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Evaluation of Effective Soil Moisture From Natural Soil Surfaces

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지표면 토양의 유효 수분함유량 산출에 관한 연구

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Abstract

In this paper several methods for retrieving appropriate values of effective soil moisture contents from natural soil surfaces are introduced and compared each other. The soil medium has usually a nonuniform moisture profile; i.e., relatively dry at the top layer and relatively wet at the bottom layer. The effective soil moisture represents the quantitative value of soil moisture of the inhomogeneous soil medium in an average sense. A simple method is an arithmetic averaging of soil moisture values obtained from several layers of a soil surface. Otherwise, the penetration depths can be computed from a homogeneous and an inhomogeneous soil surfaces and compared in order to obtain the effective soil moisture. The other method is to obtain the effective soil moisture by comparing the reflectivities from both of a homogeneous and an inhomogeneous surfaces. Those methods are compared and the reflectivity technique is examined in more detail since the radar scattering is dominated by the reflectivity instead of the penetration.

요 약

본 논문에서는 지표면의 유효 토양 수분함유량의 적정한 값을 추출하는 몇가지 방법을 소개하고 그

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방법들을 서로 비교하였다. 지표면의 꼭대기 층은 비교적 말라 있고, 밑바닥 층은 젖어 있어서 종단면으로 봤을 때 토양은 대개 균일하지 않은 수분함유량 분포를 갖는다. 이러한 비균일적인 토양의 수분함유량을 어떤 평균적인 값으로 나타낸 것이 유효 수분함유량이다. 이 유효 수분함유량을 구하는 간단한 방법 중의 하나는 층층이 측정한 수분함유량의 산술 평균을 취하는 것이다. 다른 방법으로는 균일한 지표면과 비균일한 지표면의 침투 두께를 각각 계산하고 비교하여 유효 수분함유량을 얻는 방법이 있다. 또 다른 방법은 균일 지표면과 비균일 지표면에서 각각 반사율을 계산하고 비교하여 유효 수분함유량을 구한다. 이러한 방법들이 서로 비교되었고, 특히 반사율 적용법이 좀 더 자세하게 연구되었는데 그 이유는 실제 레이다 산란은 전파의 침투보다는 반사에 의해 좌우되기 때문이다.

1. Introduction

Since microwave can penetrate to some extent into soil surface and thus provide some information about subsurface, satellite SAR data are often used to provide soil moisture map within fine spatial resolution. Radar backscatter (SAR image) of the earth terrain is influenced by two sets of parameters: 1) physical parameters such as complex dielectric constant of the scatterers and surface roughness, and 2) radar parameters such as frequency, incidence angle and polarization. For a set of given radar parameters, the strength of the backscattered field from a soil surface and its statistics are complex functions of the surface irregularity and the dielectric constant of soil medium. For soil surfaces, the dielectric constant is strongly dependent upon the liquid water content, and the effects of other soil parameters like soil type (particle size distribution) are less important, particularly at the lower microwave frequencies [Ulaby et al., 1986]. Since one of the major contributions on radar backscattering from soil surfaces is the soil moisture, the soil moisture of a given surface can be estimated from the measured radar backscattering coefficients.

Accurate measurements and analyses of the target parameters; soil moisture and surface roughness, in addition to accurate radar backscatter measurements are necessary to develop an accurate scattering model. However, it is difficult to obtain quantitative values of moisture content of the soil medium accurately, because the radar wave interaction within the inhomogeneous soil medium is very complicated.

In this paper microwave penetration and scattering from the layered inhomogeneous soil surface is studied, specially at the frequencies of 1.25, 5.3 and 9.6 GHz. The backscattering coefficients of rough surfaces computed using the small perturbation method (SPM) show a large sensitivity on the dielectric constant (or the soil moisture), as well as those measured from bare soil surfaces using a truck-mounted scatterometer do. The soil moisture effect on the backscattering coefficient is studied in more detail in next section. The field measurement techniques for soil moisture contents are introduced in section 3, and several methods for retrieving the effective soil moisture from the field measurements are explained in section 4.

2. Soil Moisture Effect on the Backscattering Coefficients

When an electromagnetic wave impinges from above upon the rough soil surface, a portion of the incident energy is scattered upward and the rest is transmitted forward into the lower medium as shown in Fig. 1 depending on th e roughness measured in wavelength and the soil moisture. Most soil surfaces have inhomogeneous moisture profiles in depth; e.g., dry layers at top and wet layers in deep soil as illustrated in Fig. 1.

The theoretical scattering models are for predicting the backscattering coefficients of homogeneous surfaces only. Among others the SPM is known as a relatively precise model for a surface with very small roughness. Figures 2 (a) and (b) show the dependency of the backscattering coefficients on the dielectric constant (or the soil moisture since the dielectric constant of the soil surface depends mainly on the soil moisture). It is worth noting that the dielectric constant is also dependent on the soil type, however, the dependency of the soil type is very weak comparing with the soil moisture so that it could be ignored [Ulaby et al., 1986]. Figure 2 (a) shows the *vv*-polarized backscattering coefficients of the rough surfaces with the dielectric constants (ε_r) of (16, 3.2) (8, 1.6), and (4, 0.8), respectively, for a surface roughness of $ks=0.2$, $kl=2.0$, where k is wavenumber, s is rms height and l is autocorrelation length. The *vv*-polarization means the vertically polarized wave incidence and the vertically polarized wave scattering. The rms height is a standard deviation of a surface height density function and the autocorrelation length is a displacement distance when the normalized correlation function of

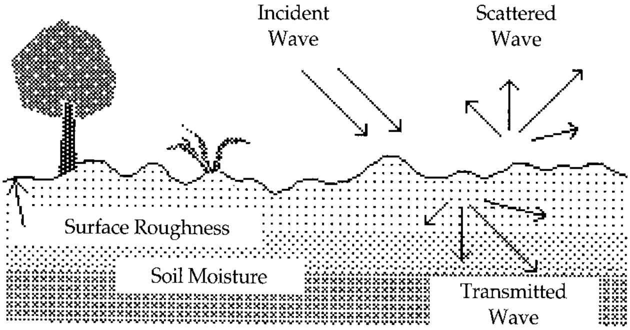

Figure 1. Electromagnetic wave interaction on the air-soil interface of a natural soil surface.

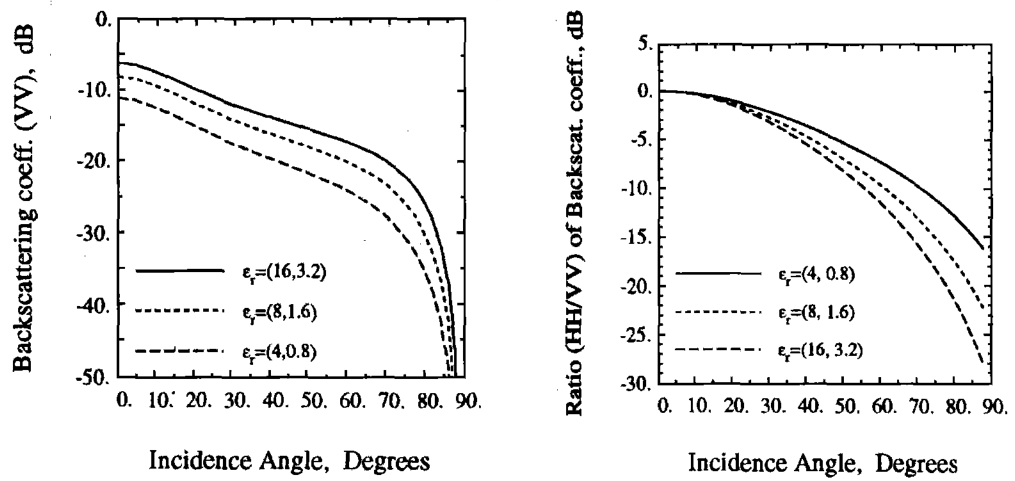

Figure 2. The backscattering coefficients computed using the SPM for rough surfaces of ks=0.2 and kl=2.0 with various values of dielectric constants, (a) vv-polarization ($\sigma^o{}_{vv}$) and (b) the co-polarized ratio ($\sigma^o{}_{hh}/\sigma^o{}_{vv}$).

the surface height distribution becomes the value of 1/e(=0.3678...). The *vv*-polarized backscattering coefficient from a very wet surface with high dielectric constant (ε_r=16+i3.2) is much higher (about 6 dB) than that from a dry surface with low dielectric constant (ε_r=4+i0.8) as shown in Fig. 2 (a). The co-polarized ratio of backscattering coefficient ($\sigma^o{}_{hh}/\sigma^o{}_{vv}$) is also a function of the dielectric constant of the surface; i.e., the ratio shows a higher value for a dry surface and the difference of the ratio between a dry and a wet surfaces increases as the angle increases as shown in Fig. 2 (b).

A truck-mounted scatterometer has been used to acquire a data set of measurements from bare soil surfaces with a wide range of roughness and soil moisture at L-, C-, and X-band frequencies at the incidence angles of 20°-70° [Oh et al., 1992 and 1994]. Figure 3 (a) shows the backscattering coefficients measured from a surface of s=0.4 cm, l=8.4 cm at 9.5 GHz (ks=0.8 and kl=16.7) for *vv*- and *hv*-polarized wave for a very wet (m_v=0.29) and a moderately wet (m_v=0.14) surfaces, respectively, where m_v is the volumetric moisture content in g/cm^3. The backscattering coefficient of the very wet surface is higher as much as about 3 dB than that of the moderately wet surface as shown in Fig. 3(a). The measured co-polarized ratios ($\sigma^o{}_{hh}/\sigma^o{}_{vv}$) from the surface at 4.75 GHz (ks=0.4, kl=8.4) are about 0 dB at low incidence angle (θ<20°) and decrease as the incidence angle increases. The co-polarized ratio for a very wet surface decrease more rapidly than that for a moderately wet surface, and the difference of the ratios between two surfaces is about 3dB at 60° as shown in Fig. 3 (b). The qualitative results of the soil moisture effects on the radar backscattering coefficients in Figs. 3 (a) and (b) agree well with Figs. 2 (a) and (b),

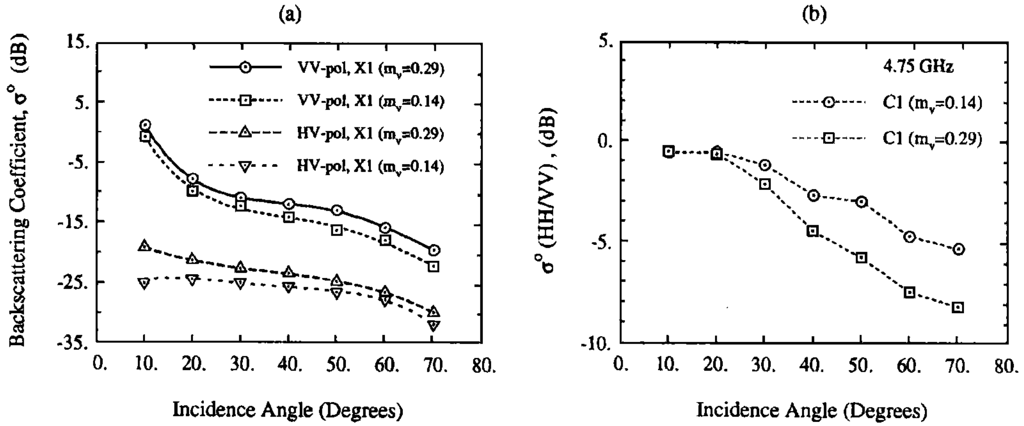

Figure 3. The backscattering coefficients for a surface of s=0.4cm and l=8.4cm for two different moisture conditions, (a) the vv-polarization at 9.5 GHz and (b) the co-polarized ratio at 4.75 GHz.

respectively. It is also shown in those figures that the maximum sensitivity of the radar backscattering on the soil moisture is about 6 dB, since dielectric constants of ε_r=16+i3.2 and ε_r=4+i0.8 correspond approximately to the maximum soil moisture (very wet soil) and the minimum soil moisture (very dry soil), respectively.

3. Soil Moisture Measurements

The moisture content of a soil sample can be represented by volumetric moisture m_v or gravimetric moisture mg given as follows, respectively.

$$mv = \frac{Vw}{Vt} = \frac{Vw}{Vd} = \frac{Ww}{\rho_w}\cdot\frac{\rho_b}{Wd} = \frac{Ww\rho_b}{Wd}\ cm^3\,cm^{-3}\ \text{or g/cm}^3 \qquad \text{...............(1)}$$

$$\text{and,}\quad mg = \frac{Ww}{Wd} = \times 100 = \frac{mv}{\rho_b} \times 100\,(\%) \qquad \text{...(2)}$$

where Vw is the water volume, Vt is the total volume of the sample which is equal to the volume of the dry sample assuming that when water is added to the sample, it fills air pockets but does not increase the total volume [Ulaby et al., 1986]. Ww and Wd are the weights of the water in the sample and of the dry sample, respectively, and ρ_b is the bulk density of the dry soil

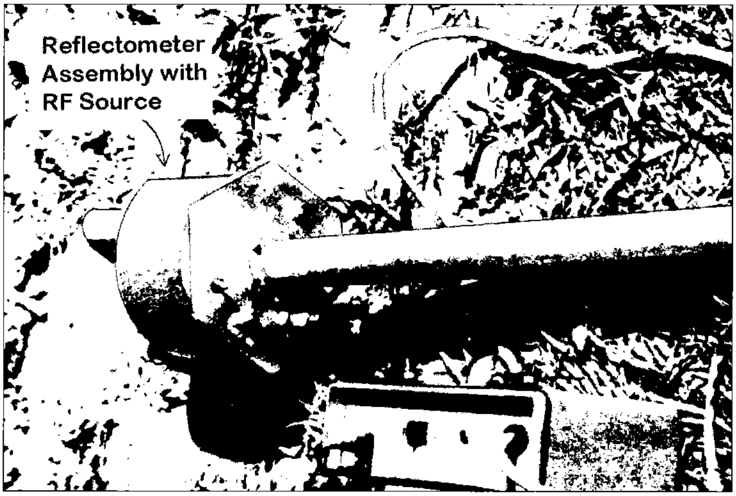

Figure 4. Picture of a C-band field-portable dielectric probe.

while the density of water, ρ_w, is 1 g/cm^3.

A classical method for obtaining the moisture content is taking soil samples and measuring weight as soon as the soil is taken (W_w) and after the soil is dried (W_d). The bulk density can be obtained by measuring the volume of the soil sample. In order to obtain more reliable moisture content, many soil samples should be taken in a soil field; e.g., 10~20 samples, and this sampling method is time consuming. While a radar measures the backscatter data, the ground truth data (soil moisture content and surface roughness) should also be taken at the same time. Therefore, the soil samples are usually taken into sealed plastic bags (or cans) at fields to save time and postpone the analysis of soil samples to post process, and the process in laboratory is very tedious. Instead of this sampling-in-bag technique, a dielectric probe has used to obtain the dielectric constant of the soil surface. A popular field-portable dielectric probe is shown in Fig. 4, which is designed to measure the reflectivity from the dielectric surface at 4.8 GHz and convert the reflectivity to a dielectric constant [Brunfeldt, 1987]. The probe consists of a reflectometer assembly with a RF source, a coaxial probe tip, a signal processing assembly containing a DC power source and a calculator (or computer) for storing data and controlling the processor. Most errors of dielectric constant measurements using this probe are from a bad contact between the soil surface and the contact tip because of hard soil clods.

An empirical model for microwave dielectric behavior of wet soil was presented in the following form [Hallikainen, et al, 1985];

$$\varepsilon = (\alpha_0 + \alpha_1 S + \alpha_2 C) + (b_0 + b_1 S + b_2 C) m_v + (c_0 + c_1 S + c_2 C) m_v^2 \quad \text{......................(3)}$$

where ε (ε' or ε'' depending on the constants) is a function of the volumetric moisture content, the constants $a_0 \sim c_2$, and the sand (S) and clay (C) textural components of a soil in percent by weight. The volumetric moisture content m_v can be obtained from the measured dielectric constant ε_r at microwave frequencies in the range of 1.4 GHz to 18 GHz inverting the empirical formula (3), where the constants are tabulated in [Hallikainen, et al, 1985].

4. Effective Moisture Content

Most soil surfaces are inhomogeneous in vertical direction as shown in Fig. 1. In order to apply a theoretical model for computation of radar scattering from a rough soil surface, the inhomogeneous soil surface should be substituted by a homogeneous dielectric surface having an effective dielectric constant (equivalently, effective soil moisture). The inhomogeneity in vertical direction is severe specially for dry soil surface since the top layer is extremely dry by evapotranspiration from the surface while the lower layer contains moisture. A typical measurement of a relatively dry soil surface is shown in Fig. 5, which will be used as an example for computation of the effective moisture contents. The solid line of Fig. 5 is drawn by data-fit of the data points (circles) measured by a portable dielectric probe at depths from 0 cm to 20 cm. The inhomogeneous part of soil medium of Fig. 5 is segmented by many layers (for example, 200 layers) having gradual changes of moisture contents, from which the corresponding dielectric constants are obtained.

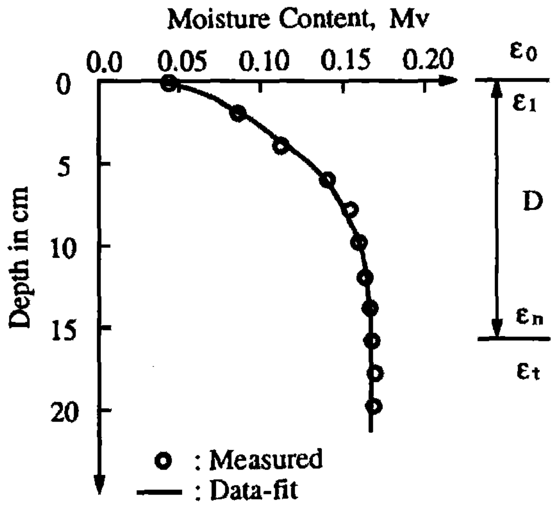

Figure 5. A typical example of soil moisture profiles.

A simple method for computing the effective soil moisture is an arithmetic averaging the measured soil moisture. The depth for data averaging, however, is not obvious since the wave penetration depth depends on frequency of the incidence wave and the soil moisture profile.

Penetration depth is a depth from surface to a point where transmitted power becomes *1/e* (=0.3678...) of the power beneath the surface [Ulaby et al., 1986];

$$\int_0^{\delta p} k_e(z)\, dz = 1 \qquad \text{.......................(4)}$$

where $k_e\,(z)$ is the extinction coefficient of each layer, comprised of scattering coefficient $k_s\,(z)$ and absorption coefficient $k_a(z)$. Integrating the extinction coefficient upto a depth *(d)* and comparing the integration with 1.0, the penetration depth (δp) can be found. Assuming the loss due to scattering can be ignored, the extinction coefficient for an inhomogeneous medium is a function of depth and is given as

$$k_e(z) \approx k_a(z) = 2\,\alpha(z) = \frac{4\pi}{\lambda o}\,\left|\, Imag\ \sqrt{[\varepsilon r\,(z)]}\,\right| \qquad \text{.......................(5)}$$

For a homogeneous medium, the penetration depth δp is simply given as

$$\delta p = \frac{1}{ke} \approx \frac{1}{2\alpha} = \left\{\frac{4\pi}{\lambda o}\,|\, Imag\ [\sqrt{\varepsilon r}]\,|\right\}^{-1}. \qquad \text{.......................(6)}$$

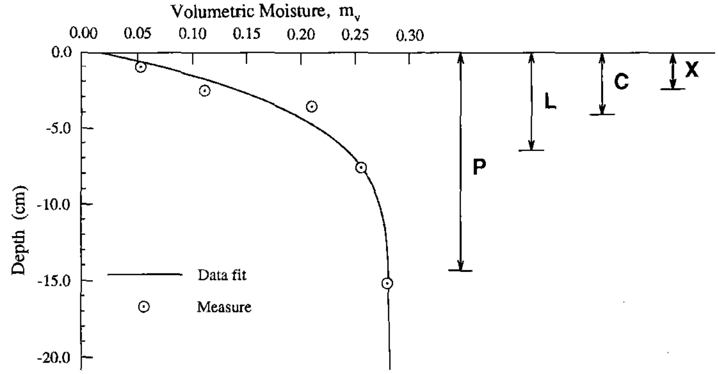

Figure 6. Another example of a soil moisture profile and penetration depths for P-, L-, C-, and X-band frequencies.

The calculated penetration depths of the inhomogeneous soil medium given in Fig. 5 are 10.2 cm, 4.2 cm, and 2.0 cm for 1.25 GHz, 5.3 GHz and 9.5 GHz, respectively. Comparing the penetration depths of the soil surface in Fig. 5 with those computed from homogeneous soil media, it is found that the volumetric moisture contents of 0.112, 0.083, and 0.063 g/cm^3 for homogeneous soil media give same penetration depths for 1.25 GHz, 5.3 GHz, and 9.5 GHz, respectively. Therefore, when we concern the wave penetration only, the equivalent volumetric moisture content m_v of the soil given in Fig. 5 is said to be 0.112, 0.083, an d 0.063 g/cm^3 at 1.25, 5.3, and 9.5 GHz, respectively.

Another example of the moisture profile for a relatively dry soil surface is shown in Fig. 6. Applying (4)-(6) to the moisture profile of Fig. 6, the penetration depths for P-(0.44 GHz), L-(1.25 GHz), C-(5.3 GHz), and X-(9.6 GHz)band frequencies are obtained as indicated in Fig. 6.

However, since radar system (SAR) detects only the scattered power regardless the wave penetration, it is reasonable to obtain the effective volumetric moisture content comparing reflectivities computed from inhomogeneous soil medium with those from homogeneous medium. The reflection coefficient R_s at nadir direction for horizontal polarization from a stratified soil media (*e.g.*, soil medium in Fig. 5) can be obtained coherently [Ulaby et al., 1986] as

$$R_s = \frac{b_{21}}{b_{11}} \text{ where } B = \begin{bmatrix} b_{11}, b_{12} \\ b_{11}, b_{12} \end{bmatrix} = B_{0,1}\, B_{1,2} \cdots B_{n,t}, \text{ and} \qquad \text{.......................... (4)}$$

$$B_{m,m+1} = \frac{1}{2}\left[1 + \sqrt{\frac{\varepsilon_{m+1}}{\varepsilon_m}} \right] \qquad \text{.. (5)}$$

$$\times \begin{bmatrix} \exp[-ik_{z,m+1}h],\ R_{m,m+1}\exp[ik_{z,m+1}h] \\ R_{m,m+1}\exp[-ik_{z,m+1}h],\ \exp[ik_{z,m+1}h] \end{bmatrix},$$

where $R_{m,m+1}$ is the reflection coefficient for homogeneous layer at nadir, h is the depth of an evenly spaced layer, and $k_{z,m+1}$ is the propagation constant (the wavenumber at nadir direction). The reflection coefficient at nadir for homogeneous dielectric surface in case of horizontal polarized wave incidence is given as

$$R_h = \frac{1-\sqrt{\varepsilon_r}}{1+\sqrt{\varepsilon_r}} \qquad \text{...(6)}$$

For the stratified soil medium given in Fig. 5, the effective moisture contents obtained by comparing the coherent reflectivity of inhomogeneous and homogeneous soil media are 0.053, 0.042 and 0.040 g/cm^3 for 1.25, 5.3 and 9.5 GHz, respectively. This result of coherent reflectivity

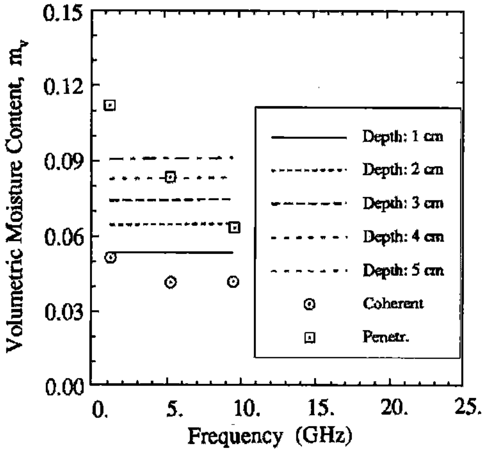

Figure 7. Soil moisture estimations by several different methods.

computation indicates that when inhomogeneous soil media has a smooth change of soil moisture as shown in Fig. 5, the contribution to the scattering is mostly from the top of the soil surface even though the wave penetrates deep in soil media. Figure 7 shows the comparison of the effective soil moisture contents computed by, so called, (1) 'arithmetic averaging technique', (2) 'penetration depth technique', and (3) 'coherent reflectivity technique'. Each line in Fig. 7 indicates the soil moisture content averaged upto a depth, 1 cm~5 cm.

The moisture contents by the penetration-depth technique are equivalent to the arithmetic averaging of the measured moisture contents from top to 10.2 cm, 4.2 cm, and 2.0 cm depths for L-, C-, and X-band frequencies, respectively, as shown in Fig. 7. The moisture contents by the coherent reflectivity, however, are equivalent to those by the algebraic averaging upto 1 cm for L-band, and the top layer only for C- and X-band frequencies as shown in Fig. 7. Therefore, only the top layer may contribute for the radar backscattering and the effective moisture content may be obtained by measuring only the top layer even for a dry soil surface.

A relatively dry soil surface usually has gradual change of moisture in depth, hence the soil medium can be considered as a composite of a scattering surface and a wave absorber since the wave scatters at the top layer and is absorbed while it penetrates into the soil medium. A wet soil surface shows homogeneity and can be generally considered as a homogeneous medium. Therefore, soil samples of top layer in depth of about 2 cm and 1 cm may be enough for 1.25 GHz and 9.5 GHz, respectively, for obtaining volumetric soil moisture contents *in situ*.

4. Conclusions

In order to develop an accurate radar scattering model, accurate measurements of soil moisture and surface roughness should be obtained. Since most soil surfaces have inhomogeneous moisture profiles in depth, specially for dry conditions, we need to compute an effective moisture content of a soil surface to develop an accurate scattering model as well as to apply a theoretical scattering model. The effective moisture content could be obtained computing the penetration depth and the coherent reflectivity of the inhomogeneous soil medium and comparing the values with those of homogeneous medium. The method of coherent reflectivity indicates that the contribution to the scattering is mostly from the top layer at microwaves, even though the wave penetrate into the dry soil quite deeply(e.g., 10.2 cm for 1.25 GHz for a relatively dry soil). Therefore, the extremely dry soil medium may act as an absorber since the wave is absorbed while it penetrates into the soil medium.

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