RETRIEVAL OF SOIL MOISTURE AND SURFACE ROUGHNESS FROM POLARIMETRIC SAR IMAGES OF VEGETATED SURFACES

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ABSTRACT: This paper presents soil moisture retrieval from measured polarimetric backscattering coefficients of a vegetated surface. Based on the analysis of the quite complicate first-order radiative transfer scattering model for vegetated surfaces, a simplified scattering model is proposed for an inversion algorithm. Extraction of the surface-scatter component from the total scattering of a vegetation canopy is addressed using the simplified model, and also using the three-component decomposition technique. The backscattering coefficients are measured with a polarimetric L-band scatterometer during two months. At the same time, the biomasses, leaf moisture contents, and soil moisture contents are also measured. Then the measurement data are used to estimate the model parameters for vv-, hh-, and vh-polarizations. The scattering model for tall-grass-covered surfaces is inverted to retrieve the soil moisture content from the measurements using a genetic algorithm. The retrieved soil moisture contents agree quite well with the in-situ measured soil moisture data.

KEY WORDS: Polarimetric SAR images, vegetated surface, soil moisture, surface roughness

1. INTRODUCTION

Soil moisture content is an essential parameter in agriculture and hydrological processes. Retrieval of this parameter from from a satellite synthetic aperture radar (SAR) image has been extensively investigated in the past decades. The soil moisture content and surface roughness can be retrieved from the polarimetric backscatter measurements with a good accuracy for bare-soil surfaces, because the backscattering coefficient is strongly dependant on the surface roughness and the moisture content of the soil surface layer (Oh, 2004). However, for vegetation-covered surfaces, the soil moisture retrieval is a challenging problem because of various scattering mechanisms in the vegetation canopy.

A regression curve between the measured backscattering coefficients and the measured soil moisture for a specific vegetation canopy can be used to retrieve the soil moisture as in (De Roo *et al.*, 2001). The ratios of different radar channels (polarization or frequency) can also be regressed against the soil moisture content. In this approach the vegetation biomass and the surface roughness are ignored. The other approach would be an inversion of a simplified scattering model, so-called water-cloud model, which represents the vegetation canopy as uniformly distributed water particles like a cloud. The parameters of the water-cloud model are derived by fitting the model with experimental data as in (Bindlish and Barros, 2001) and (Sidkar et al., 2005). The model parameters are dependant on the vegetation type and the polarization.

This paper addresses the polarimetric characterization of the model parameters for a tall-grass field. A set of measurement data is used to estimate the model parameters for vv-, hh-, and vh-polarizations. The scattering model for tall-grass-covered surfaces can be inverted to retrieve the soil moisture content and the surface roughness from the measurements using a genetic algorithm.

2. RADAR MEASUREMENTS

One of the authors is a PI of JAXA ALOS Second Research. Therefore, PALSAR images could be obtained as in Fig. 1. However, it was not easy to obtain enough numbers of temporal polarimetric SAR images throughout a season.

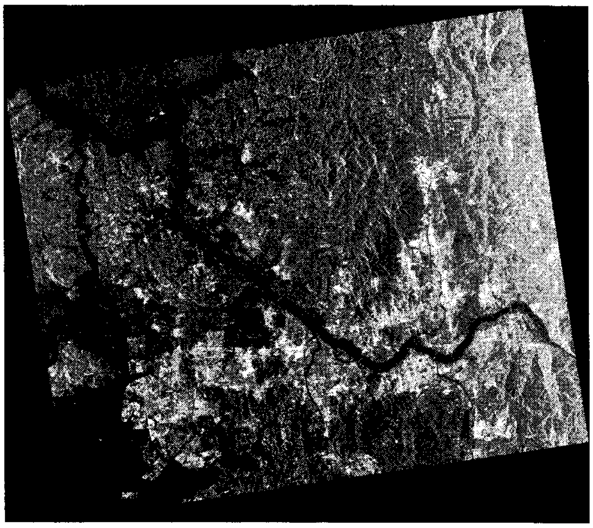

Figure 1. PALSAR image on March 22, 2008.

Therefore, a set of temporal scatterometer measurement data of a vegetated surface were used in this study. The backscattering coefficients of the tall-grass-covered field were measured at 1.85 GHz using the polarimetric scatterometer installed on a tower during a season. The radar measurements will be used for developing and verifying a scattering model and an inversion algorithm of this study. The scatterometer consists of a vector network analyzer, two horn antennas, and a laptop computer. The antenna system was installed on top of a tower and thirty independent data were collected at each measurement to reduce signal-fading variations. Fig. 2 shows the scatterometer system on the tower in the field.

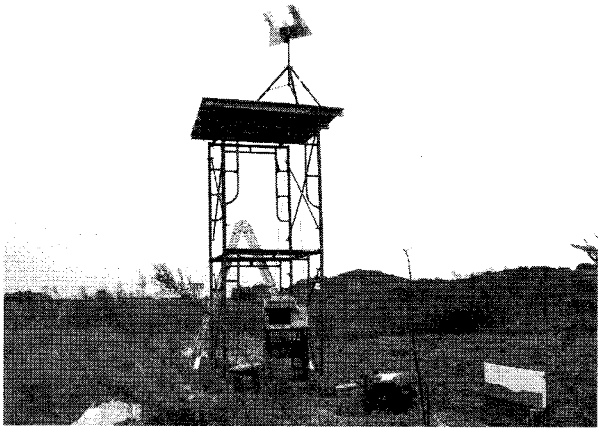

Figure 2. Measurement system

The wave reflections from the coaxial-to-waveguide adapter and the tower were gated out using the time-gating function of the vector network analyzer. The surface height distribution was measured using a pin-type profilometer, from which the rms height was computed. The volumetric soil moisture contents m_v (cm^3/cm^3) were also collected for each measurement. The vegetation water mass m_w (kg/m^2) of the tall-grass and the leaf gravimetric moisture content mg (g/cm^3) were measured by cutting the tall-grasses in the area of 30 cm x 30 cm. Fig. 3 shows the tall grass field.

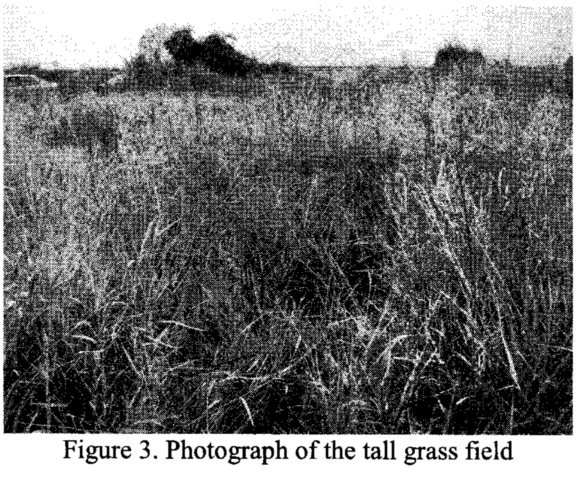

Figure 3. Photograph of the tall grass field

Fig. 4 shows the backscattering coefficients measured form the tall-grass field. The L-band scatterometer system was precisely calibrated using the single-target calibration technique (STCT), which is convenient and capable to correct the radar cross-talk contamination and channel imbalances by measuring the backscatter cross section of a conducting sphere or a corner reflector. The true scattering matrix $\overline{\overline{S}}$ can be obtained from the scatterometer measurements $\overline{\overline{M}}$ inverting the following matrix equation.

$$\overline{\overline{M}} = \overline{\overline{R}}\,\overline{\overline{C}}\,\overline{\overline{S}}\,\overline{\overline{C}}^t\,\overline{\overline{T}} \tag{1}$$

where $\overline{\overline{R}}$ = receive channel imbalance matrix

$\overline{\overline{T}}$ = transmit channel imbalance matrix, and

$\overline{\overline{C}}$ = the cross-talk matrix.

The elements of those matrices can be obtained by the theoretical and measured radar cross section (RCS) of a calibration target. The illumination integral could be computed using three-dimensional antenna pattern which was generated by interpolating the measured principal E- and H-plane antenna patterns.

As shown in Fig. 4, the hh-polarized backscattering coefficients are higher than the vv-polarized backscattering coefficients because of the microwave scattering from the vegetation canopy. For bare soil surface, the vv-polarized backscatter is higher than the hh-polarized backscatter. The cross-polarized backscatters are about 10 dB lower than the co-polarized backscatters. The variation of the radar backscatters in the period is relatively small because the moisture content does not vary much during the period.

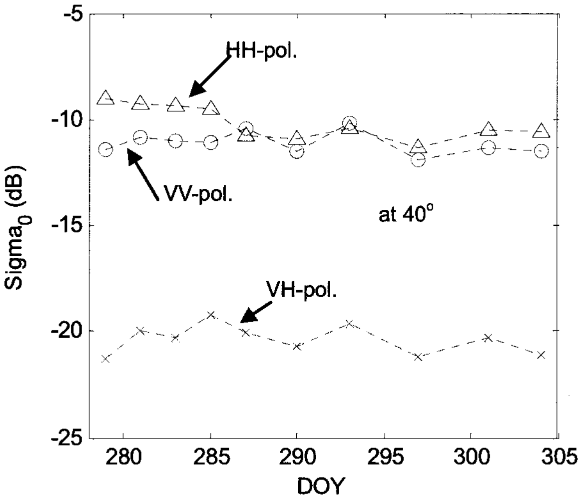

Fig. 4. Measured polarimetric backscattering coefficients.

Fig. 5 shows the variations of the vegetation water mass m_w, leaf moisture content m_g, and the soil moisture content m_v during the experiment period. The vegetation water mass decreases because of the seasonal effect as shown in Fig. 5.

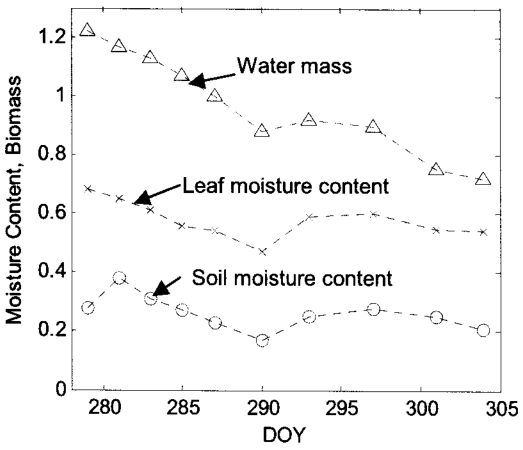

Fig. 5. Measurements of the ground truth data.

3. SCATTERING MODEL

The first-order radiative transfer scattering model includes four basic scattering mechanisms; i.e., direct backscatter contribution of the canopy, direct backscatter contribution of the underlying soil surface, contribution of canopy-ground interaction (ground-canopy, canopy-ground, and ground-canopy-ground). The canopy-ground interactions are ignored in the water-cloud model. The backscattering coefficients for q-polarized wave incidence and p-polarized wave backscatter of the water-cloud model can be expressed in the following form.

$$\sigma_{pq}^0 = \sigma_{v,pq}^0 + T^2 \sigma_{s,pq}^0 \, . \qquad (2)$$

where $\sigma_{v,pq}^0$ = direct backscatter of vegetation layer

$\sigma_{v,pq}^0$ = direct backscatter of soil surface

$T = \exp[-\kappa h \sec\theta]$ = transmissivity

h = canopy height

θ = incidence angle.

It was shown in (De Roo *et al*, 2001) that the mean extinction coefficient κ was proportional to $\sqrt{m_w}$, where the m_w is the vegetation water mass in kg/m^2, analyzing the computational results of the Michigan Microwave Canopy Scattering Model (MIMICS). Therefore, the transmissivity of a canopy can be represented as

$$T = \exp\left[-B\sqrt{m_w}\,\sec\theta\right] \qquad (3)$$

where B = an unknown constant

m_w = vegetation water mass.

Similarly, the direct backscatter from the vegetation canopy is also modeled as a function of the vegetation water mass m_w such as

$$\sigma_{v,pq}^0 = A\sqrt{m_w}\cos\theta\left(1 - T^2\right) \qquad (4)$$

For the backscatter of soil surface in the absence of vegetation cover, the semi-empirical model developed by Oh *et al.* is adopted (Oh, 2004);

$$\sigma_{s,vh}^0 = 0.11 {m_v}^{0.7} \cos\theta^{2.2}\left[1 - \exp\left[-0.32(ks)^{1.8}\right]\right] \qquad (5)$$

$$\sigma_{s,vv}^0 = \sigma_{s,vh}^0 / q \qquad (6)$$

$$q = 0.095\left(0.13 + \sin(1.5\theta)\right)^{1.4}\left[1 - \exp\left(-1.3(ks)^{0.9}\right)\right] \qquad (7)$$

$$\sigma_{s,hh}^0 = \sigma_{s,vv}^0 p \qquad (8)$$

$$p = 1 - \left(\theta/90^0\right)^{0.35 {m_v}^{-0.65}} \cdot \exp\left[-0.4(ks)^{1.4}\right] \qquad (9)$$

where m_v = soil moisture content

s = surface RMS (root-mean-squre) height

$k = 2\pi / \lambda$ = wave number

4. INVERSION ALGORITHM AND INVERSION RESULTS

When the vegetation water mass m_w is not available, we may need to represent m_w as a function of time (day of year: DOY) and the soil moisture content. Considering the seasonal growing pattern of tall-grasses, we suggest the following functional form,

$$m_w = C(D - t)\, e^{-\left(\frac{t-D}{E}\right)^2} \, , \qquad (10)$$

where t = DOY

C, D, F = the constants

The constants C, D, and E are 0.03, 328, and 100, respectively, which are determined by data-fitting with *in-situ* measurements. Fig. 6 shows the comparison between the measured and modeled vegetation water masses. The vegetation water mass m_w may also be dependant on the soil moisture contents. Therefore, (10) is revised as follows;

$$m_w = 0.03(328 - t)\, e^{-\left(\frac{t-328}{100}\right)^2} + 0.6\left(m_v - \langle m_v \rangle\right) . \qquad (11)$$

Fig. 7 shows the comparison between estimated and measured vegetation water mass m_w (kg/m^2) for a full growing period, while Fig. 7 shows the comparison for a period of the measurement.

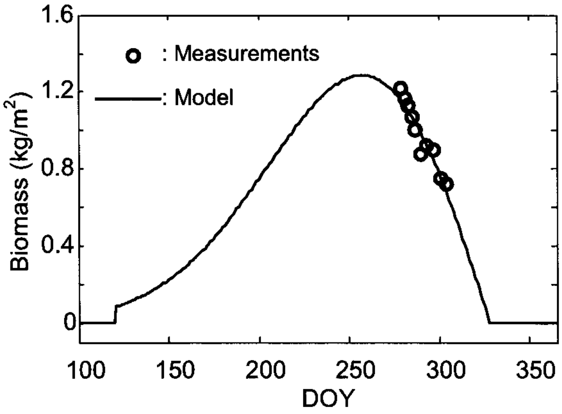

Figure 6. Data-fitting of the measured vegetation water mass for a full growing period.

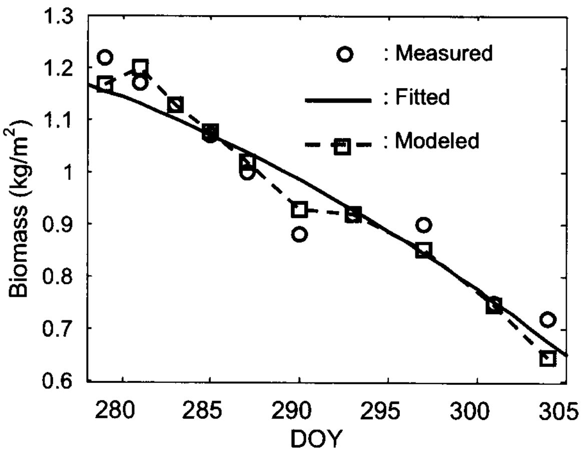

Figure 7. Data-fitting of the measured vegetation water mass for a period of the measurement.

The unknown constants A and B in (3) and (4) were determined by comparison between the scattering model and the measurements using the minimum mean square error (MMSE) evaluation method. It was shown that B is not sensitive on polarization. The estimated values of A_{vv}, A_{hh}, A_{vh}, and B are 0.0977, 0.1328, 0.0117, and 7.5, respectively. The scattering model with the estimated constants agrees quite well with the measured backscattering coefficients.

The scattering model is now a function of only two parameters; the soil moisture content m_v and the surface rms height s, which can be retrieved together from the measurements. A genetic algorithm (Oh, 2006) was used to estimate the soil moisture content m_v and the surface rms height s from the measured polarimetric backscattering coefficients, *i.e.*, σ_{vv}^0, σ_{hh}^0, σ_{vh}^0, $p=\sigma_{hh}^0/\sigma_{vv}^0$, and $q=\sigma_{vh}^0/\sigma_{vv}^0$. At first 120 chromosomes were generated for the genetic algorithm. Each chromosome consisted of twelve bits for two input parameters, the soil moisture contents and surface rms height. Then the cost function for each chromosome was computed using the scattering model. The chromosomes were ranked, the inferior chromosomes were discarded, and the superior chromosomes were mated. A few chromosomes were muted to avoid being stuck in a local minimum. This process was iterated for converging to an optimum solution. The optimum input parameters for measurements of σ_{vv}^0, σ_{hh}^0, σ_{vh}^0, p, and q, were found and averaged. The averaged values of the measured and estimated soil moisture contents are 0.263 cm^3/cm^3 and 0.258 cm^3/cm^3, and the averaged values of the measured and estimated rms height s are 2.35 *cm* and 2.38 *cm*, respectively.

The errors between the estimated and measured soil moisture contents may be from the scattering model and measurements. In the scattering model, the contribution of ground-to-canopy multiple scattering was ignored, and moreover, the model parameters are empirically determined. The *in-situ* measurements of the soil moisture content m_v and the vegetation water mass m_w may also have errors because of finite number (or size) of samples.

5. CONCLUDING REMARKS

A simple scattering model was proposed in this study for an inversion algorithm, based on the analysis of the quite complicate first-order radiative transfer scattering model for vegetated surfaces. The backscattering coefficients were measured with a polarimetric L-band scatterometer during two months. At the same time, the biomasses, leaf moisture contents, and soil moisture contents were also measured. Then the measurement data were used to estimate the model parameters for vv-, hh-, and vh-polarizations. The scattering model for tall-grass-covered surfaces was employed as a cost function for a genetic algorithm to retrieve the soil moisture content and surface roughness from the radar measurements. The retrieved soil moisture contents and surface RMS heights agree quite well with the in-situ measured data. This inversion algorithm can be applied to other vegetation canopies for retrieving soil moisture and surface roughness from SAR images as well.

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