave. This study examined the radar sensitivities for surface parameters such as soil moisture content and surface roughness of both bare and vegetated surfaces at X-band. Because L-band frequencies are often used for sensing the surface parameters, the sensitivities of X-band are also compared with those of the L-band. The sensitivities of the X-band radar backscatter were examined with respect to soil moisture content and surface roughness of rough bare soil surfaces. These sensitivities were also examined using the same parameters for vegetated surfaces for various vegetation densities and incidence angles. Use of the X-band radar for soil moisture detection was as effective as L-band radar for bare soil surfaces. For vegetated surfaces, the soil moisture could be detected using an X-band radar at lower incidence angles, where the upper limit of the incidence angles was dependent on vegetation density.

Key words : Radar Backscatter, KOMPSAT-5, Soil Moisture, Surface Roughness, Vegetation Density.

Ⅰ. Introduction

Synthetic aperture radar (SAR) is a high-resolution microwave active remote sensor for monitoring earth surfaces. Among the surface parameters that SAR can measure, soil moisture content is one of the most essential measurements as it determines the earth's water, energy, and carbon cycles, and in turn affects agriculture and hydrological processes, climate prediction, and flood and drought monitoring. In past decades, retrieval of soil moisture information from radar measurements has been extensively investigated for high-resolution soil-moisture mapping, using primarily the L-, C-, and X-bands [1～3]. However, the inversion algorithms available are unable to provide accurate results without taking into consideration the surface roughness of the bare soil surface. Radar measurements of bare soil surfaces are known to be affected by surface roughness as well as by soil moisture.

Oh *et al*. [4] developed an inversion technique to retrieve both the RMS surface height and the dielectric constant (consequently, soil moisture content) from polarimetric radar measurements. This allows the retrieval of soil moisture contents, apart from the surface roughness, from the polarimetric SAR data [5, 6]. Many polarimetric satellite SARs have now been launched, including the PALSAR at the L-band, RADARSAT-2 at the C-band, and TerraSAR-X and COSMO-SkyMed at the X-band, and can now provide data that might be applicable for retrieving soil moisture and surface roughness.

The first Korean satellite SAR, KOMPSAT-5, is designed to operate at the X-band for single polarization. However, the retrieval of surface parameters from a set of single polarized radar data remains a challenging problem. Therefore, we need to examine the radar sensitivities at X-band in more detail in order to provide an effective base for developing accurate inversion algorithms.

The radar measurement of an area of earth surface is affected by both the vegetation canopy characteristics and the surface roughness condition, in addition to the soil moisture. However, the sensitivity of radar backscatter on frequency, incidence angle, and polarization has not been thoroughly examined yet for vegetated surfaces because of the complicated scattering mechanisms. Nevertheless, the radar backscatter measurements reported in [2] imply that soil moisture estimated from vegetated surfaces can be affected by the vegetation density and incidence angle.

In this paper, the radar backscatter of bare soil surfaces is first analyzed to examine the sensitivity of radar backscatter to varying surface parameters. For this examination, we use the polarimetric empirical model (PEM) reported in [7] and the integral equation model (IEM). The scattering from vegetated surfaces is then examined for various vegetation densities over a wide range of incidence angles, using the polarimetric empirical scattering

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Department of Electronic Information and Communication Engineering, Hongik University, Seoul, Korea.
Corresponding Author : Yisok Oh (e-mail : yisokoh@hongik.ac.kr)

models for the underlying soil surface and the radiative transfer model for scattering from vegetation canopies [8]. We also compare the radar sensitivity for surface parameters at the X-band with that at the L-band for bare or vegetation-covered soil surfaces.

Ⅱ. Radar Backscatter from Bare Soil Surfaces

The IEM [10]~[11] is well known to have a wider validity region when compared to other classical theoretical models, such as the small perturbation method (SPM) and the physical optics (PO) model [12]. The IEM for rough surfaces with small to moderate roughness(*e.g.*, *ks*<2) is given by

$$\sigma_{qp}^{o} = \frac{k^2}{2}\exp[-2(k_z s)^2] \sum_{n=1}^{\infty} \left| I_{qp}^{n} \right|^2 \frac{W^{(n)}(-2k_x,0)}{n!}, \tag{1}$$

where $k_z = k\cos\theta$, $k_x = k\sin\theta$, p, q=v or h and s is the RMS height,

$$I_{qp}^{n} = (2k_z s)^n f_{qp} \exp[-(k_z s)^2] + \frac{(k_z s)^n}{2}\left[F_{qp}(-k_x,0) + F_{qp}(k_x,0)\right], \tag{2}$$

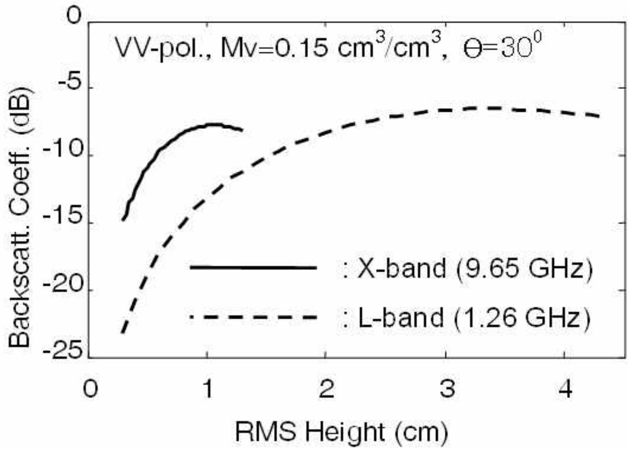
with $f_{vv} = 2R_{//}/\cos\theta$, $f_{hh} = -2R_{\perp}/\cos\theta$, f_{vh}=0, and f_{hv}=0. $R_{//}$, $R_{\perp}$ are the Fresnel coefficients for vertical and horizontal polarizations and F_{qp} is the field coefficient at qp-polarization which is given in [11, p. 249-250]. The symbol $W^{(n)}(-2k_x,0)$ is the Fourier transform of the n^{th} power of the surface autocorrelation function [11, p. 117],

$$W^{(n)}(-2k_x,0) = \int_0^{\infty} \rho^n(r) J_o(2kr\sin\theta)\, r dr, \tag{3}$$

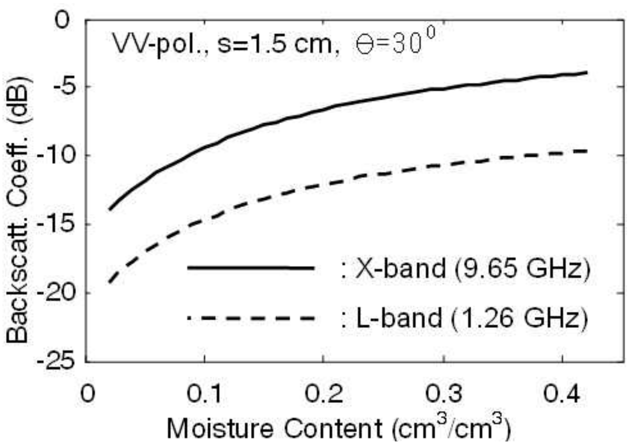
where $\rho(r)$ is the normalized surface autocorrelation function and $J_o(\cdots)$ is the 0th order Bessel function of the first kind. Since the dielectric constant is an input parameter in the IEM, the dielectric constant is computed from the measured soil moisture content with an empirical formula given in [9].

Fig. 1(a) shows the backscattering coefficients for various surface RMS heights, *s*, from 0.3 cm to 4.3 cm, with the volumetric soil moisture content *Mv* of 0.15 cm^3/cm^3 with the incidence angle of 30° at vv-polarization, as an example. In this Fig., the backscattering coefficients at the X-band were computed only in the range of $0.3 \le s \le 1.3$ cm ($0.6 \le ks \le 2.6$), because the above equations are only adequate in the range of *ks*<2. In this case, the maximum sensitivity of the radar backscatter on the surface roughness at the X-band is only about 7 dB, while the maximum sensitivity at the L-band is about 16 dB.

Fig. 1(b) shows the backscattering coefficients for various volumetric soil moisture contents, *Mv*, from 0.02 cm^3/cm^3 to 0.42 cm^3/cm^3, with the surface RMS height, *s*, of 1.5 cm, with the incidence angle of 30° at vv-polarization as an example. In this case, the maximum sensitivity of the radar backscatter on the surface roughness at the X-band is 9.9 dB, which is quite similar to the maximum sensitivity of 9.6 dB at the L-band. According to the theoretical model, the sensitivity of the radar backscatter for soil moisture is same between the X- and L-bands, while the sensitivity for roughness at the X-band is substantially lower than at the L-band.



(a) Surface roughness (RMS height)



(b) Soil moisture (volumetric soil moisture content)

Fig. 1. Sensitivities of the radar backscatters for bare soil surfaces based on the IEM.

Oh *et al.*'s polarimetric empirical model (PEM) [7] was developed empirically based on an extensive database consisting of the L-, C-, and X-band scatterometer data, L- and C-band AirSAR data, and classical theoretical scattering models for the vv-, hh-, and hv-polarized backscattering coefficients and the co-polarized phase-difference parameters for bare soil surfaces:

$$\sigma_{hv}^{0} = 0.11\, M_v^{0.7} (\cos\theta)^{2.2} \left[1 - e^{-0.32(ks)^{1.8}} \right] \tag{4}$$

$$\sigma_{vv}^{0} = \sigma_{hv}^{0} / q \quad (5)$$

$$q = 0.1\left(s/l + \sin 1.3\theta\right)^{1.2}\left(1 - e^{-0.9(ks)^{0.8}}\right) \quad (6)$$

$$\sigma_{hh}^{0} = \sigma_{vv}^{0}\ p \quad (7)$$

$$p = 1 - \left(\theta/90\right)^{0.35 M_v^{-0.65}} \cdot e^{-0.4\,(ks)^{1.4}} \quad (8)$$

$$\alpha = 1 - \left(17 + 0.01\,kl + 0.5\,M_v\right) \cdot \left(\sin\theta\right)^{1.1(ks)^{-0.4}} \quad (9)$$

$$\zeta = \left(0.44 + 0.95\,M_v - \frac{s}{l}\right)\theta \quad (10)$$

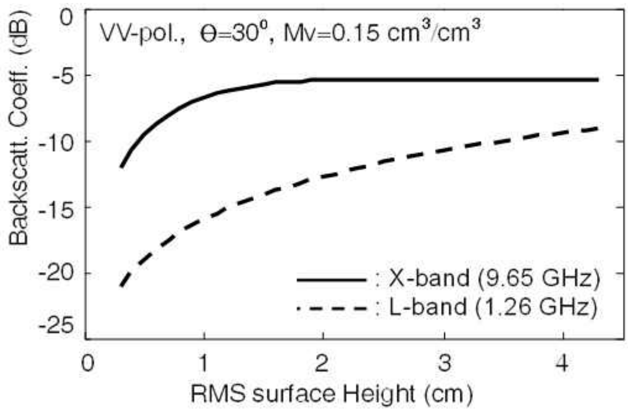
where α is the degree of correlation and ζ is the co-polarized phase-difference [7]. The Mueller matrix (or the Stokes scattering operator matrix) of the polarimetric radar backscatter of a bare soil surface can be computed using σ_{vv}^{0}, σ_{hh}^{0} and σ_{vh}^{0}, α, and ς in (4)~(10), which allows the polarization synthesis to be generated from the Mueller matrix(or the Stokes scattering operator matrix) [13]. The backscattering coefficients have been used for retrieving the soil moisture and surface roughness parameters with a modified cross-polarized ratio q, as in [14]:

$$q = 0.095\left(0.13 + \sin 1.5\theta\right)^{1.4}\left(1 - e^{-1.3(ks)^{0.9}}\right) \quad (11)$$

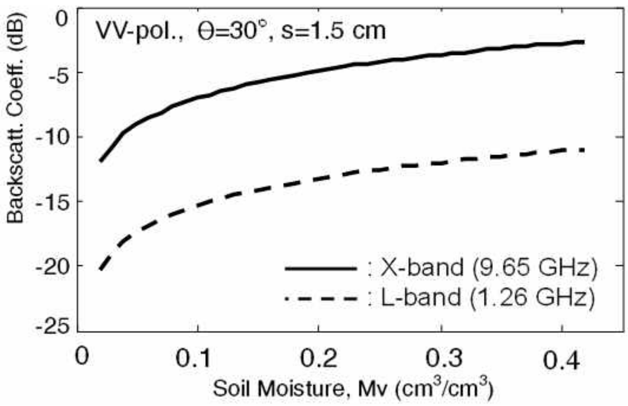
Using the PEM, the sensitivities of the radar backscatter on surface roughness and soil moisture at L- and X-bands were computed at 30° for vv-polarization, as an example, as shown in Fig. 2.

Fig. 2(a) shows the backscattering coefficients for various surface RMS heights, s, from 0.3 cm to 4.3 cm with the volumetric soil moisture content, Mv, of 0.15 cm^3/cm^3, and the incidence angle of 30° at vv-polarization. The PEM has a wider validity region than does the IEM so that the radar backscatter could be computed for large RMS height values even at the X-band. The maximum sensitivity of the radar backscatter on the surface roughness at the X-band is only 6.7 dB, while the maximum sensitivity at L-band is 12.1 dB.

Fig. 2(b) shows the backscattering coefficients computed using the PEM for various volumetric soil moisture contents, Mv, from 0.02 cm^3/cm^3 to 0.42 cm^3/cm^3 with the surface RMS height, s, of 1.5 cm and the incidence angle of 30° at vv-polarization, as an example. In this case, the maximum sensitivities of the radar backscatter on the surface roughness at both L- and X-bands are 9.3 dB, as shown in Fig. 2(b). The radar backscattering coefficient is proportional to $Mv^{0.7}$ in the model, and therefore its sensitivity to soil moisture is independent of the frequency. According to the PEM, as well as the IEM, the sensitivity of the radar backscatter for



(a) Surface roughness (RMS height)



(b) Soil moisture (volumetric soil moisture content)

Fig. 2. Sensitivities of the radar backscatter for bare soil surfaces based on the PEM.

soil moisture is the same between the X- and L-bands, while the sensitivity for roughness at the X-band is substantially lower than at the L-band.

Ⅲ. Radar Backscatter from Vegetated Surfaces

The backscattering coefficients are computed theoretically using the radiative transfer model (RTM) for vegetated surfaces. In the first-order RTM-based scattering model, the radar backscattering from a two-layered vegetation canopy comprises four main scattering mechanisms: (1) direct vegetation scattering (I-V-S), (2) vegetation-ground/ ground-vegetation scattering (I-V-G-S/I-G-V-S), (3) ground-vegetation-ground scattering (I-G-V-G-S), and (4) direct ground scattering (I-G-S) with attenuation/ scattering in the vegetation canopy, as shown in Fig. 3.

The backscattering coefficients can be obtained by multiplying $4\pi\cos\theta_0$ to the transformation matrix elements: *e.g.*, $\sigma_{vv}^{o} = 4\pi\cos\theta_0 T_{11}$ and $\sigma_{vh}^{o} = 4\pi\cos\theta_0 T_{12}$. The 4×4 transformation matrix $\overline{\overline{T}}$ can be computed using the phase matrices $\overline{\overline{P}}$, the eigen matrices $\overline{\overline{E}}$, the reflectivity matrices $\overline{\overline{R}}$, the diagonal extinction matrices $\overline{\overline{D}}$, and the

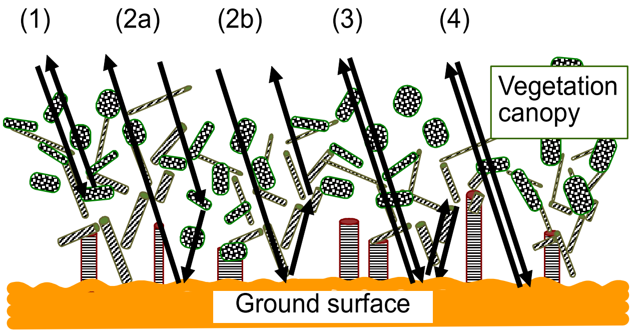


Fig. 3. Scattering mechanisms in the first-order radiative transfer method.

Stokes scattering operator matrix $\bar{\bar{M}}$ [8, 13].

$$\begin{aligned}\bar{\bar{T}} = \sec\theta_0[&\bar{\bar{E}}_4\{\bar{\bar{E}}_4^{-1}\bar{\bar{P}}_{41}\bar{\bar{E}}_1 C_1\}\bar{\bar{E}}_1^{-1} \\ &+\{\bar{\bar{E}}_4\bar{\bar{D}}_4\bar{\bar{E}}_4^{-1}\}\bar{\bar{R}}\bar{\bar{E}}_3\{\bar{\bar{E}}_3^{-1}\bar{\bar{P}}_{31}\bar{\bar{E}}_1 C_2\}\bar{\bar{E}}_1^{-1} \\ &+\bar{\bar{E}}_4\{\bar{\bar{E}}_4^{-1}\bar{\bar{P}}_{42}\bar{\bar{E}}_2 C_3\}\bar{\bar{E}}_2^{-1}\bar{\bar{R}}\{\bar{\bar{E}}_1\bar{\bar{D}}_1\bar{\bar{E}}_1^{-1}\} \\ &+\{\bar{\bar{E}}_4\bar{\bar{D}}_4\bar{\bar{E}}_4^{-1}\}\bar{\bar{R}}\bar{\bar{E}}_3\{\bar{\bar{E}}_3^{-1}\bar{\bar{P}}_{32}\bar{\bar{E}}_2 C_4\}\bar{\bar{E}}_2^{-1}\bar{\bar{R}}\{\bar{\bar{E}}_1\bar{\bar{D}}_1\bar{\bar{E}}_1^{-1}\} \\ &+\{\bar{\bar{E}}_4\bar{\bar{D}}_4\bar{\bar{E}}_4^{-1}\}\bar{\bar{M}}\{\bar{\bar{E}}_1\bar{\bar{D}}_1\bar{\bar{E}}_1^{-1}\}]\end{aligned} \quad (12)$$

The first, second, third, firth, and fifth terms of the above equation correspond to the scattering mechanism (1), (2a), (2b), (3) and (4) in Fig. 3, respectively. The eigen matrix elements can be computed from the averaged scattering matrix elements over the orientation and size distribution of the scattering particles. The phase matrix is the average of the Mueller matrix over the distribution of particles in terms of size, shape, and orientation, where the Mueller matrix elements are the covariance between the scattering matrix elements [13].

The RTM-based theoretical model needs numerous input parameters, such as vegetation canopy height, leaf density, leaf size, leaf thickness, branch density, branch length, branch diameter, trunk density, trunk length, trunk diameter, water contents of leaf, branch, and trunk, the probability density functions (PDF) of the leaf size, branch size, branch diameter, trunk length, and trunk diameter, among others, in addition to the soil moisture and surface roughness parameters. The input parameters of the model in the present study are the volumetric soil moisture content M_v (cm^3/cm^3), the rms surface height s (cm), the vegetation canopy height h (m), leaf density n_l (m^{-3}), leaf length l_l (cm), leaf width W_l (cm), leaf thickness (cm), leaf vertical angle θ_l, branch density n_b (m^{-3}), branch length l_b (cm), branch diameter d_b (cm), branch vertical angle θ_b, trunk (stem) density n_t (m^{-3}), trunk (stem) length l_t (m), trunk (stem) diameter d_t (cm), trunk (stem) vertical angle θ_t, standard deviations of those parameters, and water contents of leaf, branch and trunk (stem). For the purpose of verification of the scattering

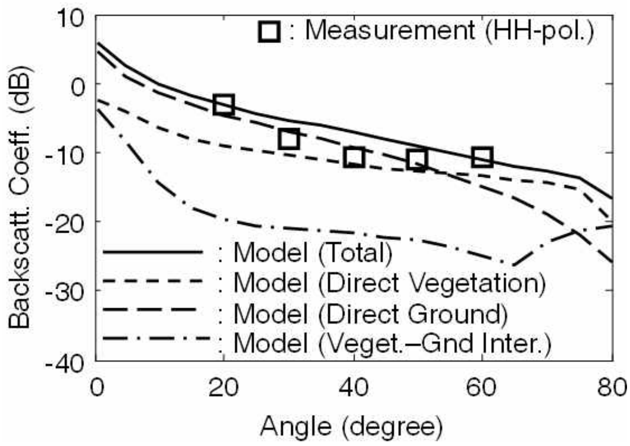


Fig. 4. Comparison between the scattering model and the measured backscatter of a soybean field.

model, the backscattering coefficients of soybean fields were measured at the X-band, using the HPS (Hongik Polarimetric Scatterometer) for vv-, hh-, and hv-polarizations. The major field-measured ground parameters of a soybean field are M_v=0.274 cm^3/cm^3, s=1.14 cm, h= 0.47 m, n_l=413 m^{-3}, l_l= 6.9 cm, W_l=5.1 cm, leaf thickness=0.02 cm, n_b=143 m^{-3}, l_b=12.6 cm, d_b=0.22 cm, n_t=21.3 m^{-3}, l_t=0.34 m, d_t=0.53 cm, and water contents of stem, branch, and leaf are 0.63, 0.87, and 0.62 g/cm^3, respectively.

Fig. 4 shows comparisons between the first-order RTM-based scattering model and the measured backscattering coefficients of the soybean field with HH-polarization. The ground scattering term is dominant at incidence angles lower than 50°, while the direct backscatter from the vegetation canopy is dominant at θ>60° for this vegetated field.

Based on the verification of the RTM-based simple scattering model, as shown in Fig. 4, the model was used in this study to examine the sensitivities of the radar backscatter on soil moisture for vegetated surfaces at X-band. At first, the radar backscatter of various farming fields such as a corn field, a wheat field, and a soybean field planted at various densities were computed for a wide range of incidence angles. Fig. 5 shows the radar backscatter of a wheat field with *LAI* (leaf-area index)= 4 and M_v=0.15 cm^3/cm^3 at X-band for vv-polarization. In this case, the ground scattering dominates at θ<20°, which indicates that the X-band wave penetrates into the vegetation canopy without a noticeable attenuation. Consequently, it provides information about the soil moisture content under the canopy at lower incidence angles.

The backscattering coefficients of vegetated surfaces will depend on the LAI (leaf-area index) of the vegetation canopy. Fig. 6 shows that the backscattering coefficients at low incidence angles decrease as the LAI

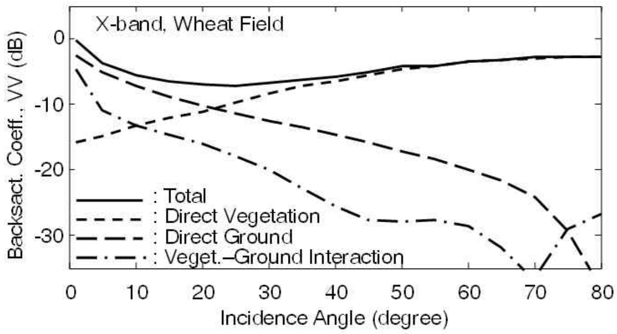


Fig. 5. Backscattering coefficients of a wheat field estimated by the scattering model.

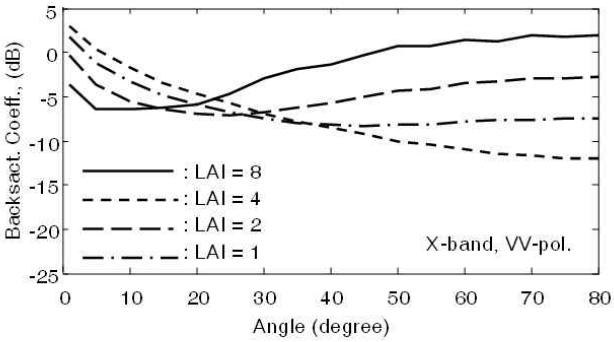


Fig. 6. The angular variations of the backscattering coefficients of a wheat field with various LAI values for vv-polarization at X-band.

increases because the attenuation of the direct ground scattering (I-G-S) in the vegetation canopy increases with the increase of the LAI.

We computed the backscattering coefficients of wheat fields with various leaf densities (LAI=0.5, 1, 2, 4, 6, 8) at the range of incidence angles from 0° to 80° for various soil moisture contents M_v=0.05, 0.15, and 0.35 cm^3/cm^3. Fig. 7 shows the sensitivity of the radar backscatter to the soil moisture for the wheat field at X-band for vv-polarization. At lower incidence angles, the backscattering coefficients are much higher at the soil moisture condition of M_v=0.35 cm^3/cm^3 (about 6 dB) than at M_v=0.05 cm^3/cm^3. The vegetation canopy looks transparent at lower incidence angles because of a short attenuation path and a high ground scattering at the low incidence angles. The maximum incidence angle for soil moisture detection with LAI=2 will be 48° for the sensitivity range of 2 dB, and about 59° for the sensitivity range of 1 dB, as shown in Fig. 7.

Fig. 8 shows the angular range for soil moisture detection with various vegetation densities (LAI) for a wheat field at X-band for vv- and hh-polarizations. As an example, for a wheat field with LAI=1, the soil moisture

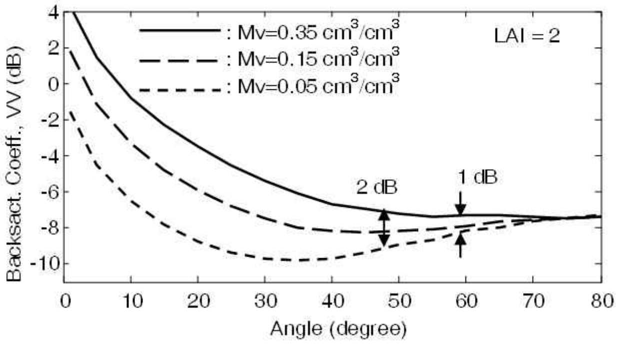


Fig. 7. Radar backscatter for three different soil moisture values for a wheat field with LAI=2 at the X-band for vv-polarization.

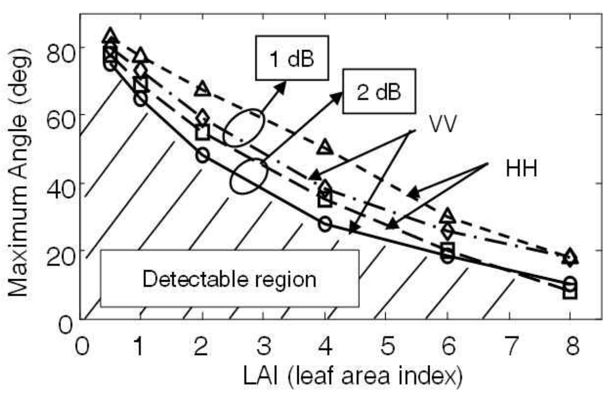


Fig. 8. Angular range for soil moisture detection in a wheat field with various vegetation densities (LAI) at the X-band for vv- and hh-polarizations.

under the vegetation canopy can be detected in the range of $0° < \theta < 70°$, while the range of incidence angle becomes $0° < \theta < 20°$ for the vegetated field with LAI=6 for 2-dB sensitivity range, as shown in Fig. 8.

Ⅳ. Conclusions

We examined the sensitivities of the radar backscatter on the volumetric soil moisture content of bare soil and vegetation surfaces at the X-band. The X-band radar was confirmed to be as good as an L-band radar for soil moisture mapping of bare soil surfaces. The angular range for soil moisture detection using an X-band radar such as the KOMPSAT-5 for vegetated surfaces has also been shown to depend on the density of the vegetation canopy. A low incidence angle should be used for detecting the soil moisture under a dense vegetation canopy, while any incidence angle would be applicable to soil moisture mapping for sparsely vegetated surfaces at the X-band.

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Yisok Oh

received the B.S. degree in electrical engineering from Yonsei University, Seoul, Korea, in 1982, the M.S. degree in electrical engineering from the University of Missouri-Rolla, in 1988, and the Ph.D. degree in electrical engineering from the University of Michigan, Ann Arbor, in 1993. Since 1994, he has been with the School of Electronic and Electrical Engineering, Hongik University, Seoul, Korea. Currently, he is a Professor at Hongik University, and an IEEE Fellow. His current research interests include microwave remote sensing, antennas, and radio wave propagation.

Soon-Gu Kwon

received the B.S. degree in electronic and electrical engineering and the M.S. degree in electronic information and communication engineering from Hongik University, Seoul, Korea, in 2007 and 2009, respectively. He is currently a Ph.D. candidate in the Department of Electronic Information and Communication Engineering, Hongik University, Seoul, Korea. His research interests include microwave scattering, microwave remote sensing, and SAR image analysis.

Ji-Hwan Hwang

received the B.S. degree in radio engineering and the M.S. degree in radio science and communication engineering from Hongik University, Seoul, Korea, in 2001 and 2003, respectively. He worked at LG Electronics Co. from 2003 to 2006. He is currently a Ph.D. candidate in the Department of Electronic Information and Communication Engineering, Hongik University, Seoul, Korea. His research interests include microwave scattering, microwave remote sensing, and antennas