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Response of Microwave on Bare Soil Moisture and Surface Roughness by X-Band Scatterometer

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SUMMARY This paper describes an individual effect of soil moisture (m_g) and surface roughness (h_{rms}) of bare soil on the back scattering coefficient (σ^0) at the X-band frequency. The study contributes to the design of an efficient microwave sensor. For this purpose, experimentally observed data was utilized to provide a composite σ^0 equation model accounting for individual effect in regression analysis. The experimental data are compared with Small Perturbation Method. It is observed that the X-band gives better agreement up to incidence angle 50° for HH-polarization and 60° for VV-polarization as compared to the C-band. The lower angles of incidence give better results than the higher angles for observing m_g at the X-band. The multiple and partial regression analyses have also carried out for predicting the dependence of scattering coefficient (σ^0) on m_g and h_{rms} more accurately. The analyses suggest that the dependence of dielectric constant (i.e., m_g) is much more significant in comparison to surface roughness at lower angles of incidence for both like polarizations. The results propose the suitable angle of incidence for observing bare surface roughness and soil moisture at the X-band. All these data can be used as a reference for satellite or spaceborne sensors.

key words: *remote sensing, soil moisture, surface roughness, scattering coefficient, scatterometer*

1. Introduction

It is well known that air-borne or space-borne remote sensing has definite advantage in collecting data in many fields. Although direct ground data collection provides precise data, the ground truth method is cumbersome with spatially distributed targets. Remote sensing is suitable for frequent observations of rapidly changing phenomena over vast area. A precise knowledge of the microwave scattering response of a target (i.e. shape, size and physical parameters) is important factor for interpreting remotely sensed data and also for developing airborne and space borne microwave sensors. For this purpose, the ground based remote sensors such as scatterometers [1]–[4] have been developed to examine and estimate scattering characteristics of targets.

Soil moisture and surface roughness of terrain are important parameters for environmental assessment. The spatial variation in soil moisture and surface roughness has direct impact on the statistics of the radar image. When electromagnetic wave is incident on a terrain, the reflection/scattering of incident wave depends mainly upon two parameters; (i) system parameters and (ii) target parameters. The system parameters are incidence angle, wavelength and polarization, whereas the target parameters include orientation and size of the scatterers, the subsurface or surface geometry of the target, and its complex dielectric properties, etc. Since the dielectric properties are strongly dependent upon the water content, the dielectric constant of soil affects the scattering characteristics of electromagnetic waves.

In this paper, we examine the effect of surface roughness and soil moisture on scattering coefficient for the X-band frequency, in combination of two parameters mentioned above. Surface roughness and soil moisture are the dominant factors that determine the radar response from bare soil. Extensive studies of the microwave signature of soil moisture and surface roughness have been carried out by a large number of scientists and researchers [1]–[9]. As a result of these investigations, the characteristics of large (size >> wavelength λ) and small (size << λ) scatterers have been distinctly known [3]. However, there still exist uncertainity in the effects of these two parameters on the scattering coefficient in the X-band.

Using a ground based X-band scatterometer system [5], we have observed the scattering coefficient in the X-band on various surface roughness and soil moisture content at different angle of incidence for both like polarizations. Section 2 briefly describes surface parameters. In Sect. 3, theoretical backscattering from relatively smooth surface is given by the SPM model [3], [7] referring to the C-band results [4]. This study proposes a simple empirical model for estimating the measured scattering coefficient for bare soil field in Sect. 4. Using this model, the multiple and partial regression analysis has been carried out in Sect. 5, which provides the multiple coefficient of determination (R^2), partial coefficient of determination (r^2) and Standard Error of Estimate (SEE). The R^2 predicts percentage dependence of σ^0 on m_g and h_{rms} both, whereas r^2 accounts for percentage dependence of σ^0 on m_g and h_{rms} individually. The result gives a new class of knowledge about surface roughness and soil moisture for remote sensing purpose.

2. Surface Roughness Parameter

A surface can be described by two-dimensional surface height $S(x, y)$. Since $S(x, y)$ exhibits a random value in general, a surface profile is characterized statistically by its mean height $\overline{S(x, y)}$, its rms height h_{rms}, and surface auto correlation func-

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tion $\eta(\xi)$ where ξ is horizontal displacement. If $S(x, y)$ is statistically independent in the (x-y) plane, it is sufficient to use $S(x)$ alone to characterize the statistical properties of the surface [10]. The rms height h_{rms} is given in terms of $\bar{S}$ and the second moment $\overline{S^2}$ by

$$h_{rms} = \sqrt{\overline{S^2} - \bar{S}^2} \ . \tag{1}$$

The surface auto correlation function $\eta(\xi)$ is a measure of the degree of correlation between the height $S(x)$ at a point x and the height $S(x+\xi)$ at a point $x+\xi$,

$$\eta(\xi) = \frac{\int [\, S(x) - S(x+\xi)\,]\, dx}{\int S^2(x)\, dx} \ , \tag{2}$$

Theoretical surface models are formulated in terms of the auto correlation function $\eta(\xi)$ of the surface. Several mathematical forms have been used to describe $\eta(\xi)$ for natural surfaces [3]

$$\eta_1(\xi) = \exp\left(-\frac{\xi^2}{\Lambda^2}\right) \ \cdots\cdots\cdots\cdots \ \text{Gaussian}\ , \tag{3}$$

$$\eta_2(\xi) = \exp\left(-\frac{\sqrt{2}\,\xi}{\Lambda}\right) \ \cdots\cdots\cdots\cdots \ \text{Exponential}\ . \tag{4}$$

In general, the rms height h_{rms} is a measure of the vertical roughness of the surface, and $1/\Lambda$ is a measure of the horizontal roughness where Λ is the correlation length. A surface with a rapidly varying height profile has a small value for Λ, whereas for perfectly smooth surface Λ is infinite.

3. Backscattering from Relatively Smooth Surfce

In remote sensing investigations, there are two types of problems, i.e., forward problem and inverse problem. In this paper, the forward problem has been taken to analyze a model that can correctly characterize the radar scattering. First, we review the back scattering coefficient $\sigma^0(\theta)$ of rather smooth soil surface by providing expressions in terms of the system parameters (θ, λ, and polarization configuration) and the soil surface properties.

The Small Perturbation Method (SPM) [3], [7] is applied to simulate back scattering from a relatively smooth surface with $k\,h_{rms} < 0.3$, $k\,\Lambda < 3$ where $k = \frac{2\pi}{\lambda}$, and with $m < 0.3$, where m is the rms slope of the surface. For a surface with a Gaussian auto correlation function, $m = \sqrt{2}\, h_{rms} / \Lambda$, and $m = h_{rms} / \Lambda$ for exponential function. For the like polarized scattering coefficient $\sigma^0_{pp}(\theta)$, where p = V or H, it consists of a coherent component $\sigma^0_{ppc}(\theta)$ and an incoherent component $\sigma^0_{ppn}(\theta)$

$$\sigma^0_{pp}(\theta) = \sigma^0_{ppc}(\theta) + \sigma^0_{ppn}(\theta), \quad p = V \text{ or } H. \tag{5}$$

The coherent component, which is significant only in the vicinity of normal incidence ($\theta = 0$), is given by [3]

$$\sigma^0_{ppc}(\theta) = \frac{4\alpha_0}{W^2} \exp\left(-4\,k^2\, h^2_{rms}\right) \exp\left(-\frac{4\,\theta^2}{W^2}\right) \tag{6}$$

where $\alpha_0 = \left| \frac{\sqrt{\varepsilon^*} - 1}{\sqrt{\varepsilon^*} + 1} \right|$ is the surface reflectivity for normal incidence with ε^* indicating the relative complex dielectric constant of the surface and W is antenna beam width. For an antenna with a beam width $W > 10°$, the coherent component $\sigma^0_{ppn}(\theta)$ becomes negligibly small for incidence angle $\theta > 10°$. Therefore, the coherent component $\sigma^0_{ppc}(\theta)$ is less important for large incidence angles $\theta > 10°$.

The expression $\sigma^0_{ppn}(\theta)$ for the incoherent component depends on the auto correlation function of the surface. For a surface characterized by Gaussian auto correlation function (3), the incoherent scattering coefficient is given by [11]

$$\sigma^0_{ppn}(\theta) = 4\,k^2\, h^2_{rms}\, \Lambda^2 \cos^4\theta \,|\,\alpha^2_{pp}\,|\, \exp\left(-\,k\,\Lambda \sin\theta\,\right)^2 \tag{7}$$

where

$$\alpha_{HH} = \frac{\cos\theta - \sqrt{\varepsilon^* - \sin^2\theta}}{\cos\theta + \sqrt{\varepsilon^* - \sin^2\theta}} \ , \tag{8}$$

$$\alpha_{VV} = \frac{\varepsilon^*\cos\theta - \sqrt{\varepsilon^* - \sin^2\theta}}{\varepsilon^*\cos\theta + \sqrt{\varepsilon^* - \sin^2\theta}} \ . \tag{9}$$

For a surface with exponential auto correlation function (4), which more closely approximates natural surfaces for small values of ξ, the incoherent scattering coefficient is given by [7]

$$\sigma^0_{ppn}(\theta) = 4\,k^2\, h^2_{rms}\, \Lambda^2 \cos^4\theta \,|\,\alpha^2_{pp}\,|\, [\, 1 + 2\,(\,k\,\Lambda \sin\theta\,)^2\,]^{-\frac{3}{2}} \ . \tag{10}$$

The expressions given by Eqs.(7) and (10) are for the like-polarized scattering coefficients, which are based on the first order solution and predicts no cross-polarized scatterer. The cross-polarized scattering coefficient consists solely of an incoherent contribution. These equations predict the theoretical scattering coefficients which we deal with hereafter.

4. Emprical Approach

As briefly described in the previous section, the back scattering coefficient $\sigma^0(\theta)$ of non-periodic random surface is governed by both the dielectric properties and the roughness parameters of that surface. To examine how the incoherent scattering coefficient $\sigma^0_{ppn}(\theta)$ depends on the dielectric properties and on the roughness, let's express $\sigma^0(\theta) = \sigma^0_{ppn}(\theta)$ as a product of two independent functions as proposed in [3],

$$\sigma^0(\theta) = f_{rt}(\,\varepsilon, \theta\,)\, f_s(\,\eta(\xi), \theta\,) \ . \tag{11}$$

The dielectric function $f_{rt}(\,\varepsilon, \theta\,)$ accounts only for the dependence of $\sigma^0(\theta)$ on the relative dielectric constant ε of the surface. Conversely, the roughness function $f_s(\eta(\xi), \theta)$ accounts for the dependence of $\sigma^0(\theta)$ on surface roughness and is independent of ε.

Our purpose in this paper is to derive an emprical relation of $\sigma^0(\theta)$ based on (11). Since $f_{rt}(\varepsilon, \theta)$ and $f_s(\eta(\xi), \theta)$ are complicated functions of (i) system parameter, and (ii) target parameters, we rewirite (11) in the decibel form

$$\sigma^0(\theta) = K_1\, m_g + K_2\, h_{rms} + C \quad [\mathrm{dB}], \qquad (12)$$

where soil moisture m_g and h_{rms} are taken as independent variables for $\sigma^0(\theta)$. Since dielectric property of soil strongly depends on moisture content among other parameters, m_g may be the representative parameter of dielectric constant which also we would like to know. K_1 and K_2 are sensitivity factors of $\sigma^0(\theta)$ on m_g and h_{rms}, respectively, and C represents noise which depends upon the system parameter and target geometry.

5. Experimental Results and Discussion

Using an X- band scatterometer [5] as shown in Fig. 1 and the specification listed in Table 1, the $\sigma^0(\theta)$ of bare ground surfaces was measured for different roughness and various moisture content. The surface was specially prepared for measurement. The moisture content was measured by taking the soil samples up to 5 cm deep from the upper surface layer. The moisture percentage given can be considered as average moisture content. Inserting a plate into the surface and spraying it with paint, we measured the surface profiles. Such a technique provides an approximate representation of the surface [3]. The soil surface had 6% gravel, 55% sand, 35% silt and 4% clay. These data were analyzed to examine the effect of surface roughness and moisture content at 9.5 GHz. The parameters derived by the ground truth data statistically are listed in Table 2.

Figures 2 and 3 show the angular variation of scattering coefficient for different soil moisture and surface roughness. The effect of surface roughness on σ^0 is clearly evident in these curves. In Fig. 2, σ^0 decreases as the angle of incidence increases for HH- polarization. For the smoothest sur-

Table 1 Scatterometer characteristics.

Central Frequency	9.5 GHz
Frequency Band Width	0.8 GHz
Antenna type	Dual Polarized Pyramidal Horn
Antenna Beam Width	8.5 degree
Antenna Gain	20 dB
Platform Height	10 m
Cross-pol Isolation	40 dB
Calibration Accuracy	1 dB

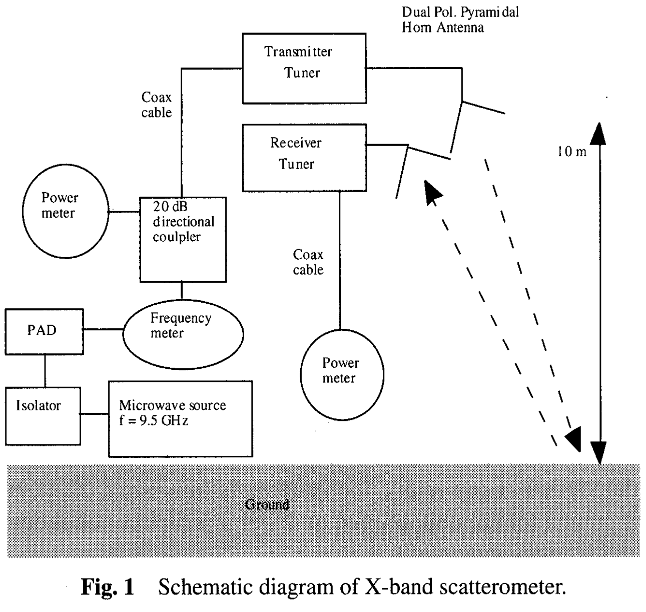

Fig. 1 Schematic diagram of X-band scatterometer.

Table 2 Soil moisture content m_g and roughness h_{rms} of test site.

	m_g (%)	h_{rms} (cm)
Field 1	6.5	0.15
Field 2	9.5	0.5
Field 3	12	0.67
Field 4	18.5	0.84
Field 5	20	2.8

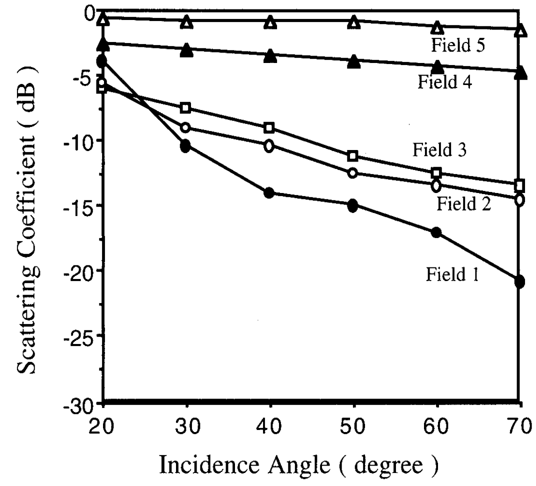

Fig. 2 Angular variation of scattering coefficient at various soil moisture and surface roughness for HH-pol. at X-band.

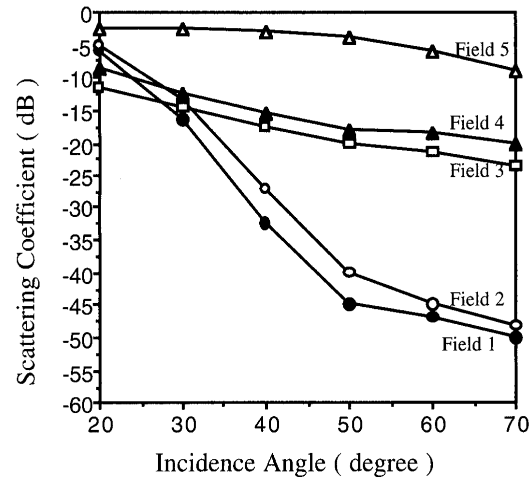

Fig. 3 Angular variation of scattering coefficient at various soil moisture and surface roughness for VV-pol. at X-band.

face (field 1) σ^0 decreases rapidly with increasing incidence angle, from –4 dB at $\theta = 20^\circ$ to –22 dB at $\theta = 70^\circ$. In contrast, the roughest surface (field 5) exhibits a small variation of only 2 dB at the same angular range. Similar tendancy has been reported in [3] at the frequency of 1.1 GHz.

The VV- polarization also gives the decreasing behavior of σ^0 with increasing θ, as shown in Fig. 3. The maximum variation of σ^0 is –6 dB to –50.2 dB in the smoothest surface. Similar results have been reported by earlier researchers [2], [3] at the C-band frequency. In general, it is anticipated that VV-polarization interacts the roughness and moisture content more than HH-polarization from the phenomenological point of view. Since VV-polarization shows wider dynamic range of σ^0, the wider range will be better for accessing the moisture content and roughness of soil more accurately.

These experimental results have been compared also by the SPM [3], [8], [12]. Figures 4 and 5 show the comparison for HH and VV polarization respectively, where $k\Lambda = 2.8$, $h_{rms} = 0.15$ cm, and $m_g = 6.5\%$ and it satisfies the criteria given for SPM [3]. The exponential auto correlation is best fitted here. For the C- and L-band, the exponential auto correlation function was also best fitted for slightly rough surface [4]. Good agreement between theory and measured data is observed for both like polarizations, up to $\theta = 50^\circ$ for HH, and $\theta = 60^\circ$ for VV. Similar results have been obtained in [4] at C-band, but it is observed that X-band results have much better agreement with SPM model in comparison to C-band. It is seen that the SPM model over estimates σ^0 for both like polarizations at higher angle of incidence. It may be due to the lack of exact surface roughness parameter [13]. As indicated in [2]–[4], [7], that roughness and moisture content are important factors for microwave scattering on bare soil. In this study, it is attempted to highlight the individual effect of m_g and h_{rms} on σ^0 at various incidence angles for the X-band.

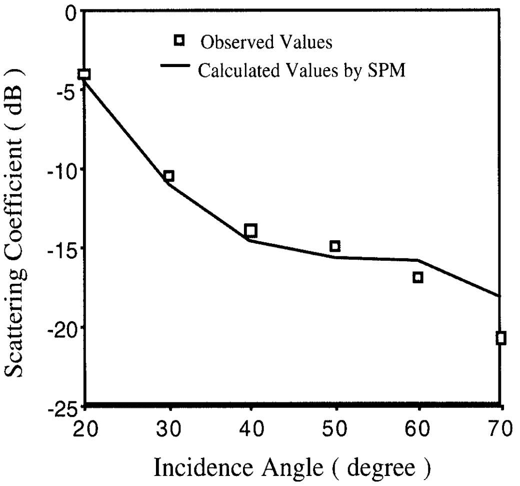

Fig. 4 Angular variation of scattering coefficient for observed and calculated values for HH-pol. at X-band ($k\Lambda = 2.8$, rms height = 0.15 cm, and soil moisture 6.5%).

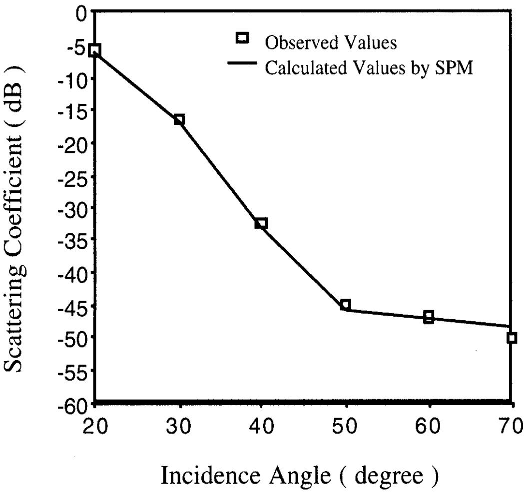

Fig. 5 Angular variation of scattering coefficient for observed and calculated values for VV-pol. at X-band ($k\Lambda = 2.8$, rms height = 0.15 cm, and soil moisture 6.5%).

The multiple regression analysis has been carried out to derive σ^0 as a function of m_g and h_{rms}. Table 3 indicates how the regression curve is close to measured data. R^2 shows the percentage dependence of m_g and h_{rms} on σ^0. The variation of R^2 in VV-polarization (0.995-0.65) is wider than that in HH-polarization (0.99-0.79) at incidence angles of 20-70 degrees. If range is wider, the dependence of σ^0 on m_g and

Table 3 Multiple regression results of scattering coefficient vs. surface roughness and soil moisture at different incidence angle for both like polarizations at X-band.

Angle	Multiple (R^2)	SEE	Partial (r^2)		Polarization
			m_g	h_{rms}	
20	0.99	0.051	0.97	0.72	HH
25	0.98	0.09	0.92	0.76	HH
30	0.975	0.25	0.86	0.79	HH
35	0.87	0.56	0.78	0.86	HH
40	0.86	0.56	0.76	0.89	HH
45	0.84	0.6	0.75	0.88	HH
50	0.83	0.63	0.72	0.68	HH
55	0.82	0.68	0.7	0.65	HH
60	0.81	0.7	0.69	0.62	HH
65	0.8	0.72	0.68	0.6	HH
70	0.79	0.73	0.65	0.58	HH
20	0.995	0.028	0.98	0.76	VV
25	0.984	0.28	0.93	0.78	VV
30	0.975	0.32	0.88	0.82	VV
35	0.97	0.38	0.76	0.88	VV
40	0.96	0.41	0.74	0.9	VV
45	0.86	0.45	0.7	0.86	VV
50	0.78	0.48	0.68	0.8	VV
55	0.76	0.74	0.675	0.78	VV
60	0.7	0.76	0.66	0.72	VV
65	0.68	0.78	0.65	0.7	VV
70	0.65	0.8	0.64	0.68	VV

h_{rms} becomes more significant and effective. Because R^2 predicts about percentage of dependence of these two parameters on σ^0. Therefore, VV-polarization is much effective than HH-polarization for observing the effect of m_g and h_{rms} on σ^0 at the X-band for incidence angles of 20-70 degrees.

The partial coefficient of determination (r^2) reveals the individual effect of target parameters (i.e., m_g and h_{rms}) on σ^0. It is observed from the same table that the value of r^2 for m_g and h_{rms} are smaller than the value of R^2 at various incidence angles for both like polarizations. It means that the composite values of surface (i.e., when we take m_g and h_{rms} both) are better correlated with σ^0, in comparison to, when we take only m_g and h_{rms} individually. The value of r^2 for m_g decreasing with increasing angle for both like polarizations. The value becomes maximum at $\theta = 20^\circ$, whereas the value of r^2 for h_{rms} firstly increase up to $\theta = 40^\circ$ and then decreases. Its maximum value is at $\theta = 40^\circ$ for both like polarizations. If we compare the value of r^2 for m_g and h_{rms} from the same table, than it is observed that the value of r^2 for m_g is greater than the value of r^2 for h_{rms} at lower angle of incidence ($\theta < 30^\circ$). It infers that the effect of moisture content is more prominent than the surface roughness on σ^0 for lower incidence angle. At higher incidence angle ($\theta > 30^\circ$), surface roughness effect is more prominent than soil moisture on σ^0 for both like polarizations at the X-band.

Measure that would predict precise σ^0 based on composite effect of m_g and h_{rms}, is known as Standard Error of Estimate (SEE). This SEE also measures the dispersion of σ^0 about average line. The value of SEE is minimum at $\theta = 20^\circ$ for both like polarizations. The value of SEE for VV-polarization is smaller than that of HH - polarization, which also suggests that VV-polarization is better than HH- polarization to observe the m_g and h_{rms} for remote sensing at X-band. This type of measurements and regression analyses, using Eq. (12), can be used to develop an inversion technique for accessing the rms height and moisture content of the bare soil surface from multi polarized radar observations.

6. Conclusions

The microwave scattering properties of soil depends upon the geometrical and physical properties (i.e., m_g and h_{rms}) of the bare field and sensor parameter such as incidence angle, polarizations, and frequency. From the experimental results and regression analyses, VV-polarization gives wide dynamic range than HH-polarization for observing effect of m_g and h_{rms} on scattering coefficient at the X-band. The value of σ^0 decreases as the angle of incidence increases for both like polarizations, and SPM model shows good agreement with measured values up to 50° to 60° angle of incidence. At lower angle of incidence $\theta < 30^\circ$) moisture effect is more prominent than the surface roughness, and roughness effect is more prominent at higher incidence angles ($\theta > 30^\circ$). These results can also be used as reference data for air borne or satellite borne sensors.

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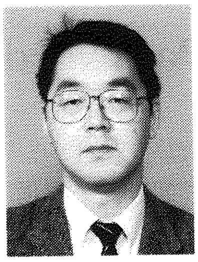

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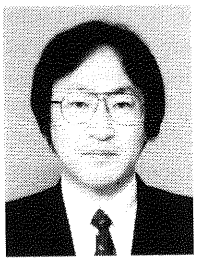

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