

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 4 kg/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 (350 MHz–100 MHz) 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 negligible 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 10–60 cm, and VHF band can reach deeper.

As a criteria of the change sensitivity of 0.1 dB 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 retrieve the soil moisture of the 3-rd layer below the depth 60 cm. 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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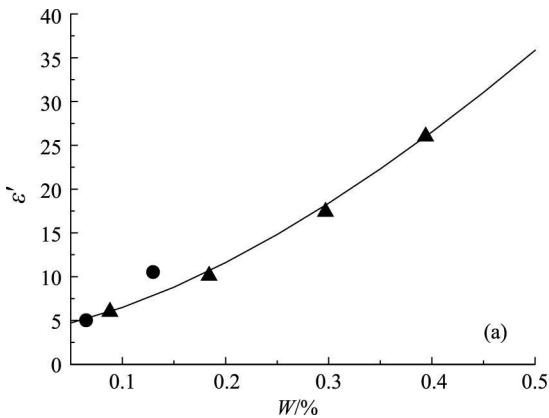
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2 DIELECTRIC CONSTANT OF MOISTURED SOIL AT UHF/VHF

The dielectric constant of moistured soil depends on frequency soil moisture physical temperature structure mixture and so on(Peplinski et al, 1995 a b). Some empirical fomulations of soil dielectric constant in microwave frequency(Peplinsk et al, 1995 a 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

$$\epsilon = \epsilon' + j\epsilon'' \quad (1)$$

$$\epsilon' = 93.1W^{0.65} + 3.79 \quad \epsilon'' = 4.9W + 0.47 \quad (2)$$

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).

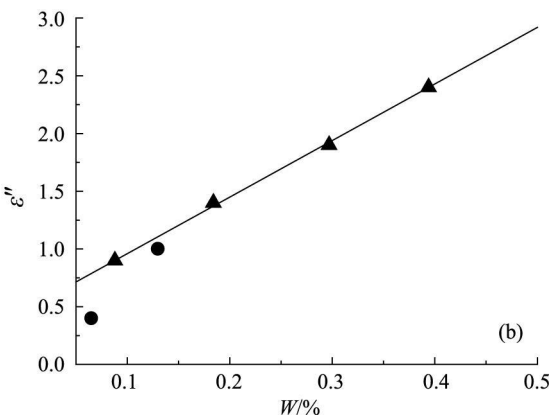


Fig 1 Soil dielectric constant and comparison with Mironov et al (2007)

- (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

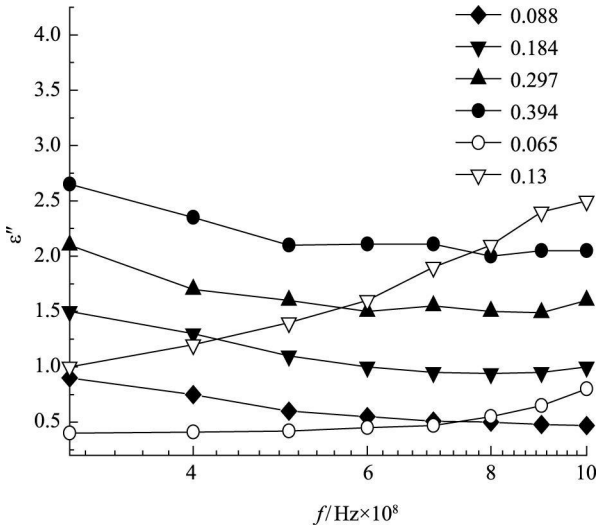


Fig 2 Imaginary part of soil dielectric constant versus frequency

3 THE MUELLER MATRIX SOLUTION OF LAYERED SOIL MODEL

The model of three layered 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

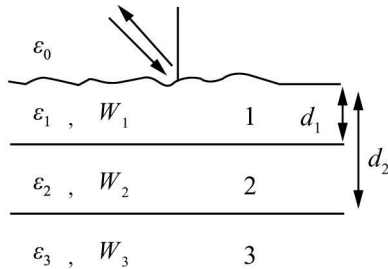


Fig 3 A layered model of land moistured media

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_1 and M_2 .

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:

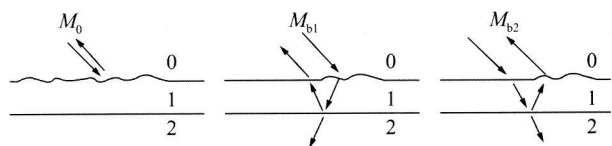
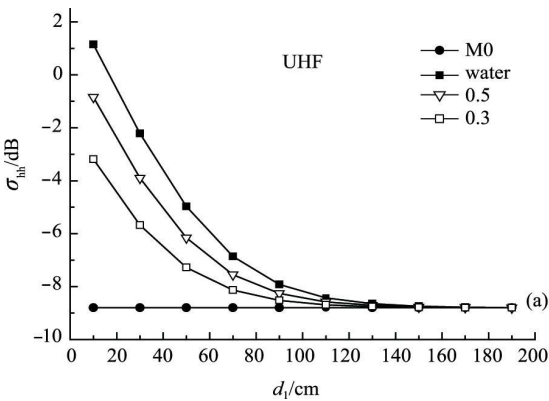


Fig 4 Scattering mechanism

$$\begin{aligned} M(\theta, \varphi_i) &= R_{01}^n(\theta_i) + T_{10}^c(\theta, \varphi; \theta_i, \pi - \varphi_i) \cdot \\ &\quad e^{\kappa d_{\text{scq}}} \cdot R_{12}^c(\theta) \cdot e^{\kappa d_{\text{scq}}} \cdot \\ &\quad T_{01}^n(\theta, \varphi; \theta_i, \pi - \varphi_i) + T_{10}^n(\theta, \varphi; \theta_i, \pi - \varphi_i) \cdot \\ &\quad e^{\kappa d_{\text{scq}}} \cdot R_{12}^c(\theta) \cdot e^{\kappa d_{\text{scq}}} \cdot T_{01}^n(\theta, \varphi; \theta_i, \pi - \varphi_i) \end{aligned} \quad (3)$$

where R and T denote the scattering and transmission matrices respectively. The superscript n denotes incoherent field and c for coherent field. the subscript ij denotes the propagation from Layer i to the Layer j and



κ is the absorption coefficient of Layer1. All matrices in Eq (3) can be found in Jin (1994).

4 SIMULATION OF SUBSURFACE OBSERVATION AT UHF/VHF

First consider a two layer model (i.e. $\epsilon_2 = \epsilon_3$), supposing $W_1 = 0.05$ for top layer variance of rough surface $\delta = 0.1 \lambda_{\text{UHF}} = 8.57 \text{ m}$, correlation length $l = 0.3 \lambda_{\text{UHF}} = 25.71 \text{ m}$ 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 (Layer2 and 3) as water, and $W_2 = 0.3 \quad 0.5$ for different depth of the top layer is calculated by Eq (3) as shown in Figs 5.

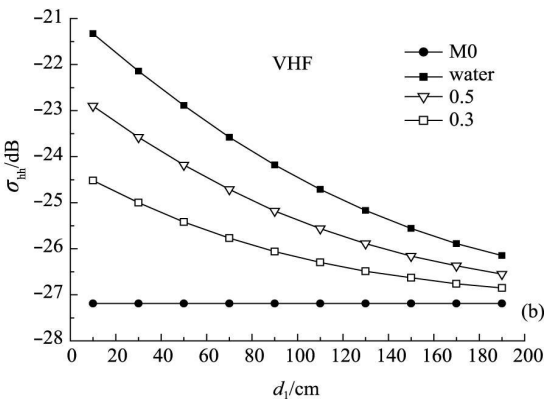


Fig 5 (a) Co-horizontally polarized backscattering at UHF (b) Co-horizontally polarized backscattering at VHF

It can be seen that the subsurface moisture at the depth of 10—50 m 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 1 m depth at UHF, while 1 dB 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 $d = 10 \text{ m}$ is assumed. Other parameters are the same as Fig 5. Suppose that the interface between Layer2 and 3

can be varying 20 m around d , backscattering from Layer 3 is averaged as

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

Suppose $d = 60 \text{ m}$, 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.

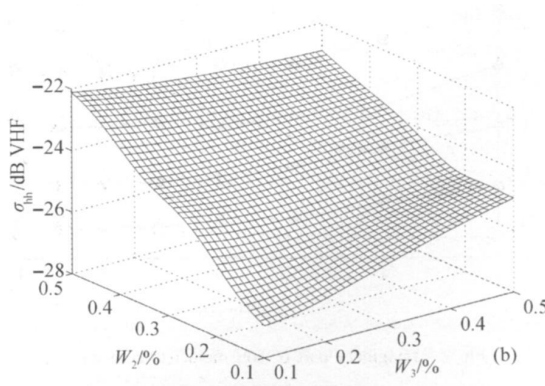
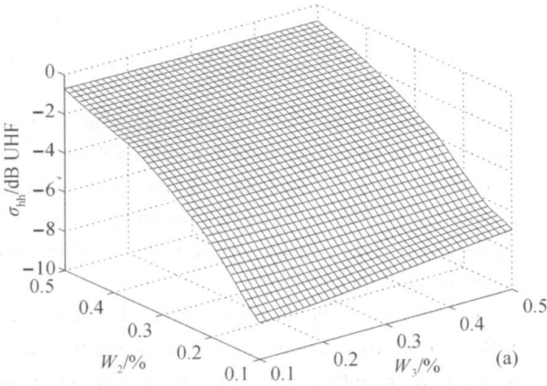


Fig 6 (a) Backscattering with different moisture W_2, W_3 at UHF (b) Backscattering with different moisture W_2, W_3 at VHF

5 MOISURE ESTIMATION OF THREE-LAYER SOIL MODEL

The penetration depth of a homogeneous medium is defined as $d=1/k''$ where k'' is the imaginary 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.

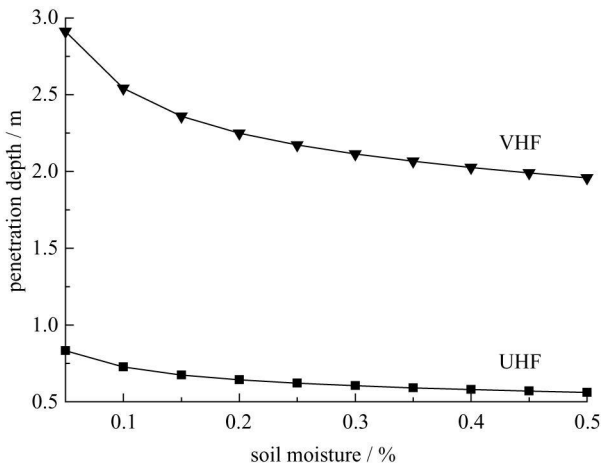
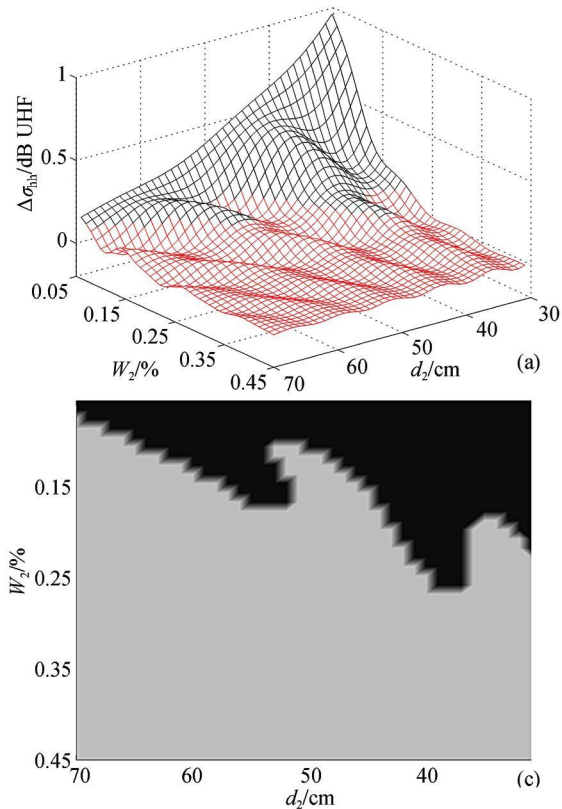


Fig. 7 Penetration depth at UHF and VHF

L band can be used to sense the soil moisture at the depth less than 10 m, and surface roughness. Suppose



that from the measurement at L band the surface roughness parameters $\delta=1$ and moisture $W_1=0.05$ are obtained. Meanwhile $d=10$ m, $\delta=0.1$, $\lambda_{UHF}=8.57$ m, $L=0.3\lambda_{UHF}=25.71$ m, and the incidence at 40° are always assumed.

Suppose that the sensitivity of SAR observation is 0.1 dB 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 $d=30$ m 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 (10–60 m), and then VHF for W_3 under the depth 60 m.

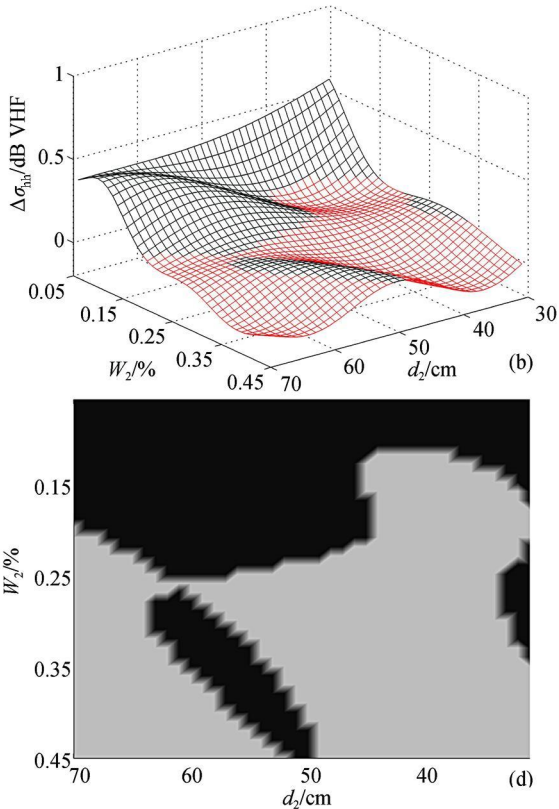


Fig. 8 (a) Impact to backscattering due to variation of W_2, d_2 at UHF

(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 Layer3 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 $W_3 \geq W_2'$, 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 inputting 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 $d = 60$ cm 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 Layer3 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 Layers2 and3 are small. Thus, our iterative inversion is feasible for soil profile inversion if parameters of d , δ , ϵ , W_1 are known.

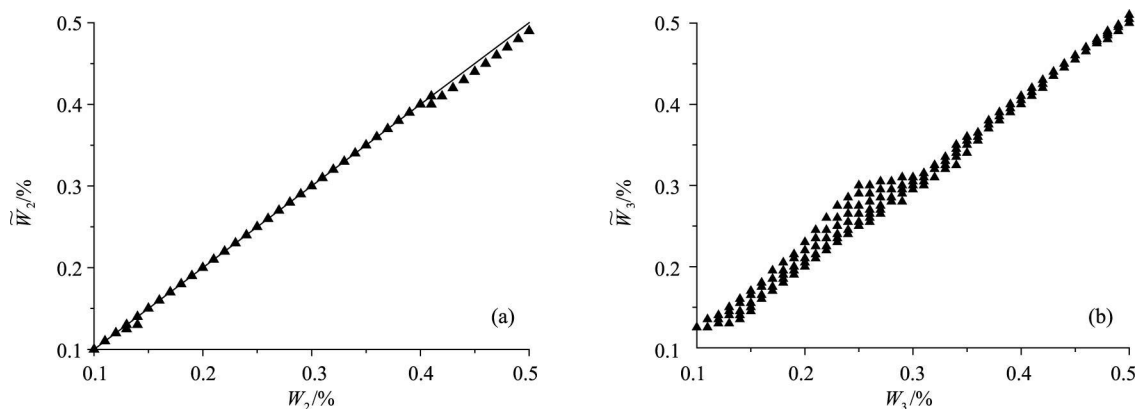


Fig 9 Inversion of soil volume moisture

(a) Inversion of soil volume moisture of Layer2 (b) Inversion of soil volume moisture of Layer3

6 CONCLUSION

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

Assuming the detectable difference of backscattering observation is 0.1 dB, evaluation of soil moisture of Layer3 below 60 cm at VHF band is applicable under the condition that the soil moisture of Layer2 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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UHF/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—60 cm 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 0.1 dB 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 的体湿度。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