Vertical Moisture Profile Effects on the Radar Penetration into Bare Soil Surface

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Key Points:

- The penetration depth is sensitive to the inhomogeneity of moisture profiles due to the temporal evaporation process.
- As for roughness parameters, the *RMS* height has a more significant influence on the penetration depth than the correlation length.
- For radar parameter dependence, the penetration depth is more sensitive to the radar frequency than the incident angle.

Abstract

This paper examines the radar penetration into a rough soil surface with a vertical moisture profile. Numerical analysis shows that the penetration depth decreases exponentially with increasing frequency, and the difference between H- and V- polarization reduces. For the incident angle dependence, the variation of penetration depth is somehow complex. For incident angle larger than 20^o, the penetration depth decreases at H polarization, but increases first and then decreases at V polarization. As for soil surface dependence, the topsoil moisture content has a greater impact on the penetration depth than the surface roughness. Of the two roughness parameters, the rms height has a more significant influence on the penetration depth than the correlation length. The dependence of penetration depth on the wave polarization moderates when the surface becomes rougher. Results suggest that the penetration depth is sensitive to the inhomogeneity of moisture profiles due to the temporal evaporation process, indicating that the penetration depth is difficult to measure and an equivalent model to estimate it may be inappropriate, or at least it is difficult to establish.

1 Introduction

Microwave sensor has the advantage of penetrating capability compared to optical sensors(Farr, 1986 & Ulaby, 2014). A general concurrency is that the penetration depth decreases with increasing radar frequency and moisture content (Bruckler,1988 & Rao, 1988 & Risman, 1991 & Boisvert,1995) . However, how deep a radar at a specific wavelength can penetrate a moist soil surface is still vague. For example, the study in (Owe,1988) found that observed "effective penetration depth" exceeded the theoretically defined value, perhaps raised from several aspects. One is the presence of a rough boundary upon which the wave is impinging. Another is the complexity of the moisture profile over depth in which the wave propagates through. Yet, the dielectric model that relates the moisture content to the permittivity as a function of radar wavelength, soil texture, and temperature may also excises some influences in determining the penetration depth (Owe,1988 & Lv, 2018 & Singh, 2018), where the penetration depth may be calculated based on power attenuation via transmissivity (Risman,1991) or field propagation via transmitted coefficient (Bruckler, 1988) through the plane boundary. In this context, the penetration depth is usually confused with the skin depth, although physically they are the same, only differ by 2. By far, the penetration depth is defined at normal incidence upon a plane boundary. This further generates two issues. A plane boundary is rarely found in natural soil surface in microwave regions. A local incidence due to roughness will alter the scattering pattern. Hence the penetration depth must be modified accordingly. Radar observation at normal incidence is not common; if not peculiar, it will lose the polarization information and result in the ground range ambiguity.

For inhomogeneous medium such as soil, an equivalent multilayered model may be applied to calculate the penetration depth (Ulaby, 2014). The influence of inhomogeneity on backscattering detailed in (Zribi, 2013) showed a dependence on the radar frequency, which subsequently altered the penetration depth. The study of (Zribi, 2013) confirmed that the inclusion of moisture inhomogeneity gave a better match between model predictions and SAR observations. The presence of surface inhomogeneity generally leads to features that do not appear in the homogeneous surface, including the scattering coefficient is enhanced on the whole scattering plane (Yang, 2019). These features offer significant implications to how we devise the moisture profile inversion effectively. Hence, in this study, it is desirable to re-examine the radar penetration depth perturbed by the soil roughness and inhomogeneity. Moreover, the polarization and angle information are taken into account. It is so in line of the radar sensing of soil moisture, and thus an effective retrieval of moisture profile.

2 Basic Wave Transmission Through a Rough Boundary with an Inhomogeneous Medium

2.1 Reflectivity and transmissivity

Referring to Fig.1, consider an uniform plane wave *p*-polarized $\mathbf{E}_p^i$ incident onto the boundary, the incident filed, reflected field, and the transmitted field can be expressed by with time-harmonic phase factor $e^{j\omega t}$ understood.

$$\vec{E}_p^i = \hat{p}E_0 e^{-j\vec{k}_i\cdot\vec{r}};\ \vec{E}_p^s = \hat{p}R_p E_0 e^{j\vec{k}_s\cdot\vec{r}};\vec{E}_p^t = \hat{p}T_p E_0 e^{-j\vec{k}_t\cdot\vec{r}} \quad (1)$$

where E_0 is the amplitude of the incident electric field, $\vec{r} = \hat{x}x + \hat{y}y + \hat{z}z$ is position vector; R_p and T_p are *p*- polarization reflection and transmission coefficients are determined by imposing the boundary conditions on the tangential and normal fields across the boundary. The propagating vectors, or the wave vectors, appearing in the spatial phase of (1) are given by $\vec{k}_i, \vec{k}_s, \vec{k}_t$ (Ulaby, 2014). Assuming that the wave incidence is in free-space and the transmitted medium (moist soil) is non-magnetic, namely, $\varepsilon_i = \varepsilon_0; \mu_i = \mu_t = \mu_0$.

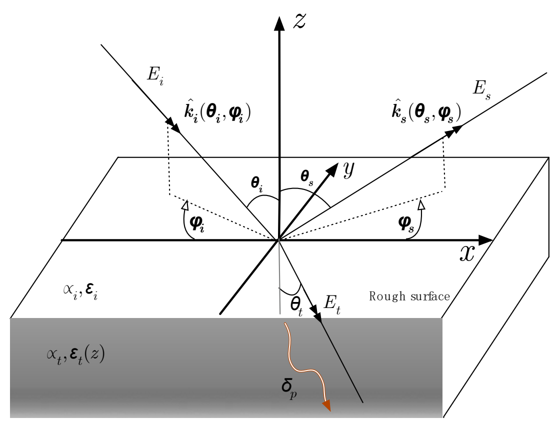


Figure 1. Geometry of wave scattering from a rough surface with inhomogeneous dielectric profile.

In what follows, we shall consider the linear polarizations, horizontal, and vertical polarization, since other polarizations can be constructed by combining two linear polarizations. Once permittivity and permeability for the media is given, both the reflection coefficient and transmission coefficient can be determined.

For horizontal polarization, the reflectivity Γ_h and the transmissivity $\Im_h$ are

$$\Gamma_h = \left|R_h\right|^2 \ \ ,\Im_h = \frac{\mathscr{Re}\{\cos\theta_t / \eta_t\}}{\mathscr{Re}\{\cos\theta_i / \eta_i\}}\left|T_h\right|^2 \quad (2)$$

For vertical polarization, the reflectivity Γ_v and transmittivity $\Im_v$ are

$$\Gamma_v = \left| R_v \right|^2 \quad , \Im_v = \frac{\mathscr{Re}\{\eta_i \cos\theta_t\}}{\mathscr{Re}\{\eta_t \cos\theta_i\}} \left| T_v \right|^2 \tag{3}$$

The incident angle θ_i to refraction angle θ_t are related by the Snell's law. Note that the transmissivity is defined at a plane interface between two media. The interface between layers, including top and bottom boundaries, in general, is rough. Hence, modification of the transmissivity to account for the rough boundary is necessary. It is understood that the Fresnel reflection coefficient for a rough boundary is dependent on the local incident angle as long as there are local tangent planes that exist. In order to convert global incidence into local incidence, the *p*-polarized reflection coefficient evaluated at a transition angle is given by (Wu, 2001). It is known that the reflection coefficient is dependent on the surface *rms* height and the correlation function, or equivalently, the roughness spectrum, to account for the full variation of surface roughness and radar parameters.

In the preceding discussion, we assumed the transmitted medium being homogeneous. However, natural surfaces are generally inhomogeneous, with permittivity being spatially non-uniform. For an inhomogeneous medium with a continuous dielectric profile, the reflectivity and transmissivity are a function of depth.

2.2 Vertical inhomogeneity

Following(Njoku,1977), the vertical moisture profile of soil surface in dry up or wet down conditions may be modelled by

$$m_v(z) = \begin{cases} m_{v0} + \dfrac{e^{\beta z} - 1}{e^{-\beta d} - 1}\left(m_{vb} - m_{v0}\right), & -d \le z \le 0 \\ m_v(-d) & z \le -d \end{cases} \tag{4}$$

where *z* is depth, and *d* is the total layer depth; m_{v0}, m_{vb} are volumetric moisture content at top and bottom boundaries, respectively. The moisture content at bottom is also referred as background moisture content.

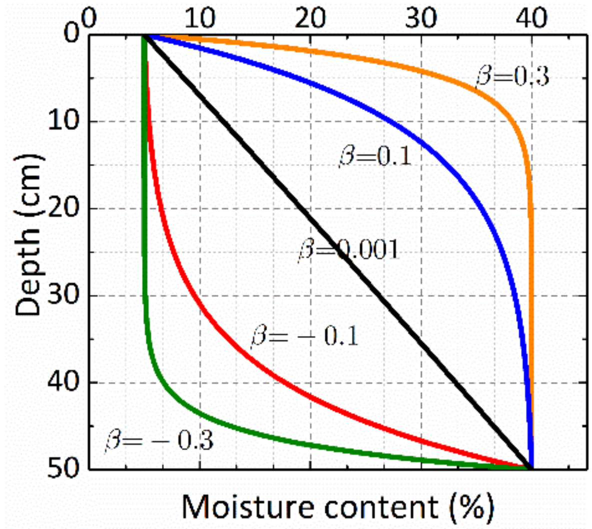


Figure 2. Moisture profile of various soil condition, top soil moisture m_{v0}=5%, background soil moisture m_{vb}=40%, $\beta = -0.3, -0.1, 0.001, 0.1, 0.3$.

In Fig.2, we present several typical monotonic dielectric profiles with moisture content varying in the z-direction by controlling β values. For a minimal amount of β, the moisture content and depth approach to a linear relationship. For unfrozen soil, we employ the generalized refractive mixing dielectric model (GRMDM) (Mironov, 2009 & Mialon, 2015)to relate the moisture content to permittivity. For more about the influence of the dielectric model on the estimating penetration depth, please refer to (Singh, 2018). Once the permittivity profile corresponding to the moisture profile (4) is established, it is possible to derive analytic expressions for the reflection coefficients. However, it is too laborious to do so. Instead, we seek a numerical solution by discretizing the continuous profile into multilayers. The number of layers is 500, and the thickness of the layers is 0.1cm. For a multi-layered medium, we used a recursive formula to calculate the reflection coefficients.

3 Penetration Depth for Homogeneous and Inhomogeneous Media

For a homogeneous medium, the power transmission into the medium is

$$P_p(z) = P_p(0)\Im_p e^{-j2k_{tz}z} \tag{5}$$

where $\Im^p$ is transmissivity at the interface between air and medium, subscript *p*=*h*, *v* indicates polarization; k_{tz} is the *z*-component of the wavenumber in the transmitted medium. The penetration depth δ_p is defined as

$$e^{-1} = \frac{P_p(z)\big|_{z=\delta_p}}{P_p(0)\Im_p} \tag{6}$$

$$\delta_p = \frac{\lambda}{4\pi}\left[\frac{\varepsilon'}{2}(\sqrt{1+\tan^2\delta}-1)\right]^{1/2} \quad (7)$$

where the loss tangent is $\tan\delta = \varepsilon'' / \varepsilon'$; $\varepsilon', \varepsilon''$ are, respectively, real part and imaginary part of the permittivity of the homogeneous medium.

For an inhomogeneous medium with continuous dielectric profile, the power transmission into the medium may be expressed as an integral form:

$$P_p(z) = P_p(0)\int_0^z \Im_p(z')\exp\left[-j2k_{tz}(z')dz'\right] \quad (8)$$

where $\Im_p(z')$ is transmissivity at the interface z', $k_{tz}(z')$ is the z-component of the wavenumber as function of z' in the medium as

$$k_{tz}(z') = k_0\sqrt{\varepsilon_r(z')\mu_r - \sin^2\theta_0} \quad (9)$$

It follows that the penetration depth is given by

$$\int_0^{\delta_p} \Im_p(z')\exp\left[-j2k_z(z')dz'\right] = e^{-1} \quad (10)$$

As argued in (Ulaby, 1974), for homogeneous soil surface, we compute the penetration δ_p using (7) but replacing moisture profile $m_v(z)$ with an averaged soil moisture $\bar{m}_v$ over the depth from top to bottom boundaries:

$$\bar{m}_v = \frac{1}{d}\int_{-d}^{0} m_v(z)dz \quad (11)$$

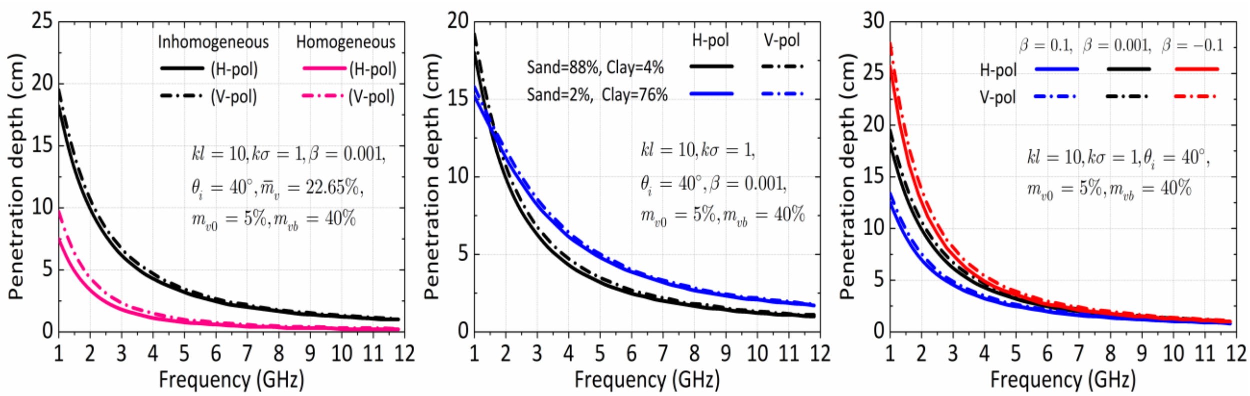
It should be noted that in calculating the reflection coefficient of a multilayered medium such as we deal with the profiles in (4), the multiple scattering and the volume scattering are ignored, among other effects. Hence, the penetration depth by the transmittivity varying with depth may be biased compared to real measurement. More discussions about the layering effects on the backscattering and the moisture retrieval can be found in (Konings, 2014). Nevertheless, the penetration depth causes a phase delay, measurable by InSAR, could be an alternative for estimating the soil moisture (Nolan, 2003).

4 Effect of Radar and Soil Parameters on Penetration Depth

4.1 Radar parameters dependence

Fig. 3 shows the penetration depth δ_p as a function of frequency for homogeneous and inhomogeneous soil surfaces, where, as an example, the top soil moisture m_{v0} is 5%, and the background soil moisture is 40%. The frequency varies from 1 GHz to 12 GHz. The normalized correlation length kl is set as 10, and the normalized rms height $k\sigma$ is 1. The incident angle is 40°. Fig. 3 shows the penetration depths from inhomogeneous soil surface are deeper than the homogeneous surfaces. This phenomenon stems from the fact that the averaged moisture of homogeneous soil is wetter than the top layer soil of inhomogeneous soil surface. Hence, the transmissivity is relatively smaller for homogeneous soil. As the frequency increases, the penetration depth decreases exponentially. The differences in penetration depth between homogeneous and inhomogeneous soil surface significantly decrease as the frequency increases. Note that the penetration depth is deeper at V-polarized than at H-polarized incidences because the transmissivity is higher at vertical polarization. The difference between H- and V-polarizations reduces with increasing frequency.

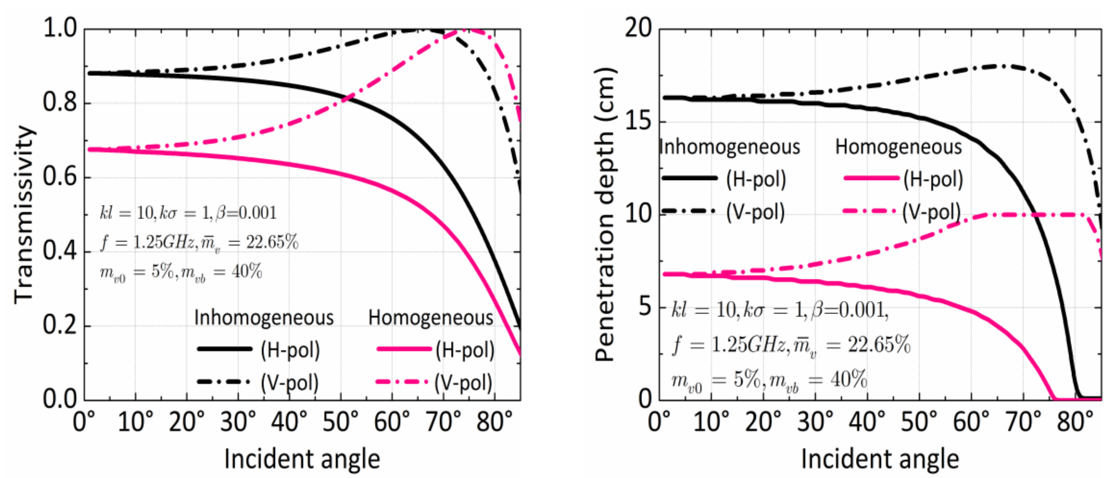
The moisture profile is a function of β, which controls the change rate of the soil moisture content in z-direction. The change rate β affects the penetration depth through the dielectric model corresponding to the vertical moisture profile in (4). Furthermore, the penetration depth for two different soil type (Mironov, 2009) shown in Figure 3(b). As a whole, the difference in penetration depth is about 3-5cm from 1-12 GHz of frequencies.



(a) (b) (c)

Figure 3. Penetration depth as a function of frequency. (a) homogeneous ($\bar{m}_v$=22.65%) and inhomogeneous soil (m_{v0}=5%,m_{vb}=40%)surfaces. (b) inhomogeneous $\beta = 0.1, 0.001, -0.1$, (b) inhomogeneous: Sand=88%,Clay=4%, and Sand=2%, Clay=76%.

To demonstrate how the penetration depth changes due to the moisture profile, in Fig. 3(c) we plot the penetration depth by varying change rates of $\beta = 0.1, 0.001, -0.1$. As the absolute value of β increases, the penetration depth decreases correspondingly. The penetration is deeper when $\beta = -0.1$. This phenomenon is easily expected for the upper layer with $\beta = -0.1$ is drier than that with $\beta = 0.1$. When the soil is dry, the transmissivity is larger, so is the penetration.

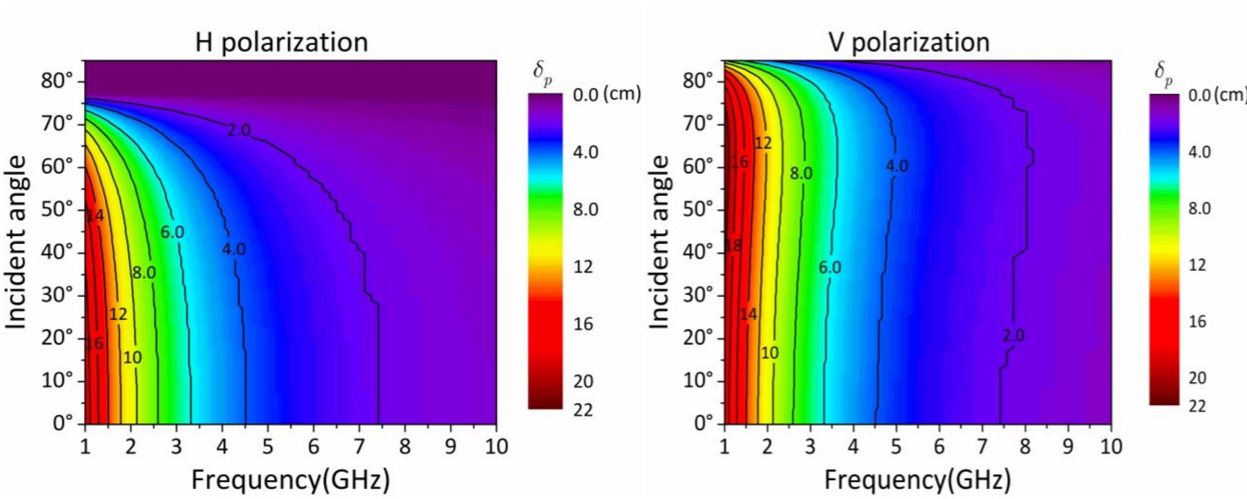


(a) (b)

Figure 4. Transmissivity (a) and penetration depth (b) as a function of incident angle at L band. Homogeneous ($\bar{m}_v$=22.65%) and inhomogeneous soil (m_{v0}=5%,m_{vb}=40%)surfaces.

Similarly, in Fig. 4, the transmissivity's dependence and the penetration depth on the incident angle are presented. For numerical illustration, we fixed the frequency at 1.25GHz. As the incident angle increases, there are two common trends both for homogeneous and inhomogeneous soil surface, including 1) the H-polarized penetration depth decreases, but the V-polarized penetration depth increase first and then decreases. The penetration depth is affected by the incident angle because it is a function of transmissivity. For the rough boundary, the V-polarized transmissivity along the incident direction increase first and then decreases, and the inflection point appears at the position of Brewster's angle; 2) Penetration depth is deeper in V-polarization than in H-polarization, and the difference in penetration depth between the two polarizations gradually increase with increasing incident angle. By comparison with the homogeneous soil surface, the penetration depth of the inhomogeneous soil surface is relatively deeper, and the polarization difference is more pronounced. This phenomenon is given rise by the top layer moisture of inhomogeneous soil being drier than the averaged moisture content over the soil depth. The maximum difference between horizontal and vertical polarizations is about 10cm around 75° of incident angle, which is just the Brewster angle in this case. To define an equivalent homogeneous model from an inhomogeneous medium is never straightforward. A large difference of the penetration depths between the two media tells that an equivalent model is difficult, if not impossible, to apply when it comes to estimate the penetration depth at a specific radar wavelength.

We now illustrate the coupling effect of frequency and incident angle on the penetration depth by changing one of them while fixing the other. Fig. 5 (a) and Fig. 5 (b) show the contour plots of penetration depth for the inhomogeneous soil surface at H- and V- polarized incidences, respectively. As can be seen from Figs. 5 (a), (b), the tendency of penetration depth in H polarization is quite different from that in V polarization. By comparison, the penetration depth occurs at a larger dynamic range of incident angle in V polarization, but in H polarization, the penetration depth is almost zero when $\theta_i > 75°$. The dynamic range of penetration depth is about 24cm when the frequency varies from 1 to 10 GHz, and the incident angle changes from 0° to 85°. The maximum polarization difference occurs at low frequencies (e.g., L band) and at a large incident angle, e.g., 70°~85°, which, however, are rarely used due to low backscattering returns.

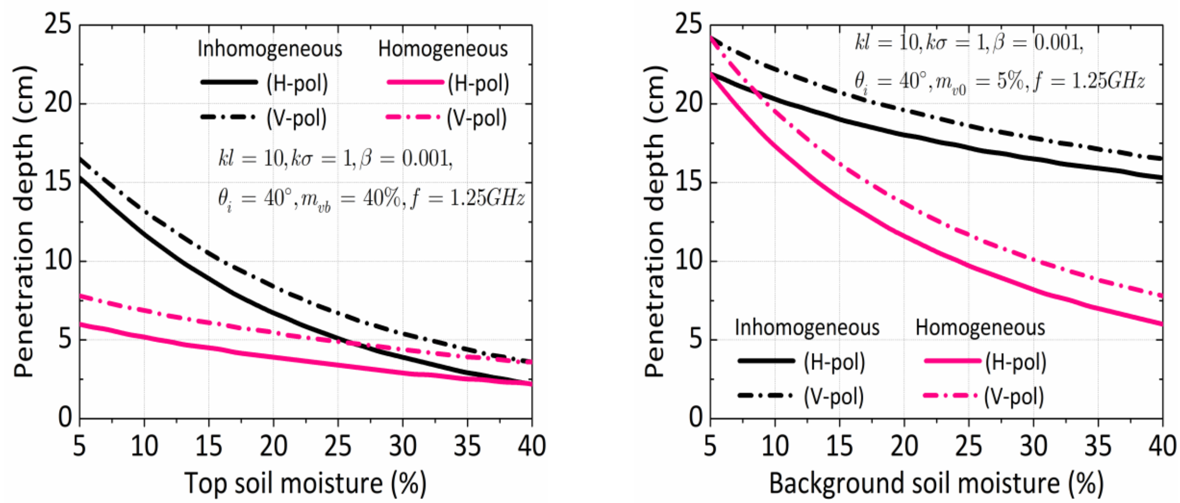


(a) (b)

Figure 5 Penetration depth as a function of frequency and incident angle for inhomogeneous soil surface m_{v0}=5%,m_{vb}=40%**,** kl=10,$k\sigma = 1$ $\beta = 0.001$**. (a): H polarization, (b): V polarization.**

4.2 Soil parameters dependence

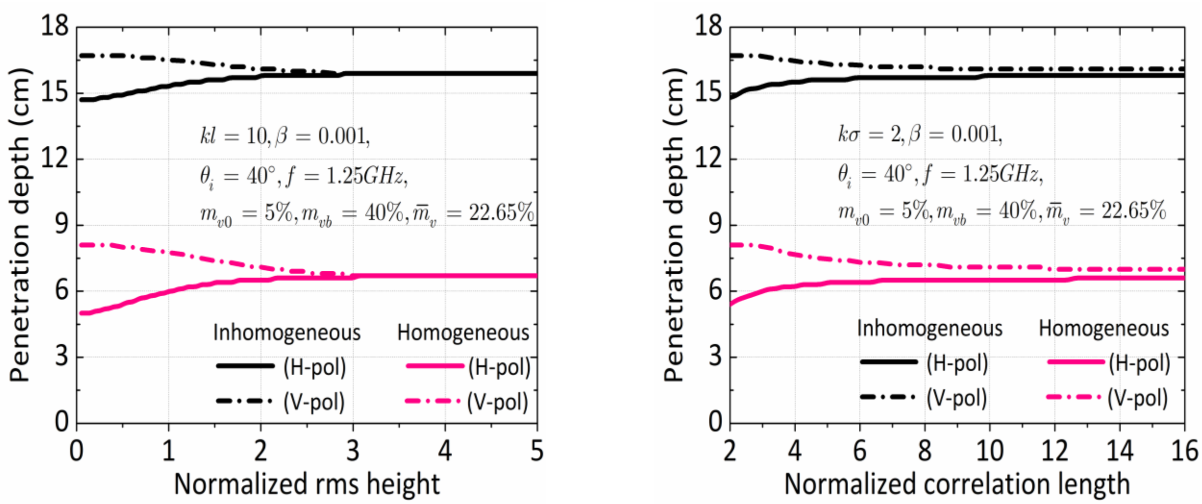
We now examine the soil parameters dependence on the penetration depth. Figs. 6 (a), (b) show the overall varying of penetration depth with top and the background soil moisture contents, respectively, with surface roughness as kl=10,$k\sigma = 1$, with an incident angle of 40° and frequency of 1.25 GHz. Fig. 6 (a) shows the penetration depth when the the backgroud soil moisture is fixed at 40% and the top soil moisture varies from 5% to 40%, and Fig. 6 (b) plots the penetration depth with the background soil moisture varying from the 5% to 40%, and topsoil moisture of 5%. It indicates that the penetration depth decreases as both the top and the background soil moistures increase. When the topsoil moisture varies from 5% to 40%, the dynamic range of penetration depth for inhomogeneous soil surface is about 10cm but that for homogeneous soil surface is only about 2cm. In the above illustration, the penetration depth of an inhomogeneous soil surface is more sensitive to the topsoil moisture. Yet for the homogeneous soil surface, it is dependent on the background soil moisture. It is worth noting that the penetration depth differences between H- and V- polarization is only about 1~2cm.



(a) (b)

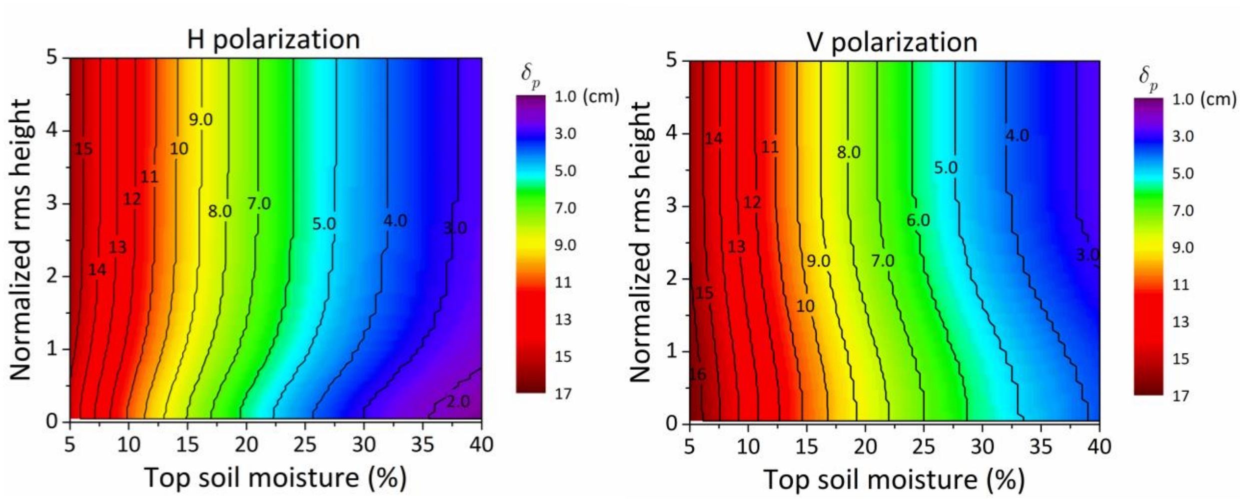
Figure 6 Penetration depth as a function of (a) top soil moisture m_{v0}=5~40% **with** m_{vb}=40%**; (b) background soil moisture** m_{vb}=5~40% **with** m_{v0}=5%**.**

We now examine the penetration depth dependence of surface roughness at L band. We set the incident angle to 40° and the normalized correlation length to 10, while changing the normalized *rms* heights from 0 to 5. From Fig.7 (a), as the *rms* height increases, the penetration depth at horizontal polarization increases first and tends to flatten, while diminishes first at vertical polarization. The difference of penetration depth between H- and V- polarization is about 2-3cm for the fairly flat boundary. But when the *rms* height is large enough, say, $k\sigma > 3$, the penetration depths are almost the same at H- and V- polarizations; that is, the difference in penetration depth at two polarizations reduces due to the roughness. Fig. 7(b) plots the penetration depth as a function of normalized correlation length. The overall penetration depth dependence on the correlation length is similar to that on the *rms* height.



(a) (b)

Figure 7 Penetration depth as a function of (a) normalized *rms* height $k\sigma$ **at** $kl = 10$ **and (b) normalized correlation length** kl **at** $k\sigma = 2$ **.**



(a) (b)

Figure 8 Penetration depth as a function of top soil moisture m_{v0} **and normalized *rms* height** $k\sigma$ **for inhomogeneous soil surface with parameters similar to Fig.3. (a): H polarization, (b): V polarization.**

We observe that the topsoil moisture and rms height are two main soil surface parameters to determine the penetration depth. As shown in Fig. 8, physically, the penetration depth is more sensitive to the topsoil moisture than the rms height. We see that the contour plots of the penetration depths are very distinct, especially for a small normalized rms height . The penetration depth is a complicated factor that strongly depends on the surface roughness of the top boundary under which the dielectric constant is vertically varying. To define a radar medium, be it a subsurface layer or a volume layer as a half-space, seems problematic. It is worth to examine such effects on the inferring surface parameters, e.g., moisture content, roughness, surface height (Dall, 2007), or snow water equivalent content (Yueh, 2017).

5 Conclusions

This study investigates the penetration depths from an inhomogeneous rough soil surface with a vertical moisture profile. The penetration depth is deeper at V polarization than at H polarization. For radar parameter dependence, the penetration depth is more sensitive to the radar frequency than the incident angle. As the frequency increases from 1 GHz to 10 GHz, the penetration depth decreases exponentially, and the difference between the two polarizations shrinks. With increasing incident angle, the penetration depth decreases in H polarization, but increases first and decreases in V polarization. As for soil conditions dependence, the topsoil moisture has a more significant effect on penetration depth than the surface roughness. As the top soil moisture becomes drier, the difference of penetration depth between two polarizations decreases. When the rms height increases, the penetration depth in horizontal polarization increases first and then tends to flat out, but that in vertical polarization diminishes first. The penetration depth is found more sensitive to polarization at smaller rms heights and correlation lengths.

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