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An Empirical Model for Backscattering Coefficients of Vegetation Fields at 5.4 GHz

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Abstract

A new, simple empirical model for microwave backscattering from vegetation fields at 5.4 GHz is proposed in this paper. First, a modified radiative transfer model (RTM) is used to generate a database of multi-polarized backscattering coefficients of various vegetation fields at 5.4 GHz with wide ranges of vegetation biomasses and soil moistures. Second, we propose a functional form of an empirical model that is a simplified water cloud model (WCM) after closely examining the behaviors of the well-known WCM based on an extensive database that includes the modified RTM outputs, scatterometer measurements, SAR datasets, and *in situ* measured ground-truth data for various vegetation fields. Finally, the unknown constant parameters of the empirical model are determined for each soil moisture condition based on the extensive database. The new empirical model is verified with the database itself, and also with independent Sentinel-1 synthetic aperture radar (SAR) data and *in situ* measured ground-truth data.

Key Words: Backscattering Coefficient, Empirical Model, Soil Moisture, Vegetation Fields, Water Cloud Model.

I. Introduction

Global soil moisture mapping using space-borne synthetic aperture radar (SAR) has been widely attempted because of its importance in global water and energy fluxes, weather and climate forecasts, flood prediction, and drought monitoring [1]. Global mapping of vegetation parameters using space-borne SAR imagery is also a very important remote sensing technique for land classification, estimation of productivity and biomass, and remote sensing of environmental changes [2]. The global mapping of soil moisture or vegetation parameters for vegetation fields is, however, still a challenge because of its complexity. Recently, Sentinel-1 SAR (5.4 GHz) and Radarsat-2 (5.4 GHz) have continually provided SAR images for land monitoring. A simple and accurate scattering model for radar backscatters of vegetation fields at 5.4 GHz would be very helpful for estimating the vegetation biomass and soil moisture of a vegetation field from its SAR image.

The radiative transfer technique has been widely used for developing microwave scattering models for vegetation fields [3, 4]. The radiative transfer model (RTM) has good accuracy for estimating backscattering coefficients for a wide range of vegetation canopies [5–7]. However, RTMs have a main drawback for practical usage: the models usually have several dozens of input parameters.

The water cloud model (WCM) is much simpler than the RTM because it has only two terms (the direct backscatter from a vegetation layer and the direct backscatter from the underlying surface with round-trip attenuation from the vegetation layer), ignoring the interaction between the vegetation crown and the

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the underlying ground surface [8, 9]. Although the direct backscatter of a soil surface can be quite accurately obtained using theoretical or empirical models [10, 11], the constant parameters for the direct backscatter and the attenuation of the vegetation layer should be determined empirically for each frequency, incidence angle, polarization, and type of vegetation, which is the main disadvantage of this model.

In this study, we focus on developing a simple and accurate model for multi-polarized backscattering coefficients of vegetation fields at 5.4 GHz. Transmissivity through a vegetation layer depends on radar frequency, incidence angle, and biomass (or leaf-area index [LAI]) [12]. The effect of vegetation on soil moisture retrieval decreases with a decrease in incidence angle and a decrease in biomass [12, 13]. We develop a simple empirical scattering model for vegetation fields using an extensive database that includes the results of the modified RTM in [7] for various vegetation fields, scatterometer data, SAR data, and *in situ* measured ground-truth datasets. Finally, the new empirical model is verified with independent Sentinel-1 SAR data and the corresponding *in situ* measured ground-truth data.

II. Development of a Simple Model

To develop an inversion algorithm to retrieve soil moisture or biomass from radar measurements, we may need to have a simpler model than the complicated RTM model with its many input parameters—about 60 input parameters in [5] and 32 input parameters in [7]. One candidate for a simple model for an inversion algorithm would be WCM [8], which was proposed four decades ago with the following form, ignoring the interactions between the vegetation layer and the underlying soil surface:

$$\sigma^o_{t,pq} = \sigma^o_{veg,pq} + T^2_{pq}\sigma^o_{soil,pq} \tag{1}$$

with

$$\sigma^o_{veg,pq} = A_{pq}\ V_1\ cos\theta_i\ (1 - T^2_{pq}) \tag{2}$$

$$T^2_{pq} = \exp\left[-B_{pq}\ V_2\ sec\theta_i\right] \tag{3}$$

where $\sigma^o_{t,pq}$ is the total backscattering coefficient of a vegetated field for *pq*-polarization, $\sigma^o_{veg,pq}$ is the direct backscatter from the vegetation layer, $\sigma^o_{soil,pq}$ is the *pq*-polarized backscattering coefficient of the underlying soil surface, T^2_{pq} is the two-way transmissivity, and A_{pq} and B_{pq} are unknown constants to be determined for *pq*-polarization for a given frequency and a vegetation type. V_1 and V_2 are vegetation parameters, such as vegetation water content (VWC, kg/m^2), biomass B_m (kg/m^2), LAI (m^2/m^2), and normalized difference vegetation index (NDVI).

Because the primary purpose of this simple model is to apply it to inversion algorithms for the global or regional mapping of soil moisture or biomass using SAR data at 5.4 GHz, we chose biomass B_m (kg/m^2) among other parameters for the vegetation parameter *V*. The transmissivity is 1 $\left(T^2_{pq} = 1\right)$ for the absence of a vegetation layer and exponentially decreases to zero $\left(T^2_{pq} \approx 0\right)$ for an extremely dense vegetation layer. Consequently, the term $\left(1 - T^2_{pq}\right)$ in (2) increases from about 0 for the absence of a vegetation layer to 1 for a very dense vegetation layer. Therefore, the term $V_1\left(1 - T^2_{pq}\right)$ in (2) increases very slowly for lower vegetation densities and increases linearly for higher vegetation densities. However, a close examination of the measurement data shows a rapid increase in the radar backscatters in the region with low vegetation densities compared to the region with higher vegetation density. Considering the examination of the radar measurement and the RTM, we propose an empirical model (a simplified WCM) that has the following form:

$$\sigma^o_{t,pq} = a_0(B_m)^{a_1}cos\theta_i + exp[-a_2B_m sec\theta_i]\ \sigma^o_{s,pq}, \tag{4}$$

where a_0, a_1, and a_2 are constant parameters to be determined for a given frequency and $\sigma^o_{s,pq}$ is the *pq*-polarized backscattering coefficient of the underlying soil surface.

In this study, we use the PRISM (polarimetric radar inversion for soil moisture) [4, 11] to estimate $\sigma^o_{s,pq}$ in the following form:

$$\sigma^o_{vv} = \frac{g\ cos^3\theta}{\sqrt{p}}\left[\Gamma_v(\theta) + \Gamma_h(\theta)\right], \tag{5}$$

$$\sqrt{p} = \sqrt{\sigma^o_{hh}/\sigma^o_{vv}} = 1 - \left(\frac{2\theta}{\pi}\right)^{\frac{1}{3\Gamma_o}} \cdot e^{-kh_{rms}}, \tag{6}$$

$$q = \sigma^o_{vh}/\sigma^o_{vv} = 0.23\ \sqrt{\Gamma_o}(1 - e^{-kh_{rms}}), \tag{7}$$

$$g = 0.7\ \left[1 - e^{-0.65(kh_{rms})^{1.8}}\right], \tag{8}$$

where p and q are the co- and cross-polarized ratios, k is the wave number, h_{rms} is the root mean square (RMS) surface height, Γ_o is the reflectivity at the nadir direction $\Gamma_0 = |(\sqrt{\epsilon_r} - 1)\ /\ (\sqrt{\epsilon_r} + 1)|^2$, and Γ_v and Γ_h are Fresnel reflectivities for *v*- and *h*-polarizations:
$\Gamma_v = |(\varepsilon_r cos\theta - C_1)/(\varepsilon_r cos\theta + C_1)|^2$, $\Gamma_h = |(cos\theta - C_1)/(cos\theta + C_1)|^2$ with $\Gamma_h = |(cos\theta - C_1)/(cos\theta + C_1)|^2$. The dielectric constant ϵ_r can be obtained using empirical formulas in [14] for a given volumetric soil moisture content m_v (cm^3/cm^3).

The unknown parameters of the simplified WCM in (4) can be obtained using other theoretical, numerical, and experimental datasets with various biomass values for a given frequency and vegetation type. In this study, we focus only on the frequency of 5.4 GHz and one-layered vegetation fields, such as meadows, rangelands, pastures, and farming land, including arid and semi-arid areas. We also consider only a relatively narrow range of incidence angles, 20° ≤ θ_i ≤ 50°, mainly considering the operating modes of Sentinel-1 SAR and Radarsat-2. Because one of its main applications may be an inversion algorithm for soil moisture retrieval, the biomass range of $0 \leq B_m \leq 5$ kg/m^2 is primarily selected in this study, considering the validity regions of soil moisture retrieval for vegetation fields [13].

To determine the unknown constants in (4) at 5.4 GHz, first, an extensive database of polarimetric backscattering coefficients for various vegetation fields at 5.4 GHz is generated using the modified RTM for various biomass values and soil moisture conditions: $0 \leq B_m \leq 5$ kg/m^2 with a step of B_m, $\Delta B_m =$ 0.25 kg/m^2, at $m_v =$ 0.03, 0.08, 0.13, 0.18, 0.23, 0.28, and 0.33 cm^3/cm^3, and at $\theta_i = 35°$.

Subsequently, the nonlinear data fitting technique was used to empirically determine the optimum values of a_0, a_1, and a_2 by comparing the modified RTM and the simplified WCM at each soil moisture condition. First, by comparing the backscatter from the underlying soil surface with the RTM and the corresponding term of the WCM, the values of the unknown constant a_2 were obtained with the best fitting between the RTM and the WCM for various conditions. Second, the unknown constants a_0 and a_1 were also obtained by comparing between the RTM and the WCM for various conditions. Finally, the unknown constants a_0, a_1, and a_2 were fitted with the first-order linear polynomials for the soil moisture content m_v.

Fig. 1 shows the comparison between the simplified WCM and the corresponding term of the modified RTM for the direct backscatter from the underlying soil surface with the attenuation through the vegetation layer, with $a_2 =$ 0.172 for VV-polarization at $m_v =$ 0.18 as an example. The estimated a_2 values are approximately 0.17 for all polarizations and moisture conditions.

Fig. 2 shows the comparison between the modified RTM and the simplified WCM for VV- and VH-polarizations at $m_v =$ 0.18 cm^3/cm^3 and $\theta_i = 35°$. For this fitting, a_0 and a_1 are 0.0163 and 0.994 for VV-polarization, 0.0225 and 0.902 for HH-polarization, and 0.0164 and 0.759 for VH-polarization.

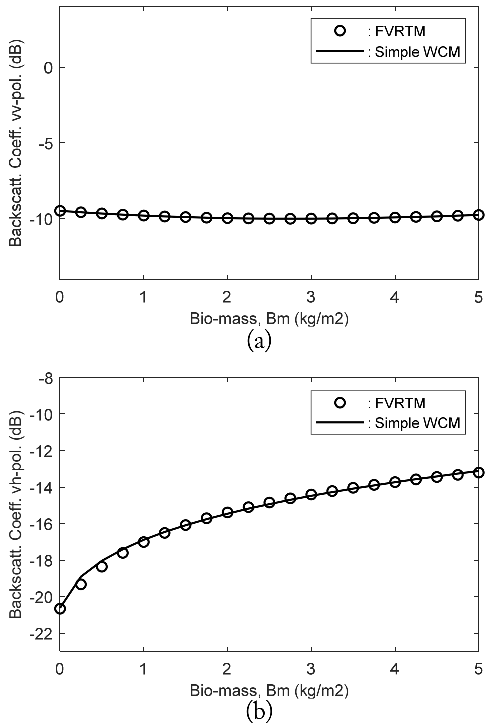


Fig. 2. Comparison between the modified RTM and the simplified WCM for (a) VV-polarization and (b) VH-polarization at $m_v =$ 0.18 cm^3/cm^3 and $\theta_i = 35°$.

Among the three polarizations, the variation in the unknown constants a_0 and a_1 over the change of soil moisture is minimal for VV-polarization and maximal for VH-polarization. For example, the ratios of the constant a_0 at $m_v =$ 0.33 cm^3/cm^3 to a_0 at $m_v = 0.03$ cm^3/cm^3 are about 1.02 for VV-polarization, 1.37 for HH-polarization, and 2.39 for VH-polarization. As an example, Fig. 3 shows the comparison between the estimated values and the best fitting line for the unknown constant a_1 for VH-polarization. The best-fitting lines are given by $a_{1,vh} = -0.66\ m_v + 0.89$ for VH-polarization, as shown in Fig. 3. The other relationships between the unknown constants and the soil moisture content are $a_{0,vv} = 0.0013\ m_v + 0.0160$ and $a_{1,vv} =$

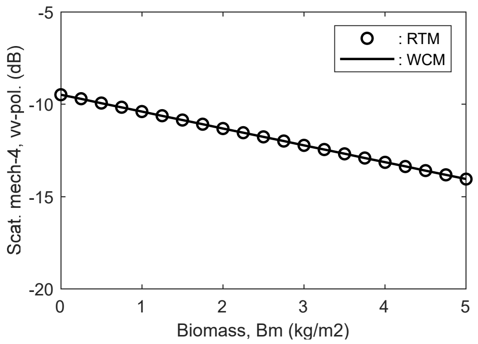


Fig. 1. Comparison between the simplified WCM and the modified RTM for the direct backscatter from the underlying soil surface with attenuation through the vegetation layer.

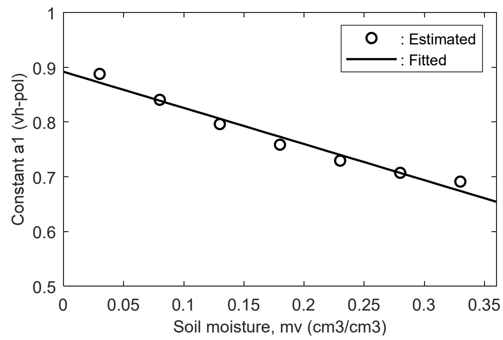


Fig. 3. Comparison between the estimated values and the best-fitting lines for the unknown constant a_1 for VH-polarization.

$-0.026\ m_v + 1.00$ for VV-polarization, $a_{0,hh} = 0.024\ m_v + 0.0181$ and $a_{1,hh} = -0.32\ m_v + 0.96$ for HH-polarization, and $a_{0,vh} = 0.047\ m_v + 0.00814$ for VH-polarization. The angular dependency of the direct vegetation layer backscatter term is mainly controlled by $cos\theta_i$ in (4); therefore, the parameters are not sensitive to the incidence angle in a narrow range of incidence angles, $20^\circ \leq \theta_i \leq 50^\circ$.

In summary, the new empirical model has the following form for the multi-polarized backscattering coefficients of single-layered vegetation canopies at 5.4 GHz.

$$\sigma_{vv}^o = (0.0013\ m_v + 0.0160) \cdot (B_m)^{(-0.026 m_v + 1.00)} cos\theta_i + e^{[-0.17 B_m sec\theta_i]}\ \sigma_{s,vv}^o, \quad (9)$$

$$\sigma_{hh}^o = (0.024\ m_v + 0.0181) \cdot (B_m)^{(-0.32 m_v + 0.96)} cos\theta_i + e^{[-0.17 B_m sec\theta_i]}\ \sigma_{s,hh}^o, \quad (10)$$

$$\sigma_{vh}^o = (0.047\ m_v + 0.00814) \cdot (B_m)^{(-0.66 m_v + 0.89)} cos\theta_i + e^{[-0.17 B_m sec\theta_i]}\ \sigma_{s,vh}^o, \quad (11)$$

where the *pq*-polarized backscattering coefficient of the underlying soil surface $\sigma_{s,pq}^o$ can be obtained from the PRISM model in (5)–(8). The simple empirical model now has only four input parameters for estimating the multi-polarized backscattering coefficients of a single-layered vegetation field: the soil surface RMS height h_{rms}, the volumetric soil moisture content m_v, the biomass B_m, and the radar incidence angle. Therefore, this simple scattering model can be applied to retrieve the soil moisture content and the surface RMS height simultaneously from a dual-polarized SAR dataset for a given incidence angle at 5.4 GHz upon being informed of the vegetation biomass.

III. Verification of the New Simple Model

Fig. 4 shows the comparison among the total backscattering coefficient σ_t^o, the vegetation-layer direct-backscatter component σ_{veg}^o, the attenuated soil-surface direct backscatter component $T^2\sigma_{soil}^o$, and the soil-surface direct backscatter component σ_{soil}^o for VH-polarization at 5.4 GHz, 35°, and $m_v = 0.18$ cm³/cm³.

The soil surface direct backscatter is dominant for lower biomass, while the vegetation layer direct backscatter is dominant for higher biomass, as shown in Fig. 4. The sensitivity of the radar backscatter to the vegetation biomass for cross-polarization is much higher than for co-polarization: e.g., σ_{veg}^o becomes larger than $T^2\sigma_{soil}^o$ at B_m = 0.5 kg/m² for VH-polarization, at B_m = 3 kg/m² for HH-polarization, and at B_m = 3.8 kg/m² for VV-polarization. It was also shown that the cross-polarized backscattering coefficient has a higher sensitivity to the vegetation biomass than co-polarization because the cross-polarized backscatter is significantly influenced by the multiple scattering effect [7], where the vegetation layer causes many different kinds of scatterings.

Fig. 5 shows a comparison between the scatterometer measurements and the simple empirical model for the multi-polarized backscattering coefficients of a full-grown cornfield at 5.4 GHz. The simple empirical model agrees quite well with the HPS measurements of a cornfield at the incidence angles of $20^\circ \leq \theta_i \leq 50^\circ$, as shown in Fig. 5.

For further verification of the new empirical scattering model, we acquired Sentinel-1 SAR data and *in situ* measured ground-truth data. Fig. 6 shows the comparison between the Sentinel-1 SAR datasets and the new simple empirical model for rangelands in Bet Shemesh and Haifa in Israel.

We acquired the dual-polarized (VV- and VH-polarized) backscattering coefficients of the two test sites (rangelands in Bet Shemesh and Haifa, Israel) on February 23, 2019, with Sentinel-1 A in interferometric wide-swath (IW) mode. We also collected the biomasses, volumetric soil moisture contents, and surface RMS heights of the sites on February 23, 2019. The

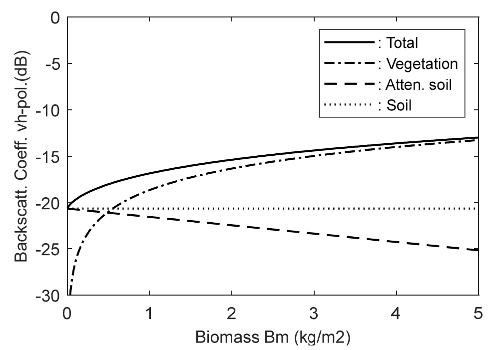


Fig. 4. Comparison between the total backscattering coefficient, the vegetation layer direct backscatter component σ_{veg}^o, the attenuated soil surface direct backscatter component $T^2\sigma_{soil}^o$, and the soil surface direct backscatter component σ_{soil}^o for VH-polarizations at 5.43 GHz, 35°, and $m_v = 0.18$ cm³/cm³.

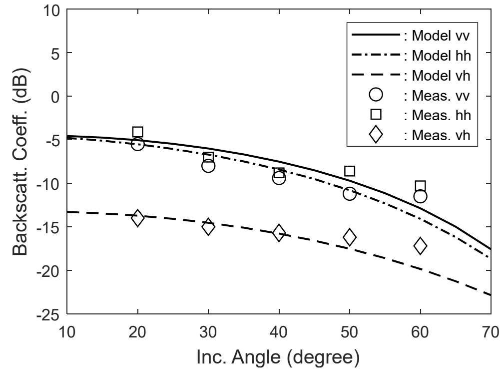
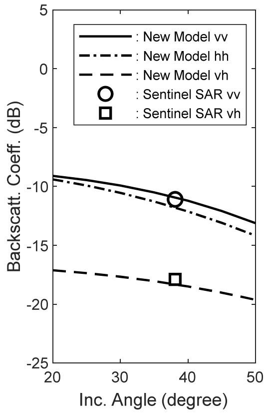
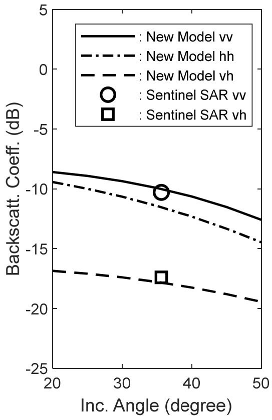


Fig. 5. Comparison between the scatterometer measurements and the simple empirical model for the multi-polarized backscattering coefficients of a cornfield at 5.4 GHz.



(a)



(b)

Fig. 6. Comparison between Sentinel-1 SAR data sets (February 23, 2019) and the new, simple empirical model for rangelands in (a) Bet Shemesh and (b) Haifa, Israel.

biomasses were 0.65 kg/m^2 and 0.43 kg/m^2, the moisture contents were 0.24 cm^3/cm^3 and 0.34 cm^3/cm^3, the surface RMS heights were 0.7 cm and 0.6 cm, and the incidence angles were 38.1° and 35.6° for the Bet Shemesh and Haifa sites, respectively. The empirical model again agrees quite well with the independent datasets of Sentinel-1 SAR. The new empirical scattering model is now proven to have good accuracy in predicting multi-polarized backscattering coefficients of one-layered vegetation canopies at incidence angles of $20° \leq \theta_i \leq 50°$ at 5.4 GHz, although the model is very simple, with only four input parameters.

IV. Concluding Remarks

First, an extensive database was generated for multi-polarized backscattering coefficients at 5.4 GHz with a modified RTM for various vegetation fields with wide ranges of input parameters. The database also included the scatterometer and SAR measurements, as well as *in situ* measured ground-truth data.

Second, the functional form of the WCM was further simplified according to the behavior of the backscattering coefficients in the database. The unknown constant parameters of the simplified WCM were then empirically obtained for each soil moisture condition by data-fitting between the database and the model.

Finally, the new empirical scattering model for multi-polarized backscattering coefficients of a one-layer vegetation canopy at 5.4 GHz was analyzed with close examinations and verified with scatterometer and SAR datasets with *in situ* measured ground-truth data. It was found that the new empirical model agrees well with the experimental data as well as with the RTM. This new empirical model might be good for estimating the backscattering coefficients of one-layered vegetation fields at 5.4 GHz in the range of $20° \leq \theta_i \leq 50°$ for VV-, HH-, and VH-polarizations.

The new model has a major advantage for being applied to any inversion algorithm because the model has only four input parameters: the incidence angle, soil moisture content, surface RMS height, and vegetation biomass. Therefore, the soil moisture content and the surface RMS height can be simultaneously retrieved from a dual-polarized SAR dataset upon being informed of the vegetation biomass, which can easily lead to the global or regional mapping of soil moisture using SAR images at 5.4 GHz.

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