A Soil Moisture Retrieval Method for Reducing Topographic Effect: A Case Study on the Qinghai-Tibetan Plateau with SMOS data

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1. Introduction

The mountainous terrain is undulating, and the mountainous directly affect the climate and environment around it through atmospheric and hydrological processes [1]. Microwave remote sensing has the special capability of all-weather and all-time monitoring of soil moisture, but its capability is very limited on the Qinghai-Tibetan Plateau due to the unique environment and the complex topography. The microwave radiation received by the satellite radiometer may be affected by the rotation of radiation polarization plane, the shadowing effect and the multiple scattering effect between adjacent terrains and thus has a serious impact on the remote sensing of soil moisture [2].However, most soil moisture retrieval algorithms assumed that the Earth's surface is horizontal [3], thus can fail to retrieve soil moisture over mountain areas like the Qinghai-Tibetan Plateau. Although many researchers indicated that the topographic effects have a significant impact on the microwave brightness temperature, the current soil moisture retrieval algorithms using spaceborne radiometer observations normally mask out the topographic areas [4] and few studies have demonstrated the evidence of topographic effects on soil moisture retrieval using satellite observations. Therefore, it is needed to quantitatively study the influence of topography on soil moisture retrievals based on spaceborne observations and explore possible solution to minimize the topography effects. In this study, a novel methodology that uses the sum of H_pol and V_pol TB (the first brightness Stokes parameter) was proposed to retrieve soil moisture based on the multi-temporal and multi-angular (MTMA) method developed in our previous study [5], which is expected to explore a solution to reduce the uncertainty of soil moisture retrievals caused by topographic effects.

2. Method

One of the major topographic effects is the polarization rotation (depolarization) effect, which can reduce the TB values at V_pol and increase the TB values at H_pol, leading to the uncertainties of soil moisture retrieval. One possible approach for reducing topographic effects (especially the polarization rotation effect) is to apply the first brightness Stokes parameter (i.e., H_pol TB + V_pol TB) in the soil moisture retrieval algorithm. This is because the first brightness Stokes parameter remains unchanged after the polarization rotation caused by the topographic effects. The implementation of our method is composed by: (1) the SMOS L1C multi-angular TB is refined using the two-step regression method [6]; (2) the first brightness Stokes parameter is substituted into the MTMA method to replace the TB of single polarization channel [5], and then the vegetation optical depth, effective scattering albedo, soil roughness and soil moisture are retrieved.

2.1 Conception of minimizing topographic effects

When the microwave radiation (TB) is affected by the topography, the polarization seen at the satellite-Earth (global reference frame) surface would be rotated with respect to that referenced to the local surface frame. The transformation from the local to the global reference frame can be expressed by:

$$\begin{pmatrix} TB_H(\theta) \\ TB_V(\theta) \end{pmatrix} = \begin{pmatrix} cos^2(\varphi) & sin^2(\varphi) \\ sin^2(\varphi) & cos^2(\varphi) \end{pmatrix} \qquad (1)$$

$$sin\,\varphi = sin(\beta-\beta_l)\cdot sin(\alpha_l)/sin(\theta_l) \qquad (2)$$

where φ represents the polarization rotation angle; TB_H and TB_V are the H_pol and V_pol brightness temperature at the global reference frame with global incidence angle of θ; TB_h and TB_V are brightness temperature at the local reference frame with local incidence angle of θ_l. The polarization rotation angle φ can be calculated using Eq. 2, α_l, β_l are the slope angle and the azimuth angle at the local reference frame, and β is the azimuth angle at the satellite reference frame.

Eq. 1 can be rewritten as:

$$TB_H(\theta)=TB_h(\theta_l)\cdot cos^2(\varphi)+TB_v(\theta_l)\cdot sin^2(\varphi) \qquad (3)$$

$$TB_V(\theta)=TB_h(\theta_l)\cdot sin^2(\varphi)+TB_v(\theta_l)\cdot cos^2(\varphi) \qquad (4)$$

$$TB_H(\theta)+TB_V(\theta)=TB_h(\theta_l)+TB_v(\theta_l) \qquad (5)$$

Therefore, before and after the polarization rotation caused by the topographic effect, the sum of the V_pol and H_pol TB, which is referred as the first brightness Stokes parameter, is unchanged. On the other hand, many researchers have indicated that the topographic effects have the depolarization effect that increases the H_pol TB and decreases the V_pol TB, and thus may bring bias to the retrieval of soil moisture when using existing retrieval algorithms usually without considering topographic effects [2]. In this study, we propose to use the first brightness Stokes parameter ($TB_H + TB_V = TB_{H+V}$) to reduce topographic effects during the soil moisture retrieval.

2.2 Soil moisture retrieval algorithm

The soil moisture retrieval algorithm used in this study is the MTMA method. The MTMA method combines microwave vegetation index (MVIs) [7] and multi-temporal method to decouple soil and vegetation contributions, and uses SMOS multi-angular observation TB data to systematically retrieve vegetation optical depth, effective scattering albedo, surface roughness and soil moisture.

In this study, we further introduce the first brightness Stokes parameter into to the MTMA method to minimize the topographic effects. The retrieval process of vegetation parameters is then given by:

$$\begin{cases} TB_{H+V}(\theta_2)=TB_H(\theta_2)+TB_V(\theta_2)=\left(m_H(\theta_1,\theta_2)+m_V(\theta_1,\theta_2)\right) \\ \qquad +\left(n_H(\theta_1,\theta_2)\cdot TB_H(\theta_1)+n_V(\theta_1,\theta_2)\cdot TB_V(\theta_1)\right) & (6) \\ m_p(\theta_1,\theta_2)=\alpha_p(\theta_1,\theta_2)\cdot V_p^a(\theta_2)+V_p^e(\theta_2)-n_p(\theta_1,\theta_2) & (7) \\ n_p(\theta_1,\theta_2)=\beta_p(\theta_1,\theta_2)\cdot \dfrac{V_p^a(\theta_2)}{V_p^a(\theta_1)} & (8) \\ V_p^e(\theta)=\left(1-\Gamma_p(\theta)\right)\cdot(1-\omega_p)\cdot\left(1+\Gamma_p(\theta)\right)\cdot T^c & (9) \\ V_p^a(\theta)=\Gamma_p(\theta)\cdot T^s-\left(1-\Gamma_p(\theta)\right)\cdot(1-\omega_p)\cdot\Gamma_p(\theta)\cdot T^c & (10) \\ \underset{X=VOD_p,\ \omega_p^{eff}}{min} COST_p^c(X)=\dfrac{\sum_{t=1}^{N}\sum_{i=1}^{K}\left[TB_p{}^t(\theta_i)-TB_p^{o\,t}(\theta_i)\right]^2}{\sigma\left(TB_p^o\right)^2} & (11) \end{cases}$$

and the retrieval process of soil parameters are described by:

$$\begin{cases} E_{H+V}^s(\theta) = E_H^s(\theta)+E_V^s(\theta)=\left(1-r_H^s(\theta)\right)\cdot H_H+\left(1-r_V^s(\theta)\right)\cdot H_V & (12) \\ H_p=A_p\cdot exp\left(B_p\cdot {Z_p^s}^2+C_p\cdot Z_p^s\right) & (13) \\ \underset{X=SM_p,\ Z_p^s}{min} COST_p^{soil}(X)=\sum_{t=1}^{N}\sum_{i=1}^{K}\left[E_p{}^t(\theta_i)-E_p^{o\,t}(\theta_i)\right]^2 & (14) \end{cases}$$

2. Method

where m_p and n_p are the SMOS multi-angle microwave vegetation index; V_p^e and V_p^a are the vegetation emission term and attenuation term, respectively; Γ_p is the vegetation transmissivity ($\Gamma_p= exp\left(-\tau_p^c/cos(\theta)\right)$) and is the function of VOD$_p$ (τ_p^c); ω_p^{eff} is the effective scattering albedo; T^c (K) and T^S (K) are the canopy and soil temperature respectively and are assumed to be equivalent and represented by the effective soil temperature (T^{eff}), which could be gained from ancillary soil temperature data (0–7 cm) in the reanalysis data of ECMWF ERA5; γ_p and μ_p are regression constants using simulation data from the advanced integral equation model (AIEM); θ_1 and θ_2 are two incidence angles, for example, θ_1 is 30° and θ_2 is 40°; t is the SMOS satellite overpass time (6 A.M.); $\sigma(TB_p^o)$ (K) is the standard deviation of SMOS observed brightness temperature; TB_p (K) is simulated brightness temperature; TB_p^o (K) is SMOS observed brightness temperature; N is the number of satellite overpasses; K is the number of angles of SMOS observations; A_p, B_p and C_p are functions of θ and obtained by regression analysis using simulation data set from AIEM; E_p^s is the simulated soil emissivity; E_p^o is soil emissivity calculated using observed brightness temperature of SMOS with retrieved VOD_p and ω_p^{eff}; X (VOD_p, ω_p^{eff}, SM_p and Z_p^s) are the retrieved parameters.

3. Results and discussions

The applicability of the proposed method is validated using in-situ soil moisture measurements collected at four networks (Pali, Naqu, Maqu and Wudaoliang) on the Qinghai-Tibetan Plateau. The results over Pali, which is a typical mountainous area, showed that soil moisture retrievals using the first brightness Stokes parameter are in better agreement with the in-situ measurements (the correlation coefficient R >0.75 and unbiased root mean square error < 0.04 m³/ m³) compared with that using the single-polarization brightness temperature. At the other three networks with relatively flatter terrains, soil moisture retrievals using the first brightness Stokes parameter are found to be comparable to the single-polarization retrievals (**Fig.1**). In the regions on the Qinghai-Tibetan Plateau where the vegetation effect can be ignored, soil moisture retrieved using horizontal polarization brightness temperature is generally underestimated, overestimated when using vertical polarization brightness temperature (**Fig.2**). Moreover, the maximum bias of the retrieved soil moisture caused by topographic effects exceeds 0.1 m³/ m³ when using vertical or horizontal polarization alone, which is far beyond the expected accuracy (0.04 m³/ m³) of SMOS satellite. It is reasonable due to the polarization rotation effect (depolarization) caused by the topographic effects. It is concluded that the proposed method for soil moisture retrieval using the first brightness Stokes parameter has a great potential in reducing the influence of topographic effects.

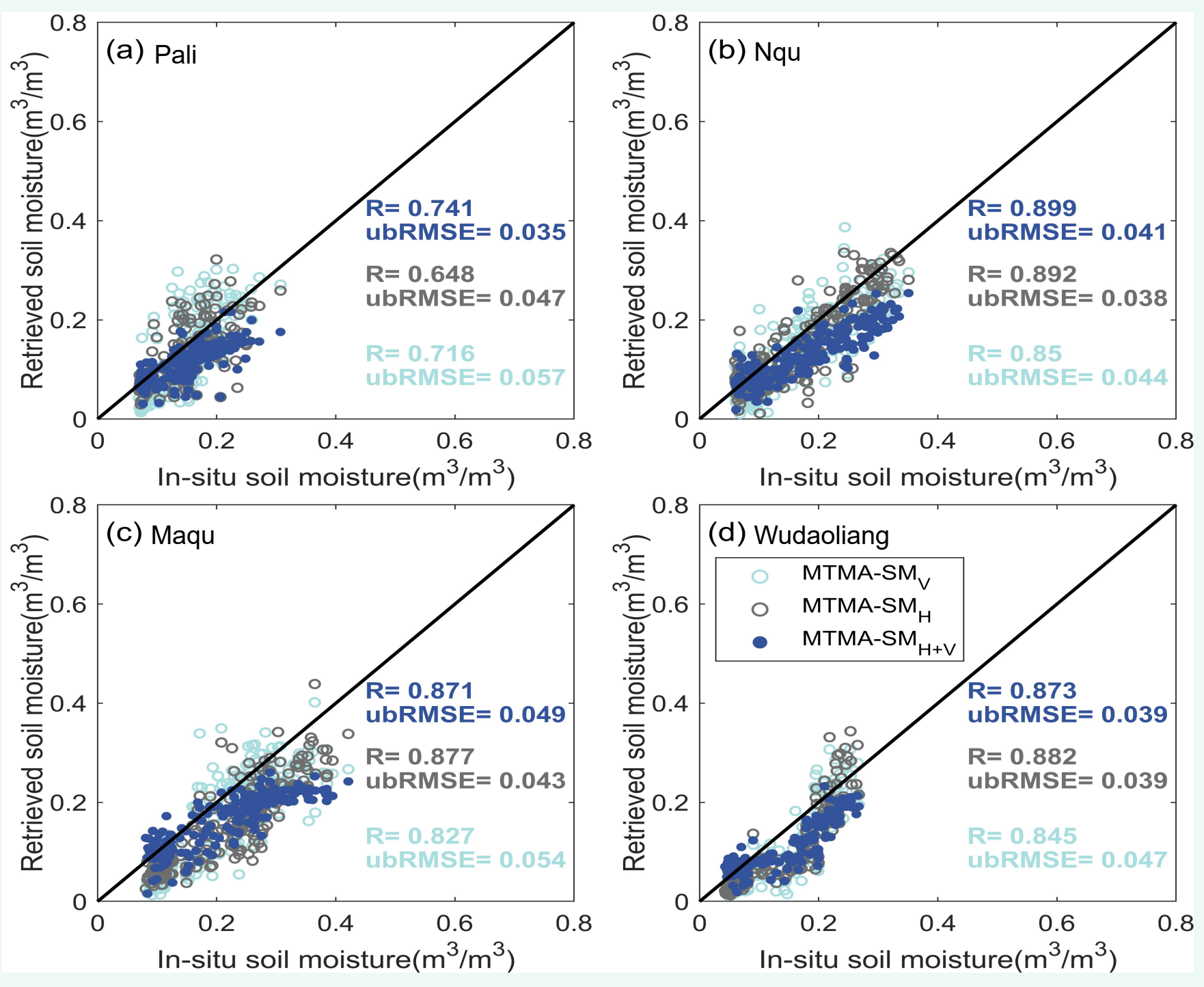

Fig.1. Comparison between the retrievals of soil moisture and the in-situ data in 2015-2016 and 2019-2020 at validation networks on the Qinghai-Tibetan Plateau.

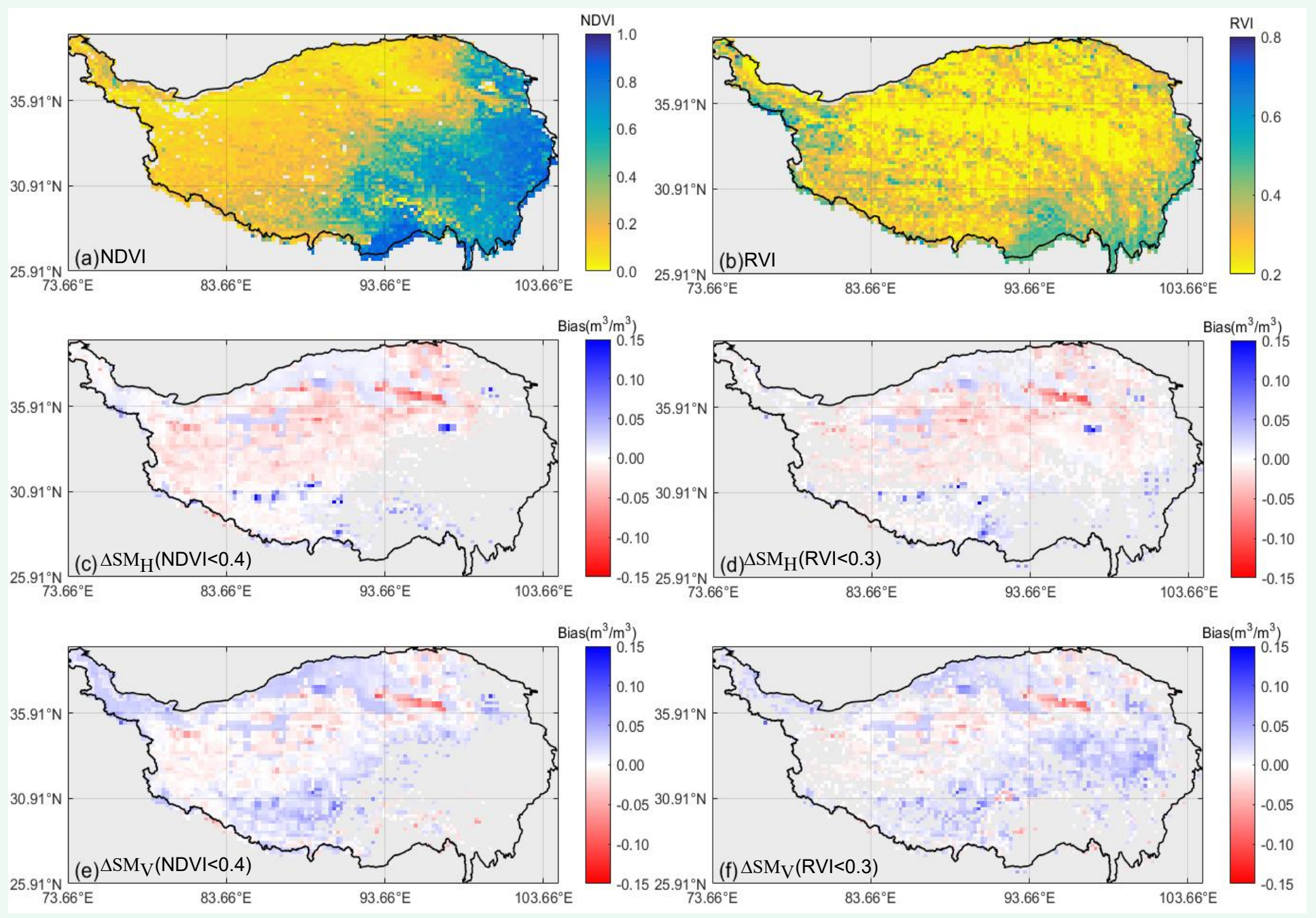

Fig.2. Spatial distribution of vegetation index and soil moisture difference ΔSM_p ($MTMA\_SM_p - MTMA\_SM_{H+V}$) on the Qinghai-Tibetan Plateau in 2015-2016.

4. outlook

Passive microwave remote sensing can provide important tool for soil moisture monitoring in mountainous areas. In this study, we proposed a methodology applying the first brightness Stokes parameter (the sum of H_pol and V_pol TB) in the MTMA method to reduce the influence of topographic effects on soil moisture retrieval. However, for most areas with dense vegetation cover over large terrain relief on the Qinghai-Tibetan Plateau, the microwave radiation was affected by both topography effects and vegetation effects (not shown in this study). The vegetation has the depolarization effect similar as the topographic effect and it can be more significant than that from the topographic effect. The uncertainty of soil moisture retrieval associated with vegetation effects might lead to an obscuration of topography effects. For example, the overestimation or underestimation of vegetation effects at H_pol or V_pol may lead to overestimation or underestimation of soil moisture. Therefore, this method may need a further detailed review in dense vegetated area.

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