Retrieval of subsurface soil moisture using SAR observation at UHF/VHF bands

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Abstract: A three-layer scatter model is developed for the retrieval of moisture profile of the terrain subsurface under SAR observation at UHF/VHF bands. Based on different penetration depths at UHF and VHF channels, scattering observations at these two bands are alternatively used to iterate the retrieved moisture of the layered media, and finally reach the convergence of the moisture profile of the layered subsurface media.

Key words: soil moisture, UHF/VHF SAR, subsurface

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1 INTRODUCTION

Moisture profiles of subcanopy and land subsurface play an important role in climate research, such as land hydrologic processes, global climate change and carbon balance. It is main motivation for MOSS mission (microwave observation of subcanopy and subsurface) (Moghaddan *et al*. ,2007). The subsurface soil moisture profile, linking with soil structure, mixture, rooted water drainage and evaporation, as a key parameter for hydrologic process, zoology, climate, etc., is of importance for the forecast of drought and flooding, irrigation planning, and estimation of crop products, etc. However, current SAR observations at L, C, X, Ku bands can only penetrate through non-dense plants (biomass is about 4kg/m^2) in centimeter order, even at low L band (Dubois *et al*., 1995; oh *et al*. ,1992). It needs lower frequency such as UHF/VHF (350MHz, 100MHz) to go through the dense subcanopy (about 20 kg/m^2 and more) with little scattering and reach subsurface. It has been studied that Faraday rotation, which affects satellite-borne measurement, especially at lower channels, can be corrected by fully polarimetric SAR technology (Qi & Jin, 2007; Freeman, 2004).

Soil moisture profile presents different weighting function at L, UHF, and VHF bands due to different penetration depths of lossy soil media. It can be seen from numerical simulation of Mueller matrix solution (Jin, 1994) that the scattering from vegetation canopy might be as much as from underlying rough surface, even at low L band. Thus, lower frequency such as UHF/VHF should be employed if main attention is focused on soil moisture of underlying soil media, instead of vegetation canopy.

Comparing with the backscattering from bare land rough surface based on small perturbation method, the first-order Mueller matrix solution from a one-layer model of vegetation canopy of non-spherical particles shows the significant impact from the canopy, which darkens the effect from underlying media, even at L band. Much lower UHF/VHF bands are proposed to explore the soil moisture profile due to larger penetration depth and negiligible canopy effect.

In this paper, making a three-layer land model, the Mueller matrix of backscattering from the 3-layer model at UHF/VHF bands is numerically presented. It is found that due to the difference of penetration depth between these two bands, UHF band is only sensitive to the soil depth around 10—60cm, and VHF band can reach deeper.

As a criteria of the change sensitivity of 0.1dB in SAR observation, it is found that as the soil moisture of the 2-nd layer is less than 0.25, the VHF can be used to retrive the soil moisture of the 3-rd layer 3 below the depth 60cm. An iterative algorithm of using alternative UHF/VHF results is developed to invert the soil moisture of the 2-nd and 3-rd layers, and the error analysis shows good applicability.

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2 DIELECTRIC CONSTANT OF MOISTURED SOIL AT UHF/VHF

The dielectric constant of moistured soil depends on frequency, soil moisture, physical temperature, structure, mixture and so on (Peplinski *et al.*, 1995a, b). Some empirical formulations of soil dielectric constant in microwave frequency (Peplinsk *et al.*, 1995a, b; Valery *et al.*, 2004; Wang *et al.*, 1980). can be found, but not in UHF or VHF regime. Based on the measurements in of Mironov *et al.* (2007), the dielectric constant of moistured soil at UHF (350MHz) is summerized as

$$\varepsilon = \varepsilon' + i\varepsilon'' \tag{1}$$

$$\varepsilon' = 93.1W^{1/0.65} + 3.79,\ \varepsilon'' = 4.9W + 0.47 \tag{2}$$

where W is soil volumetric moisture.

Figs. 1(a, b) show the results of Eqs. (1, 2) and the comparisons with the measurements, where the triangle points from Mironov, *et al.* (2007) and solid circles from Jin (1994).

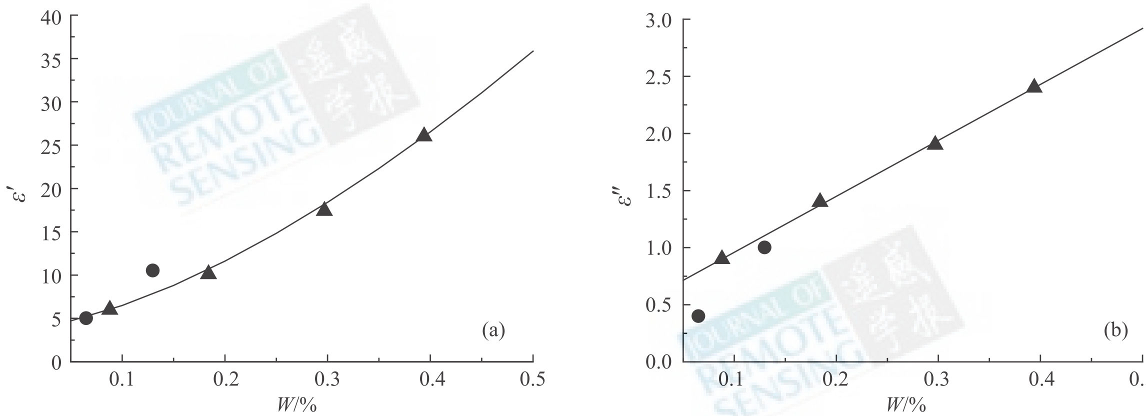

Fig. 1 Soil dielectric constant and comparison with Mironov *et al.* (2007)
(a) Real part of soil dielectric constant versus volumetric moisture;
(b) Imaginary part of soil dielectric constant versus volumetric moisture

From Mironov *et al.* (2007), the real part of dielectric constant almost keeps constant for different frequency. However, the graph of imaginary part versus frequency, as shown in Fig. 2, has non-consistent trends, one is from Mironov *et al.* (2007) and another from (Jin, 1994). For simplicity, imaginary part of soil dielectric constant at VHF is assumed as the same as one at UHF.

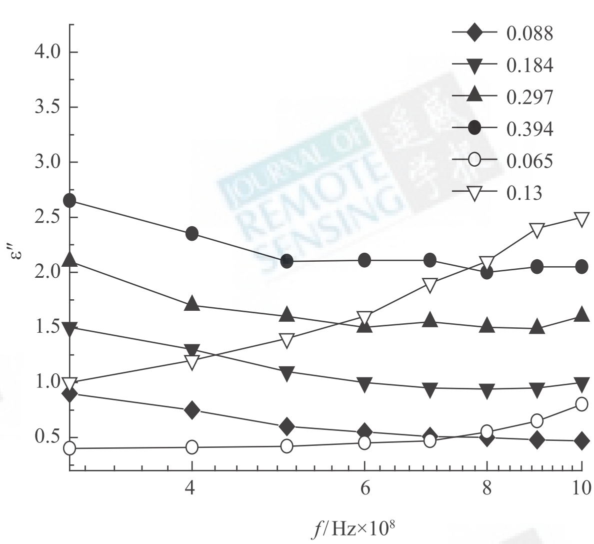

Fig. 2 Imaginary part of soil dielectric constant versus frequency

3 THE MUELLER MATRIX SOLUTION OF LAYERED SOIL MODEL

The model of three-layer media with top rough surface is shown in Fig. 3, where W_1, W_2, W_3 denote the volumetric moisture (wetness) of the layers 1, 2, 3, respectively.

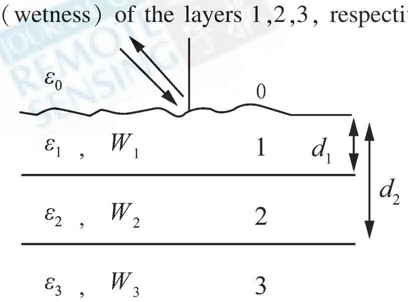

Fig. 3 A layered model of land moistured media

For less rough boundaries, coherent scattering is dominant for small perturbed rough surface. Under low frequency incidence, scattering of the layered media can be described by three parts as shown in Fig. 4: direct backscattering from rough surface (M_0), and scattering due to interactions M_{b1} and M_{b2}.

In Fig. 4, the straight line indicates coherent reflection or transmission, and curve denotes incoherent scattering. Hereby, the solution of Mueller matrix for the layered soil model can be written as:

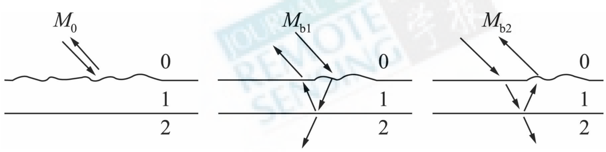

Fig.4 Scattering mechanism

$$\bar{\bar{M}}(\theta_i,\varphi_i) = \bar{\bar{R}}^n_{01}(\theta_i) + \bar{\bar{T}}^c_{10}(\theta,\varphi_i;\theta_i,\pi-\varphi_i)\cdot e^{-\kappa d_1\sec\theta}\cdot\bar{\bar{R}}^c_{12}(\theta)\cdot e^{-\kappa d_1\sec\theta}\cdot \bar{\bar{T}}^n_{01}(\theta_i,\varphi_i;\theta,\pi-\varphi_i) + \bar{\bar{T}}^n_{10}(\theta,\varphi_i;\theta_i,\pi-\varphi_i)\cdot e^{-\kappa d_1\sec\theta}\cdot\bar{\bar{R}}^c_{12}(\theta)\cdot e^{-\kappa d_1\sec\theta}\cdot\bar{\bar{T}}^c_{01}(\theta_i,\varphi_i;\theta,\varphi_i) \quad (3)$$

where $\bar{\bar{R}}$ and $\bar{\bar{T}}$ denote the scattering and transmission matrices, respectively. The superscript n denotes incoherent field and c for coherent field, the subscript $i\,j$ denotes the propagation from Layer i to the Layer j, and κ is the absorption coefficient of Layer 1. All matrices in Eq. (3) can be found in. Jin (1994).

4 SIMULATION OF SUBSURFACE OBSEVATION AT UHF/VHF

First, consider a two-layer model (i.e. $\varepsilon_2=\varepsilon_3$), supposing $W_1=0.05$ for top layer, variance of rough surface $\delta=0.1\lambda_{\mathrm{UHF}}=8.57$cm, correlation length $l=0.3\lambda_{\mathrm{UHF}}=25.71$cm, and evaluating ε_2 of underlying media by Eqs. (1,2). Under incidence of 40° at UHF and VHF, co-horizontally polarized backscattering coefficient σ_{hh} due to surface roughness, underlying media (Layer 2 and 3) as water, and $W_2=0.3$, 0.5 for different depth of the top layer is calculated by Eq. (3), as shown in Figs. 5.

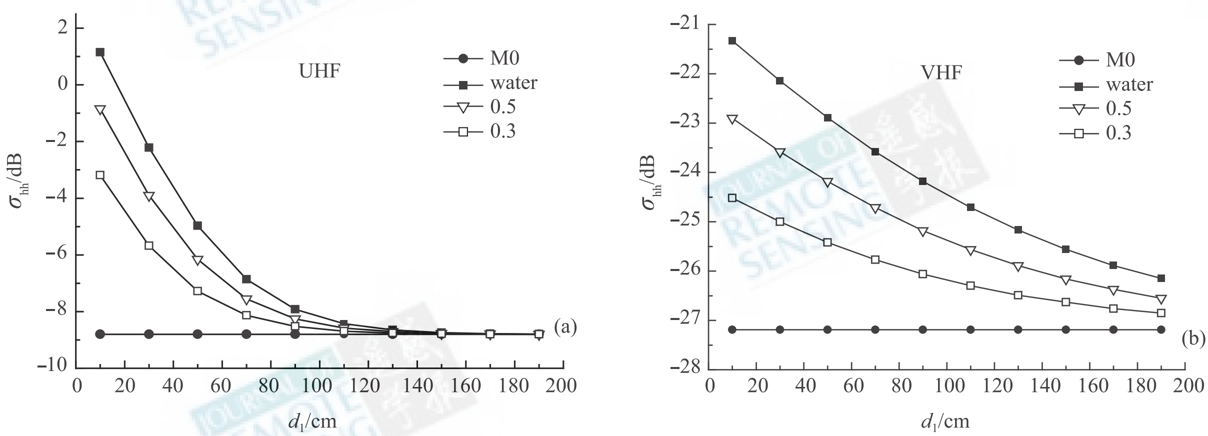

Fig.5 (a) Co-horizontally polarized backscattering at UHF; (b) Co-horizontally polarized backscattering at VHF

It can be seen that the subsurface moisture at the depth of 10—50cm might affect backscattering observation by several dB. Since the soil is loss-dielectric medium, as the depth increases, this effect from underlying media becomes much weaker. It is almost negligible below 1m depth at UHF, while 1dB difference can be seen at VHF. Lower VHF should be employed for probing soil moisture at deeper depth.

Now consider a three-layer model as shown in Fig.3, where $d_1=10$cm is assumed. Other parameters are the same as Fig.5. Suppose that the interface between Layer 2 and 3 can be varying 20cm around d_2, backscattering from Layer 3 is averaged as

$$\bar{\sigma} = \frac{1}{40}\int_{d_2-20}^{d+20}\sigma(z)\,\mathrm{d}z \quad (4)$$

Suppose $d_2=60$cm, backscattering coefficients at UHF and VHF bands versus W_2, W_3 are shown in Figs. 6. It is obvious that both UHF and VHF are sensitive to W_2-change. In Fig.6. (a), due to larger attenuation at UHF band, W_3-change cannot be well detected. However, in Fig.6(b), the variation of backscattering versus W_3 at VHF band is clearly identified.

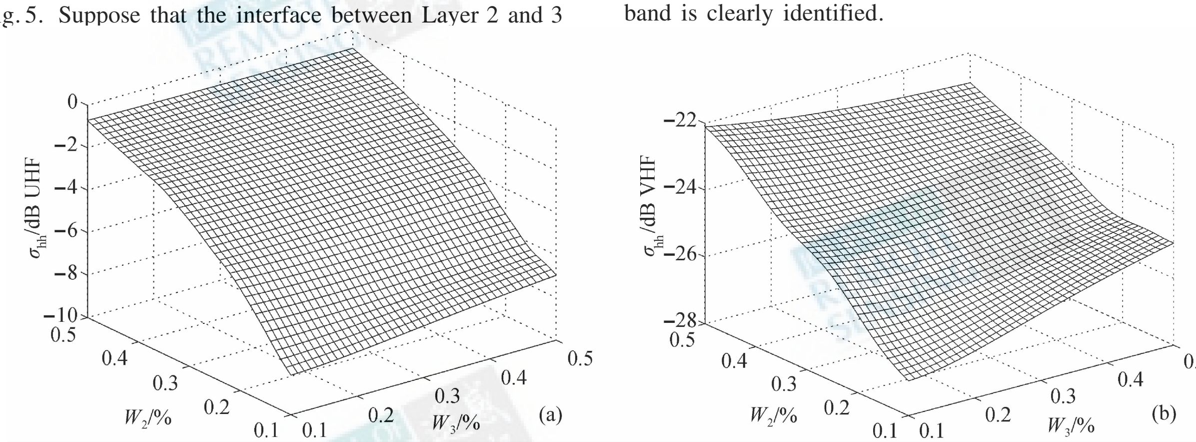

Fig.6 (a) Backscattering with different moisture W_2, W_3 at UHF; (b) Backscattering with different moisture W_2, W_3 at VHF

5 MOISTURE ESTIMATION OF THREE-LAYER SOIL MODEL

The penetration depth of a homogeneous medium is defined as $d = 1/k''$, where k'' is the imagenary part of the wave number of the medium. The penetration depth at UHF and VHF is shown in Fig. 7. Different penetration depth at UHF and VHF is sensitive to soil moisture at different depth.

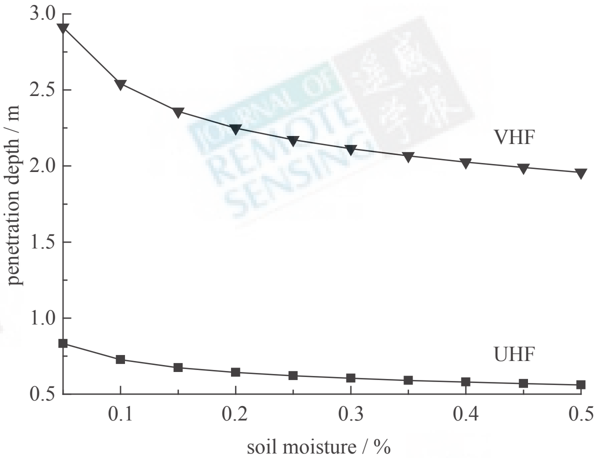

Fig. 7 Penetration depth at UHF and VHF

L band can be used to sense the soil moisture at the depth less than 10cm, and surface roughness. Suppose that from the measurement at L band the surface roughness parameters δ, l and moisture $W_1 = 0.05$ are obtained. Meanwhile, $d_1 = 10$cm, $\delta = 0.1\lambda_{UHF} = 8.57$ cm, $l = 0.3\lambda_{UHF} = 25.71$cm, and the incidence at 40° are always assumed.

Suppose that the sensitivity of SAR observation is 0.1dB to detect moisture variation of 0.1. It presents a criteria of the retrieval applicability as follows:

$$\Delta\sigma = \sigma(W_1, W_2, W'_3) - \sigma(W_1, W_2, W_3) > 0.1\text{dB} \quad (5)$$

Firstly, let a variation $W'_3 = W_3 + 0.1$ and $W_3 = W_2$. Then, the change of backscattering σ_{hh} for different W_2 and d_2 at UHF and VHF is shown on Figs. 8(a,b), respectively. The red area in Figs. 8(a,b) indicates $\Delta\sigma_{hh} < 0.1$dB as undetectable for W_3. Figs. 8(c,d) show a projection map and might be easier to see where the W_3-change cannot be identified.

It can be seen that the change of backscattering due to the moisture at UHF around $d_2 = 30$cm is larger than VHF. The detectable areas given by Figs. 8(a,b) are largely restricted within $W_2 < 0.25$, because the strong reflection from the interface of Layers 1 and 2 shadows the weaker reflection from the interface of Layers 2 and 3, which causes difficulty for estimation of soil moisture of Layer 3.

As increasing d_2, the change of W_3 cannot be detected at UHF band. VHF band should be alternatively used. Thus, we use UHF to obtain the average W_2 of Layer 2 (10—60cm), and then VHF for W_3 under the depth 60cm.

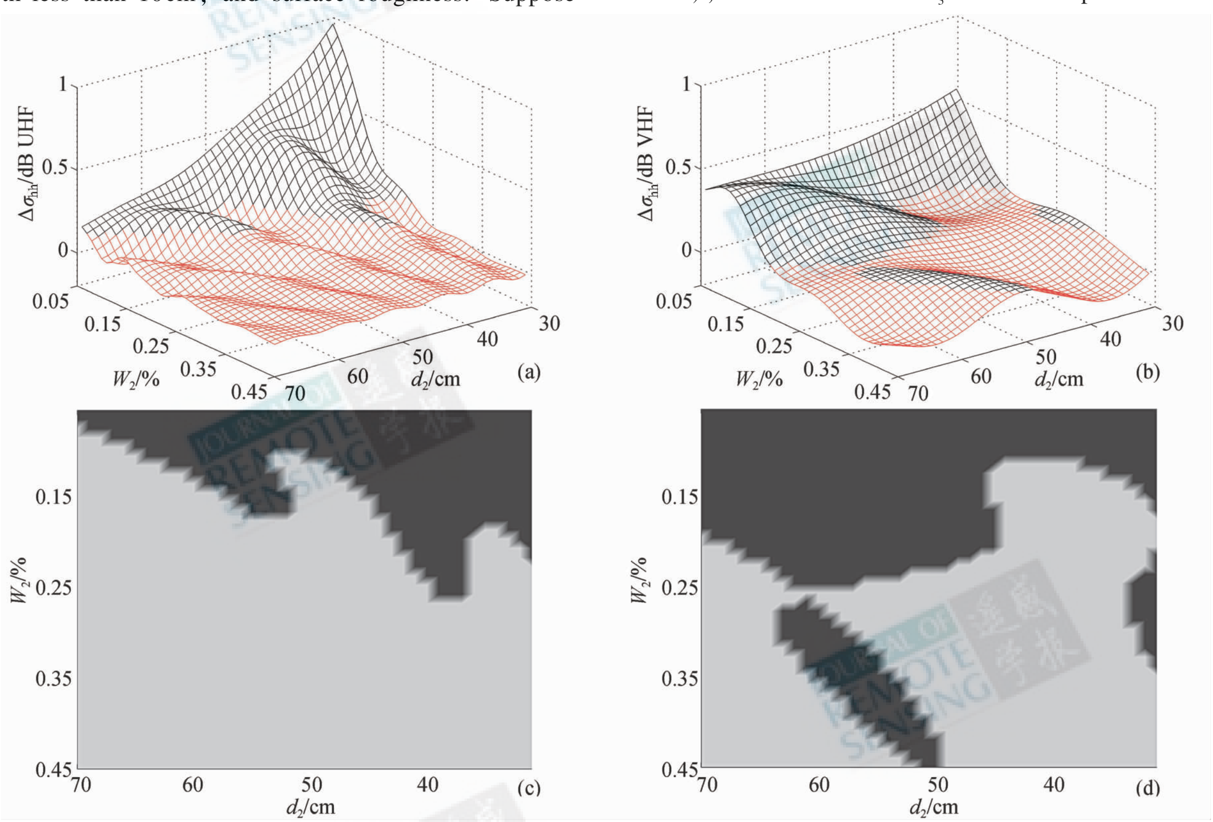

Fig. 8 (a) Impact to backscattering due to variation of W_2, d_2 at UHF; (b) Impact to backscattering due to variation of W_2, d_2 at VHF; (c) Projection map of Fig. 8(a); (d) Projection map of Fig. 8(b)

Since the impact from Layer 3 on backscattering is negligible at UHF, we first use two-layer model with $W_2 = W_3$ to evaluate W_2 by linearly increasing W_2. Taking the inverted result of W'_2 into the three-layer model and assuming $W_3 \geqslant W_2$, linearly increase W_3 and obtain inverted result W'_3 at VHF band. Iterative approach is used to invert W_2 as W''_2 by inputing W'_3 into three-layer model at UHF band, and again, to invert W''_3 by W''_2 at VHF band and so on until convergence is finally reached.

Backscattering simulation of three-layer model is tested for various W_2 and W_3, where d_2 = 60cm is assumed. The inversion result is shown in Fig. 9. The average relative error of Fig. 9(a) is 0.18%.

Since the detectable area of Layer 3 is restricted by $W_2 < 0.25$, the inversion result is shown in Fig. 9(b). Average relative error is 2.3%. Inversion errors of both Layers 2 and 3 are small. Thus, our iterative inversion is feasible for soil profile inversion if parameters of d_1, δ, l, W_1 are known.

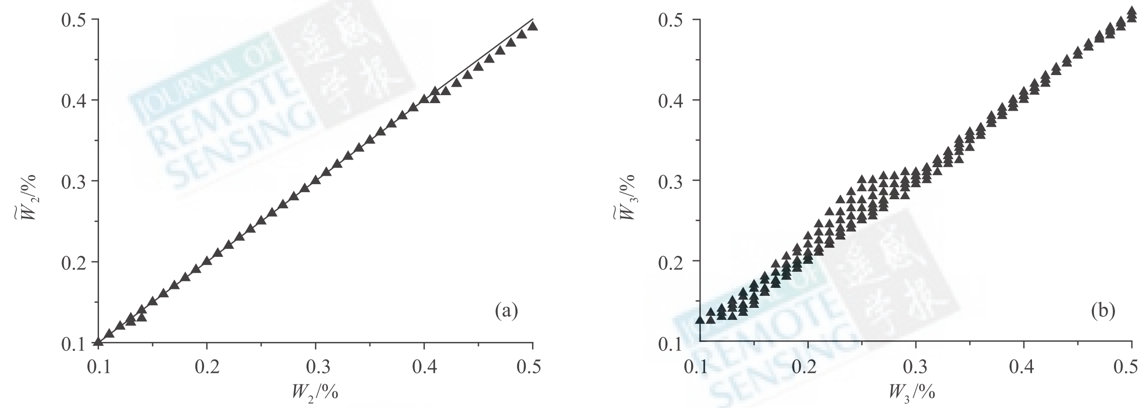

Fig. 9 Inversion of soil volume moisture

(a) Inversion of soil volume moisture of Layer 2; (b) Inversion of soil volume moisture of Layer 3

6 CONCLUSION

In this paper, a three-layer model of moistured soil media and the Mueller matrix solution are applied to simulacte backscattering observation of layered moistured land soil at UHF/VHF bands.

Assuming the detectable difference of backscattering observation is 0.1dB, evaluation of soil moisture of Layer 3 below 60cm at VHF band is applicable under the condition that the soil moisture of Layer 2 is less than 0.25.

Using our iterative approach of UHF/VHF alternative inversions, the soil moisture profile of layered media can be inverted.

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UHV/VHF 波段 SAR 对次地表层土壤湿度探测与反演

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摘 要: 首先采用一层非球形粒子植被模型,计算各波段矢量辐射传输方程 Mueller 矩阵一阶散射解,对比微扰法所得各波段地表粗糙面直接后向散射解,结果证明 L 波段植被层的散射对观测结果仍有影响,与下垫土壤粗糙表面的散射不易分离。因此,宜采用更低频率的 UHF 和 VHF 波段,对地表和次地表层能有较大的渗透深度,并可忽略植被层影响。接着,运用矢量辐射传输的 3 层土壤全极化 Mueller 矩阵解,计算 UHF/VHF 波段分层土壤的散射与传输,分析该两波段探测深度的差异,证实 UHF 波段可探测大致 10—60cm 深处的土壤湿度,而 VHF 波段探测深度能更大一些。根据第 3 层中土壤体湿度变化 0.1 时能否引起土壤表面观测的后向散射系数变化 0.1dB 这一判据,分析 VHF 波段反演第 3 层土壤体湿度的必要条件,证实当第 2 层的体湿度较小时(<0.25)才能反演层 3 的体温度。基于 UHF/VHF 两波段探测深度的差异,耗散土壤层的贡献有不同的权重,先后采用 UHF 和 VHF,迭代法实现 3 层土壤湿度廓线反演。误差分析表明,该方法是有意义的。

关键词: 土壤湿度,UHF/VHF SAR,次地表层