Quantitative Retrieval of Soil Moisture Content and Surface Roughness From Multipolarized Radar Observations of Bare Soil Surfaces

Yisok Oh, *Senior Member, IEEE*

***Abstract*—A semiempirical polarimetric backscattering model for bare soil surfaces is inverted directly to retrieve both the volumetric soil moisture content M_v and the rms surface height s from multipolarized radar observations. The rms surface height s and the moisture content M_v can be read from inversion diagrams using the measurements of the cross-polarized backscattering coefficient $\sigma^0_{\rm vh}$ and the copolarized ratio $p(=\sigma^0_{\rm hh}/\sigma^0_{\rm vv})$. Otherwise, the surface parameters can be estimated simply by solving two equations ($\sigma^0_{\rm vh}$ and p) in two unknowns (M_v and s). The inversion technique has been applied to the polarimetric backscattering coefficients measured by ground-based polarimetric scatterometers and the Jet Propulsion Laboratory airborne synthetic aperture radar. A good agreement was observed between the values of surface parameters (the rms height s, roughness parameter ks, and the volumetric soil moisture content M_v) estimated by the inversion technique and those measured *in situ*.**

***Index Terms*—Backscattering coefficient, direct inversion model, semiempirical polarimetric model, soil moisture, surface roughness.**

I. Introduction

Soil moisture content is an essential parameter in agriculture and hydrological processes. Retrieval of this parameter from microwave synthetic aperture radar (SAR) measurements has been extensively investigated in the past three decades [1]–[4]. It is well known that radar measurements of bare soil surfaces are affected by surface roughness as well as by soil moisture. Theoretical scattering models [5], [6] as well as radar measurements [7] show that the backscattering coefficients are more sensitive to surface roughness than soil moisture. Oh *et al.* [8] have developed an inversion technique to retrieve both the rms surface height s and the relative dielectric constant from measurements of the copolarization ratio $p(=\sigma^0_{\rm hh}/\sigma^0_{\rm vv})$ and the cross-polarization ratio $q(=\sigma^0_{\rm vh}/\sigma^0_{\rm vv})$, where σ^0_{pq} refers to the backscattering coefficient for q-transmitting, p-receiving polarization and p, $q = v$ or h. Dubois *et al.* [9] also developed an empirical model for vertically (vv) and horizontally (hh) polarized backscattering coefficients based on scatterometer datasets. The dielectric constant could be retrieved from the copolarized backscattering coefficients using the method with a limited validity region. Rao *et al.* [10] introduced a statistical linear inversion algorithm, and tested it with limited number of datasets. Shi *et al.* [11] developed an inversion algorithm based on a regression analysis of simulated backscattering coefficients using the integral equation method (IEM).

A semiempirical polarimetric backscattering model has recently been introduced for randomly rough bare soil surfaces [7], which agrees not only with a combination of truck-mounted scatterometer measurements and airborne SAR observations over a wide range of soil surface conditions, but also with the IEM and GO models over their individual regions of validity. The volumetric soil moisture content M_v is used as an input parameter of the model instead of the complex dielectric constant, because the backscatter depends weakly on soil type in comparison with its response to surface roughness and soil moisture. For a typical agricultural soil, such as silt loam or sandy loam, the Fresnel reflectivity exhibits an approximately linear dependence on the volumetric soil moisture content [12] over the range of $0.03 \leq M_v \leq 0.35$. The soil moisture content M_v, therefore, can be retrieved directly from the model without an additional computation procedure to convert a dielectric constant into an M_v value [13].

In this paper, the behavior of the backscattering coefficients of the semiempirical model is analyzed at first. Then, the vertically–horizontally (vh) polarized backscattering coefficient and the copolarized ratio p are inverted directly to get the surface roughness parameter ks and the volumetric moisture content M_v together. The rms height s is obtained from the roughness parameter ks with a given frequency. The cross-polarized ratio q can also be used to improve the accuracy of the inversion method. The inversion results are compared with the values measured *in situ*, and the averaging effect of the multifrequency and/or multiangle data is discussed.

II. Model Analysis

The semiempirical polarimetric model in [7] was developed based on existing theoretical scattering models and an extensive database obtained by ground-based polarimetric scatterometers and the Jet Propulsion Laboratory (JPL) airborne SAR system over a wide variety of bare soil surfaces. The database also included extensive ground observations of the soil surface roughness statistics and soil moisture contents, as well as the backscattering coefficients $\sigma^0_{\rm vv}$, $\sigma^0_{\rm hh}$, and $\sigma^0_{\rm vh}$. The input parameters of the semiempirical polarimetric model are the incidence angle θ, the volumetric soil moisture content M_v, and the roughness parameters ks and kl, where s is the rms height, l is the correlation length, and k is the wavenumber ($k = 2\pi f/c$). The soil moisture content M_v of the top 3-cm soil-surface layer is used at all

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The author is with the School of Electronic and Electrical Engineering, Hongik University, Seoul 121-791, Korea (e-mail: yisokoh@hongik.ac.kr).

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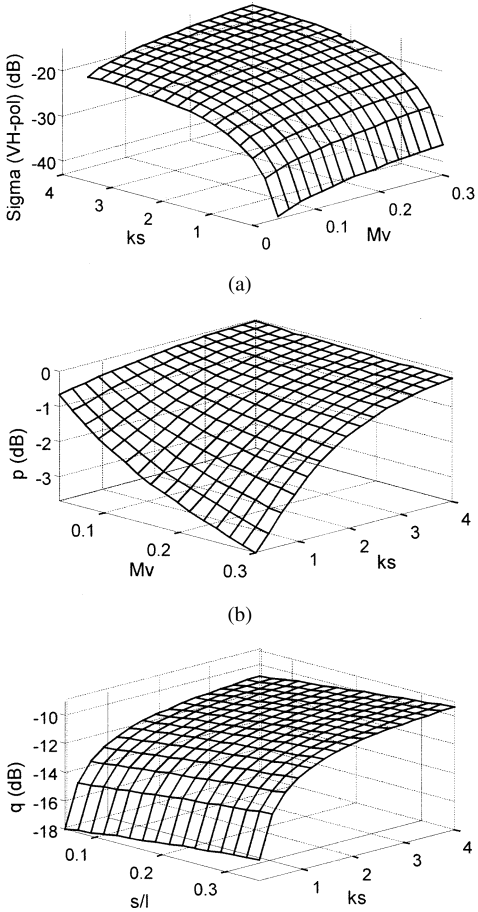


Fig. 1. Mesh plots of (a) $\sigma^0_{\rm vh}$ against ks and M_v, (b) p against M_v and ks, and (c) q against s/l and ks, for $\theta = 45°$.

frequencies because it was shown that the top 2–3-cm soil layer exhibits the greatest influence on the radar backscatter response even though the wave may penetrate deeper into the soil for a dry surface at L-band [14]. The semiempirical model for bare soil surfaces is given by [7]

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

$$p \equiv \frac{\sigma^0_{\rm hh}}{\sigma^0_{\rm vv}} = 1 - \left(\frac{\theta}{90°}\right)^{0.35\ M_v^{-0.65}} \cdot e^{-0.4(ks)^{1.4}} \quad (2)$$

$$q \equiv \frac{\sigma^0_{\rm vh}}{\sigma^0_{\rm vv}} = 0.1\left(\frac{s}{l}+\sin 1.3\theta\right)^{1.2}\left\{1-\exp\left[-0.9(ks)^{0.8}\right]\right\} \quad (3)$$

where the vv- and hh-polarized backscattering coefficients can be computed from the vh-polarized backscattering coefficient with the copolarized ratio p, and the cross-polarized ratio q($\sigma^0_{\rm vv} = \sigma^0_{\rm vh}/q$ and $\sigma^0_{\rm hh} = \sigma^0_{\rm vh}p/q$). The model agrees with experimental observations over a wide range of soil surface conditions: $0.04 < M_v < 0.291$ m^3/m^3, $0.13 < ks < 6.98$ at $10° \leq \theta \leq 70°$.

Each of (1)–(3) has two input soil parameters, i.e., both the vh-polarized backscattering coefficient $\sigma^0_{\rm vh}$ and the copolarized ratio p depend on M_v and ks, and the cross-polarized ratio q depends on s/l and ks. Fig. 1(a) is a surface plot depicting the sensitivity of $\sigma^0_{\rm vh}$ with respect to the roughness parameter ks and the soil moisture content M_v at an incidence angle of 45°. The vh-polarized backscattering coefficient $\sigma^0_{\rm vh}$ increases as ks and M_v increase, with different growth rates. At 45°, the dynamic range of $\sigma^0_{\rm vh}$ is found to be about +6 dB for $0.04 < M_v < 0.30$ cm^3/cm^3 and +20 dB for $0.15 < ks < 4.0$ as shown in Fig. 1(a) and [7, p. 1354]. Fig. 1(b) shows that the copolarized ratio p increases toward 0 dB ($\sigma^0_{\rm hh} \approx \sigma^0_{\rm vv}$) for really dry surfaces ($M_v < 0.04$ cm^3/cm^3) and for very rough surfaces ($ks > 4$). Fig. 1(c) shows that the sensitivity of the cross-polarized ratio $q(\sigma^0_{\rm vh}/\sigma^0_{\rm vv})$ to ks is very high (dynamic range of about 7 dB), while that on the surface slope s/l is very low (dynamic range of about 1 dB).

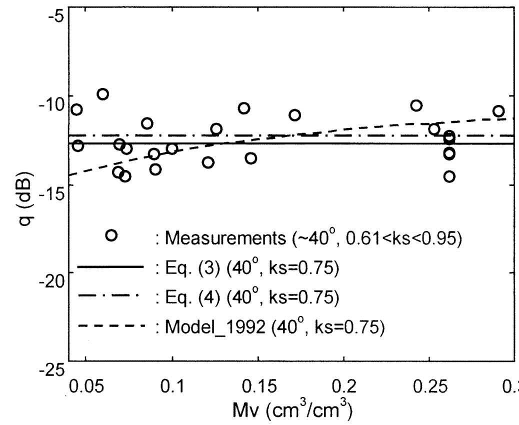


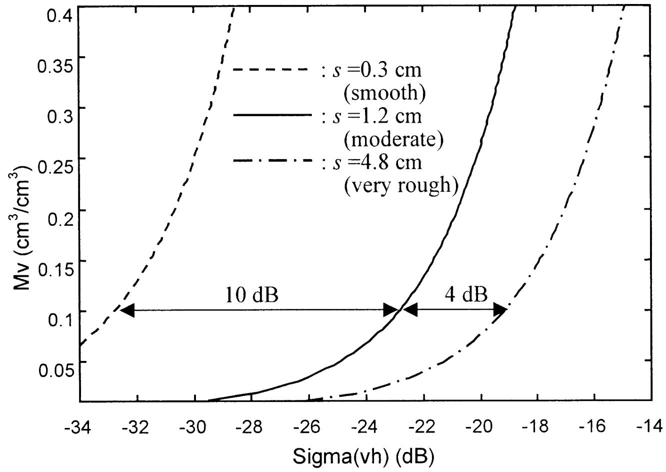
Fig. 2. Measured cross-polarized ratio q compared with empirical models.

The retrieval of the correlation length may not be accurate because of the insensitivity of the cross-polarized ratio q on the roughness parameter s/l, and of the problem of measuring the correlation length in the field [15]. The cross-polarized ratio, therefore, has been modeled empirically ignoring the correlation length for the purpose of the inversion technique. The minimum-mean-square error (MMSE) data-fitting process based on the experimental database in [7] ($0.04 < M_v < 0.291$ m^3/m^3, $0.13 < ks < 6.98$, and $10° \leq \theta \leq 70°$) led to the following expression with an rms error of 1.47 dB:

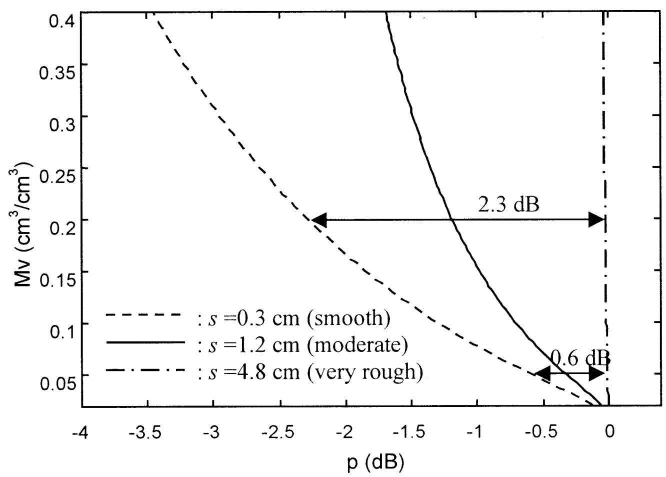
$$q \equiv \frac{\sigma^0_{\rm vh}}{\sigma^0_{\rm vv}} = 0.095(0.13+\sin 1.5\theta)^{1.4}\left\{1-\exp\left[-1.3(ks)^{0.9}\right]\right\}. \quad (4)$$

Data analysis shows that the sensitivity of the measured q to incidence angle θ is high enough for modeling, while that to the soil moisture M_v is very weak. Therefore, (3) and (4) for the cross-polarized ratio $q(\sigma^0_{\rm vh}/\sigma^0_{\rm vv})$ have no dependence on soil moisture, in contrast with the empirical model in [8]. Fig. 2 shows the measured variation of the cross-polarized ratio q with M_v for measurement over the range $0.61 < ks < 0.95$, and $35° < \theta < 45°$. The measurements are compared with curves calculated using (3) and (4) and the empirical models in [8] for $ks = 0.75$ and $\theta = 40°$. The measured cross-polarized ratio q is almost insensitive to the soil moisture as shown in Fig. 2.

Fig. 3(a) and (b) shows the relationship between M_v and the measurements of the vh-polarized backscattering coefficients $\sigma^0_{\rm vh}$ and the copolarized ratio p for three different values of s (0.3, 1.2, and 5.0 cm) at 5.3 GHz and 40°. The rate of increase of M_v with respect to $\sigma^0_{\rm vh}$ is the same irrespective of s as shown



(a)



(b)

Fig. 3. Moisture content M_v versus (a) $\sigma^0_{\rm vh}$ and (b) $p(\sigma^0_{\rm hh}/\sigma^0_{\rm vv})$ at 5.3 GHz and 40°.

in (1) and Fig. 3(a). Fig. 3(a) also informs us that the roughness sensitivity of $\sigma^0_{\rm vh}$ drops as the rms height increases for a given soil moisture content. For example, $\sigma^0_{\rm vh}$ increases 10 dB when s increases (four times) from 0.3–1.2 cm, and only 4 dB when s increases another factor of 4 from 1.2–4.8 cm as shown in Fig. 3(a). In Fig. 3(b), it is clearly observed that the moisture sensitivity of p drops rapidly as s increases, e.g., p changes only 0.04 dB for a very rough surface ($s = 4.8$ cm) over the entire range of M_v ($0.04 < M_v < 0.4$ cm^3/cm^3). It is also shown that the dynamic range of p for a relatively wet surface ($M_v = 0.2$ cm^3/cm^3) is 2.3 dB and that for a dry surface ($M_v = 0.05$ cm^3/cm^3) it is only 0.6 dB. Therefore, Fig. 3(b) implies that the copolarized ratio p cannot be used to retrieve M_v for very rough or very dry surfaces.

III. Direct Inversion Method

Having examined experimental radar observations of bare soil surfaces through the semiempirical scattering model in the previous section, we are now ready to invert the model directly to retrieve estimates of the rms height s and the moisture content M_v from radar observations of $\sigma^0_{\rm vv}$, $\sigma^0_{\rm hh}$, and $\sigma^0_{\rm vh}$. An inversion diagram (or a lookup table) can be generated combining

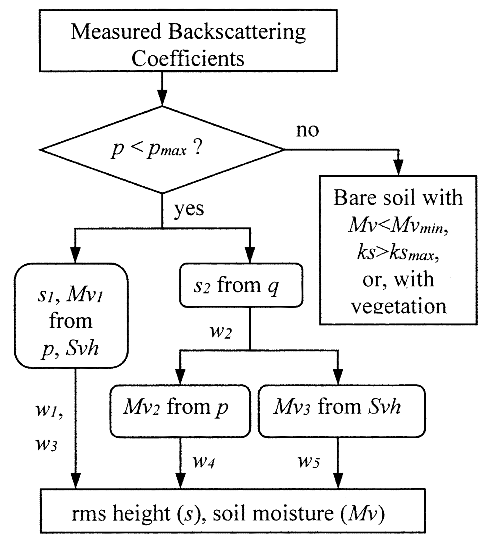


Fig. 4. Flowchart for retrieving s and M_v from measured backscattering coefficients.

(1) and (2) for a frequency and an incidence angle to retrieve s and M_v from measured $\sigma^0_{\rm vh}$ and p. From the measurements of $\sigma^0_{\rm vv}$, $\sigma^0_{\rm hh}$, and $\sigma^0_{\rm vh}$ for a given surface at an incidence angle and a frequency, we can read the rms height s and the volumetric moisture content M_v from inversion diagrams using the measured copolarized ratio $p = \sigma^0_{\rm hh}/\sigma^0_{\rm vv}$ and $\sigma^0_{\rm vh}$.

The estimates of s and M_v can also be obtained from measurements of $\sigma^0_{\rm vh}$ and p by the following simple computation. Solving (1) for the estimate of ks yields

$$ks\left(\theta, M_v, \sigma^0_{\rm vhm}\right) = \left[-3.125 \ln\left\{1 - \frac{\sigma^0_{\rm vhm}}{0.11\, M_v^{0.7}(\cos\theta)^{2.2}}\right\}\right]^{0.556} \quad (5)$$

where $\sigma^0_{\rm vhm}$ is the measurement of the vh-polarized backscattering coefficient and M_v is the estimate of the soil moisture content to be determined. By substituting (5) into (2), we obtain the following nonlinear equation for M_v:

$$1 - \left(\frac{\theta}{90^\circ}\right)^{0.35\, M_v^{-0.65}} \cdot e^{-0.4\left[ks\left(\theta, M_v, \sigma^0_{\rm vhm}\right)\right]^{1.4}} - p_m = 0 \quad (6)$$

where p_m denotes the measured copolarized ratio p and $ks(\theta, M_v, \sigma^0_{\rm vhm})$ is given in (5). After solving (6) using a root-finding numerical technique, M_v can be obtained. The roughness parameter ks can be computed from (5), and the rms height s can also be obtained, subsequently, for a radar frequency.

The cross-polarized ratio q in the form of (4) can contribute to finer accuracy of this inversion technique as follows. After obtaining an estimate of ks from (4) using a measured cross-polarized ratio $q = \sigma^0_{\rm vh}/\sigma^0_{\rm vv}$, M_v can be computed either from (1) with measured $\sigma^0_{\rm vh}$, or from (2) with measured p.

A detailed block diagram in Fig. 4 shows the inversion algorithm for the retrieval of s and M_v from measured backscattering coefficients. The value of the copolarized ratio p approaches to 0 dB ($\sigma^0_{\rm hh} = \sigma^0_{\rm vv}$) for a very dry and/or very rough surface as shown in Figs. 1(b) and 3(b). Moreover, the effect of sparse vegetation can make p greater than 0 dB

($\sigma^0_{\rm hh} > \sigma^0_{\rm vv}$), because $\sigma^0_{\rm hh}$ may be higher than $\sigma^0_{\rm vv}$ for microwave scattering from a vegetation canopy. Therefore, only measurements of $\sigma^0_{\rm vv}$, $\sigma^0_{\rm hh}$, and $\sigma^0_{\rm vh}$ satisfying $p < p_{\rm max}$ are selected for the inversion, where the maximum copolarized ratio $p_{\rm max}$ is computed with maximum s (5.5 cm) and minimum $M_v(0.01\ {\rm cm}^3/{\rm cm}^3)$. For example, $p_{\rm max}$ is 0 dB for $f = 5.3$ GHz and $\theta = 10°$, and -0.4 dB for $f = 1.25$ GHz and $\theta = 70°$.

If the measurements of $\sigma^0_{\rm vv}$, $\sigma^0_{\rm hh}$, and $\sigma^0_{\rm vh}$ pass the screening test $(p < p_{\rm max})$, the primary estimates of $s(s_1)$ and $M_v(M_{v1})$ can be obtained from (5) and (6) (Fig. 4). A second estimate of $s(s_2)$ can be obtained from (4) and substitute this value s_2 into (1) and (2) subsequently to get M_{v2} and M_{v3}. Then, the multiple estimates of the rms height and the volumetric moisture content can be averaged as

$$s = \frac{(w_1 s_1 + w_2 s_2)}{(w_1 + w_2)} \tag{7}$$

$$M_v = \frac{(w_3 M_{v1} + w_4 M_{v2} + w_5 M_{v3})}{(w_3 + w_4 + w_5)} \tag{8}$$

where w_1, w_2, w_3, w_4, and w_5 are weights. Comparing the correlation coefficients between the estimated and field-measured parameter values for various combinations of the weights, using the database discussed in the previous section, have we determined the optimum values of the weights empirically. The values for w_1, w_2, w_3, w_4, and w_5, which give the best inversion results, are 1, 1/4, 1, 1, and 1, respectively.

IV. Results and Discussion

In addition to seven datasets measured by polarimetric scatterometers and the JPL airborne SAR, which were used to derive the semiempirical relationships [7], two additional polarimetric measurement sets, which were not used in modeling procedure, are included in the database to verify the direct inversion method. The datasets are summarized in Table I.

- *Data-8:* During the PACRIM-2 campaign in 2000, the JPL airborne SAR was used to measure the polarimetric radar backscatter response of various fields near Gong-ju, Korea. The surface roughness and soil moisture data for seven different bare soil fields were collected. The rms surface heights of those fields ranged from 0.72–3.0 cm, and the volumetric moisture contents varied from 0.045–0.35 ${\rm cm}^3/{\rm cm}^3$. The incidence angles varied from 42° to 58°.
- *Data-9:* The backscattering coefficients of a bare soil surface were measured by a polarimetric scatterometer system at 2.1 GHz at incidence angles of 20°, 30°, 40°, 50°, and 60° at Hongik University, Seoul, Korea, in 1999. The measured surface parameters for the surface were $s = 0.52$ and $l = 4.07$ cm and $M_v = 0.03\ {\rm cm}^3/{\rm cm}^3$.

It was found that about 25% of the measurements in the database fail to satisfy $p < p_{\rm max}$, and many of those measurements have the value of p larger than 0 dB. We can consider several reasons for $p \approx 0$ dB$(\sigma^0_{\rm hh} \approx \sigma^0_{\rm vv})$ or even $p \geq 0$ dB$(\sigma^0_{\rm hh} > \sigma^0_{\rm vv})$ as follows: (1) A vegetation canopy over a bare soil surface may cause higher $\sigma^0_{\rm hh}$ than $\sigma^0_{\rm vv}$. (2) The backscattering coefficient from a very rough surface will agree with the geometrical optics

TABLE I
Description for Datasets. A Brief Summary Can Be Found in [7]

No	Radar	Place/Year	For Model	For Inv. Test
1	POLARSCAT	U of M/1990*	O	O
2	POLARSCAT	Pellston/1991*	O	O
3	POLARSCAT	Ypsilanti/1991*	O	O
4	Scatterometer	Hongik U./1999*	O	O
5	AirSAR	Pellston/1991*	O	O
6	AirSAR	Chichasha/1992*	O	O
7	AirSAR	Davis/1993*	O	O
8	AirSAR	Gong-Ju/2000	X	O
9	Scatterometer	Hongik U./1999	X	O

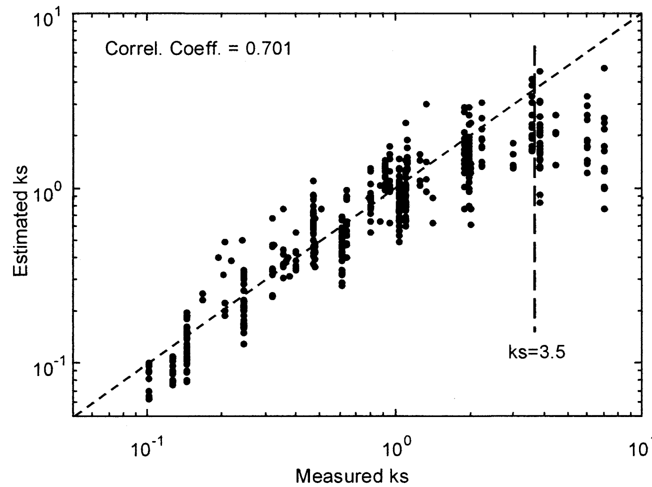


Fig. 5. Comparison between the surface parameter $ks(k = 2\pi f/c, s =$ rms height) estimated by the inversion technique and that measured *in situ*.

(GO) model [6], which predicts $\sigma^0_{\rm hh} = \sigma^0_{\rm vv}(p = 0$ dB). Considering the measurement precision about ±0.5 dB, the roughness parameter ks needs to be less than about 3.5 for the best performance of the inversion algorithm. (3) It was shown that the copolarized ratio p measured from a very dry soil surface also approaches to 0 dB [Fig. 1(b)] The measured copolarized ratio might be smaller than -0.5 dB (the calibration precision) for best inversion results as shown in Fig. 1(b). When the minimum value of $ks(= 0.1)$ is substituted in (2), we get the following condition $M_v > [-6.286/\ln(\theta/90)]^{-1.538}$, e.g., $M_v > 0.068\ {\rm cm}^3/{\rm cm}^3$ for 30° and $M_v > 0.026\ {\rm cm}^3/{\rm cm}^3$ for 50°. (4) The copolarized ratio p is 0 dB at 0°. If the maximum value of $M_v(= 0.3)$ and the minimum value of $ks(= 0.1)$ are substitute in (2), the incidence angle might be larger than about 6° to get $p \leq -0.5$ dB.

It should be noted that 57 data among 171 total failed-data $(p > p_{\rm max})$ are from very rough surfaces $(ks > 3.5)$, and 56 data from very dry surfaces $(M_v > [-6.286/\ln(\theta/90)]^{-1.538})$. The rest of the failed-data may be from the effect of sparse vegetation, errors of radar measurements, errors of ground-truth measurements, or errors from modeling.

Fig. 5 shows a comparison between the values of ks estimated by the inversion method and those measured *in situ*, for 482 data points satisfying $p < p_{\rm max}$. The correlation coefficient

TABLE II
CORRELATIONS BETWEEN MEASURED AND ESTIMATED VALUES FOR THE RMS HEIGHT (s) AND THE VOLUMETRIC MOISTURE CONTENT (M_v)

Data Description	Correlation coefficient, ρ		Number of Data Point
	s (ks)	Mv	
Data with $p < p_{max}$	0.681 (0.701)	0.742	482
Data with $ks < 3.5$	0.895 (0.822)	0.777	414
Averaging for Multi-frequency data	0.899	0.881	140
Averaging for Multi-frequency and multi-angle data	0.926	0.920	31

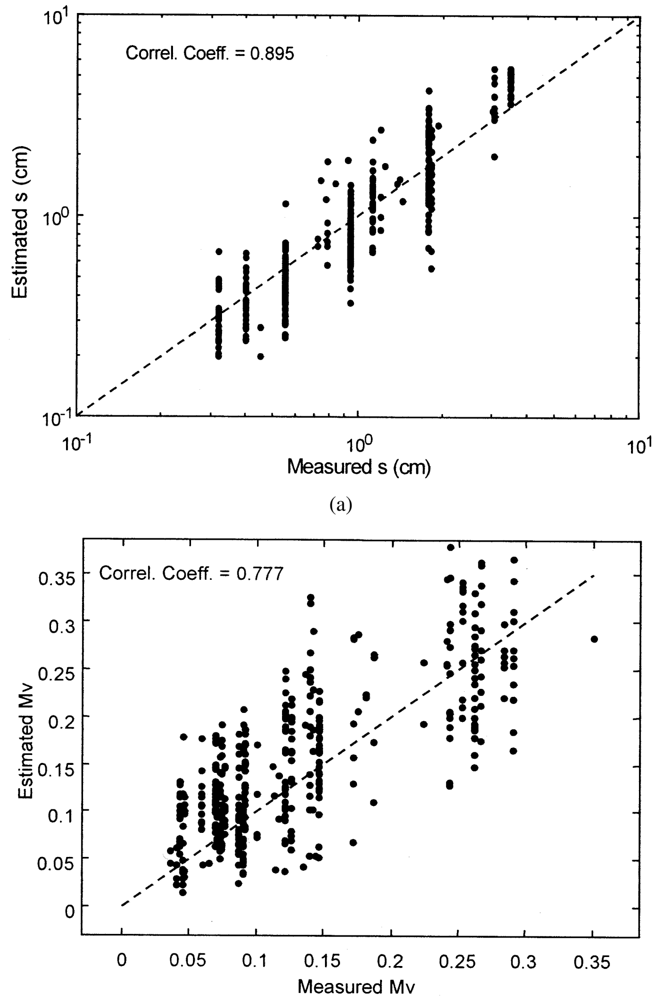


Fig. 6. Comparison between the surface parameters estimated by the inversion technique and those measured *in situ* for (a) the rms height s and (b) the volumetric moisture content M_v.

between the estimated and field-measured values of ks is 0.701 as shown in Table II. It is shown that the agreement between the estimated and measured values of ks is quite good for $ks < 3.5$. The estimated values of ks deviate from the measured values

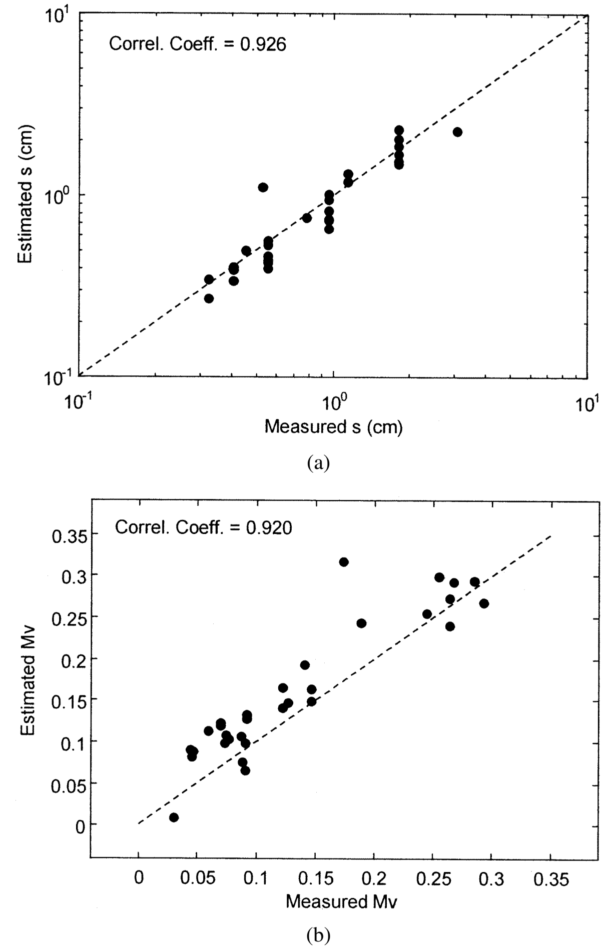


Fig. 7. Comparison between the estimated and field-measured surface parameters for multifrequency and multiangle data. (a) RMS height s. (b) Volumetric moisture content M_v.

over the range $ks > 3.5$ as shown in Fig. 5, because of small variations of the backscattering coefficients for $ks > 3.5$ as in Fig. 1. The range of the rms height for natural surfaces is about $0.4\ \text{cm} \leq s \leq 4.0\ \text{cm}$, where $s = 4$ cm corresponds to a plowed surface. Therefore, all natural surfaces are in the range $ks < 3.5$ for $f < 4.2$ GHz. However, the inversion is limited to a certain range of the rms height for higher frequencies ($f < 4.2$ GHz), e.g., a surface might have the rms height less than 3.15 cm for 5.3 GHz and 1.74 cm for 9.6 GHz.

Fig. 6(a) shows a comparison between the rms height s estimated by the inversion method and those measured *in situ*, for 414 data points satisfying $ks < 3.5$. The correlation coefficient between the estimated and field-measured values of s is 0.895 as shown in Table II. Relationship between the estimated s and field-measured s is shown in a log-log scale instead of a linear scale for a better view as shown in Fig. 6(a). The correlation coefficient with a log-log scale as in Fig. 6(a) is 0.911. Fig. 6(b) shows the results for the volumetric moisture content M_v for the data with $ks < 3.5$. We can consider various sources of error affecting soil moisture retrieval, such as imperfection of the semiempirical scattering model used in the inversion technique, inaccurate radar measurements due to radar system calibration error, and inaccurate *in situ* measurements of the surface roughness and soil moisture.

Polarimetric radar systems usually have multiple frequency bands, e.g., P-, L-, and C-bands for the JPL airborne SAR and L-, C- and X-bands for the University of Michigan's LCX POLARSCAT. Two or three radar systems with different frequencies have usually been operated simultaneously to measure the backscattering coefficients of a surface at an incidence angle. When we average the estimated surface parameters over multifrequency data, the correlation coefficients increase from 0.895 to 0.899 for the rms height s, and from 0.777 to 0.881 for the volumetric moisture content M_v as shown in Table II. If we average again the estimated surface parameters over multiangle data, the correlation coefficients increase from 0.899 to 0.926 for s and from 0.881 to 0.920 for M_v (Table II). Fig. 7(a) and (b) shows the values of the rms height s and the volumetric moisture content M_v estimated by the inversion method plotted against the values measured *in situ*, for multifrequency and multiangle data.

V. Conclusion

A simple inversion technique has been developed using a semiempirical polarimetric scattering model for retrieving the rms height of a surface and its moisture content from multi-polarized radar observations. The copolarized ratio p and the vh-polarized backscattering coefficient $\sigma^0_{\rm vh}$ of the semiempirical model have been inverted directly to retrieve the soil parameters. A new model of the cross-polarized ratio q has been introduced for the purpose of improving the inversion results. Good agreement was found between the values of ks estimated by the inversion method and those measured *in situ* for $ks < 3.5$, with a correlation coefficient of 0.822. It was also shown that the correlation coefficient between the estimated and measured M_v increased from 0.777 to 0.881 after averaging the multifrequency data, and to 0.920 after averaging the multifrequency multiangle data. This inversion technique gives best results for bare soil surfaces without vegetation canopy if $ks < 3.5$ and ($M_v > [-6.286/\ln(\theta/90)]^{-1.538}$) (e.g., $M_v > 0.068\,{\rm cm}^3/{\rm cm}^3$ for 30°).

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Yisok Oh (S'88–M'94–SM'03) received the B.S. degree in electrical engineering from Yonsei University, Seoul, Korea, in 1982, the M.S. degree in electrical and computer 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.

He is currently an Associate Professor in the School of Electronic and Electrical Engineering, Hongik University, Seoul. His current research interests include microwave scattering from earth surfaces, antennas, and radio wave propagation.