Theoretical Modelling Study on the Relationship between Multi-Frequency Microwave Vegetation Index and Vegetation properties (optical depth and single scattering albedo)

Somayeh Talebi 1*, Jiancheng Shi 1 Tianjie Zhao 1

1 State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing 100101, China; Email: (soma, shjc, zhaot}@ radi.ac.cn

KEY WORDS: Microwave Vegetation Index, Matrix Doubling Model, Optical Depth, Single Scattering Albedo, Soil Moisture, Roughness

ABSTRACT:

This paper presents a theoretical study of derivation Microwave Vegetation Indices (MVI) in different pairs of frequencies using two methods. In the first method calculating MVI in different frequencies based on Matrix Doubling Model (to take in to account multi scattering effects) has been done and analyzed in various soil properties. The second method was based on MVI theoretical basis and its independency to underlying soil surface signals. Comparing the results from two methods with vegetation properties (single scattering albedo and optical depth) indicated partial correlation between MVI from first method and optical depth, and full correlation between MVI from second method and vegetation properties. The second method to derive MVI can be used widely in global microwave vegetation monitoring.

1. INTRODUCTION

Monitoring vegetation properties by satellites will enhance our understanding of vegetation. Remote sensing-based index is the most popular used tool in vegetation monitoring. Microwave portion of the electromagnetic spectrum (1cm to 1m) are effective for composition and structure of the surface or volume under observation. Specifically, microwave emissivity varies strongly with surface roughness, polarization, look–angle(England and Johnson 1977) and particularly water content due to liquid water’s high permittivity at microwave frequencies (Hunt et al. 2018; Miller 2016; Seo et al. 2010). Investigating on microwave vegetation indices make it clear that they can be influenced by soil emission. This issue can limit application of those products in global vegetation monitoring(Becker and Choudhury 1988; Shi et al. 2008). Shi et al. made a new passive microwave vegetation index (MVI) by AMSRE data from zero-order model, which minimized the surface emission signal and maximized the vegetation signal. The τ→ω model represents a zero-order RT solution that links terrain geophysical variables to the observed brightness temperature through soil reflectivity and two vegetation parameters: optical depth and single-scattering albedo (Kerr and Njoku 1990a; Kerr and Njoku 1990b; Mo et al. 1982). As mentioned above, MVI is derived from the zeroth-order radiative transfer solution. The zero-order solution is only applicable at low frequency or for sparse vegetation layer(Ferrazzoli et al. 2002, Kurum et al. 2012). But at high frequencies or dense vegetation, the contribution of scattering within the layer cannot be ignored. This approach will tend to underestimate the total emission. So MVI from zero- order model works well for grasslands, short agricultural crops, and light to moderate vegetation under C-band, otherwise MVI may not correlate well with vegetation parameters (Chai et al. 2010b). In the present study, MVI in different frequencies based on Matrix doubling model calculated (to take in to account multi scattering effects) and tried to analysis its behavior at different soil moisture and roughness in different densities of corn canopy (a high crop) to understand how it changes. Here, this MVI has been named $MV_{10}$. Afterward base on $MV_{10}$ limitations we tried to derive MVI-A and MVI-B by a new method. MVI from new method was named $MV_{11}$ and $MV_{12}$. Then analyzing $MV_{11}$ and $MV_{12}$ behavior compare to vegetation properties (optical depth and single scattering albedo) has been done. Analyzing these relationships will indicate MVI potential in global vegetation monitoring.

As well as, water cycle observation mission (WCOM) also is designed with new configuration and examine the performance of MVI in multi frequency in the context of this new mission is necessary, so currently the simulation is the only way to do that.

2. DATA AND METHODOLOGY

2.1 Experimental Data

Detailed vegetation architecture and radiometer data for corn canopy to simulate brightness temperature from Matrix Doubling Model and validating the results were acquired in 2014 in Huaihai province China on June and July form 2014,06.22-2014,07.13. Individual plants were defined by sampling randomly selected crop. Measurements for corn were made of leaf width, length and thickness, stalk diameter and length, stalk and leaf moisture, soil and plant temperature, canopy height and stalk length, leaf inclination angle (alpha, beta, and gamma) and density. The vegetation sampling strategy was to choose 5 or 6 moderate ones in growth at different sites around the field-of- view. The terminal value of every parameter was an average of all the measurement. As to soil parameters, a JM624M Platinum resistance thermometer was utilized to obtain the temperature of soil profile, vegetation and environment. Volumetric soil moisture (SMC) was measured at
different depths also (Chai et al. 2010a). Table 1 is experimental data of corn in Huailai province.

The passive microwave sensor system used in this study was the Truck Mounted Microwave Radiometer (TMMR) (Zhao et al. 2008) which had four-frequency (6.925/10.65/18.7/36.5GHz) antenna, dual-polarized (V/H) truck-mounted microwave radiometer designed. The receiver modules by the azimuth and elevation angle of the viewing direction could be changed at a precision of 0.1° is fixed on the petitioner. More introductions about TMMR can be found in (Rose and Czekala 2006).

Table1. vegetation parameters for corn

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leaf Radius</td>
<td>cm</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Thickness</td>
<td>mm</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Gravimetric Moisture</td>
<td>degree</td>
<td>0.70</td>
<td>0.90</td>
</tr>
<tr>
<td>Angle distribution</td>
<td>degree</td>
<td>5</td>
<td>85</td>
</tr>
<tr>
<td>Stalk Radius</td>
<td>cm</td>
<td>0.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Length</td>
<td>cm</td>
<td>4</td>
<td>140</td>
</tr>
<tr>
<td>Gravimetric Moisture</td>
<td>%</td>
<td>0.60</td>
<td>0.85</td>
</tr>
<tr>
<td>Angle distribution</td>
<td>degree</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Leaf density</td>
<td>m2</td>
<td>52</td>
<td>110</td>
</tr>
<tr>
<td>Stalk density</td>
<td>m2</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Layer height</td>
<td>m</td>
<td>0.2</td>
<td>2</td>
</tr>
</tbody>
</table>

In the present study, MVI in different frequencies based on Matrix doubling model calculated. The Matrix Doubling Model has been validated several times using field data,(Eom and Fung 1984; Ferrazolli et al. 1995; Ferrazolli et al. 2002; Ferrazolli et al. 2000) and here we made an additional comparison with TMMR measured brightness temperature. Using the radiometer experiment measurements of the vegetation and soil, simulation from matrix doubling model under different frequencies has been validated.

Table 2 is the statistical parameters of comparison TMMR measured brightness temperature and the matrix doubling model simulated for eight days experiment data at vertical and horizontal polarization. R value of TMMR observed and simulated data shows the correlation coefficient at C band is more than X band in both frequencies. Paying attention to p-value indicated the probability of 95% of the observed relationship is not coincidental.

<table>
<thead>
<tr>
<th>Measured and Simulated BT</th>
<th>R^2</th>
<th>RMSE</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>X band V pol</td>
<td>0.80</td>
<td>3.4</td>
<td>0.01</td>
</tr>
<tr>
<td>X band H pol</td>
<td>0.69</td>
<td>1.8</td>
<td>0.00</td>
</tr>
<tr>
<td>C band V pol</td>
<td>0.84</td>
<td>0.8</td>
<td>0.00</td>
</tr>
<tr>
<td>C band H pol</td>
<td>0.81</td>
<td>3.1</td>
<td>0.00</td>
</tr>
</tbody>
</table>

2.2 Methodology

MVI from Multi-Frequency Observations: In the MVI technique the brightness temperature from 0-order model has been linearly linked to the soil emissivity by two ingredient models (vegetation transmission component as slope and vegetation emission component as intercept). Then to minimize the effect of ground surface emission signal the characteristics of bare surface emission signals at different frequencies are evaluated. The bare soil surface emissivity at two frequencies extremely correlated and the linear function can display this relationship. By eliminating the surface emissivity, brightness temperature observations at a given polarization P observed with two adjacent frequencies can be describe as a linear function. The intercept and slope of this linear function are the microwave vegetation indices. More information about MVI technique can be found at(Shi et al. 2008).

\[ T_M^{(1)}(f_2) = A_v(f_2,f_2) + B_v(f_2,f_2) T_M^{(1)}(f_1) \] (1)

\[ T_M^{(1)}(f_2) \] and \[ T_M^{(1)}(f_1) \] are the brightness temperature observations at a given polarization P in a pair of frequency. \( B_v(f_2,f_2) \) and \( A_v(f_2,f_2) \) are MVI-B and MVI-A respectively.

\[ B_v(f_2,f_2) = b(f_2,f_2) \left( \frac{V(f_1)}{V(f_2)} \right) \] (2)

\[ A_v(f_2,f_2) = a(f_2,f_2) V(f_1) + V(f_2) - B_v(f_2,f_2) V(f_2) \] (3)

\( V_1 \) is vegetation transmission and \( V_2 \) is vegetation emission component at the given frequency; \( a \) and \( b \) are the slope and aspect of the linear function of bare surface emissivity at a pair of frequency.

Here MVI is derived from two methods. In plenty and numerous different types of vegetation canopies with different cover sizes, shapes and distributions, can assume there is no considerable impact of the polarization dependence for vegetation signals (Paloscia et al. 2006; Shi et al. 2008; Van de Griend and Wigneron 2004). The first way to drive MVI here was based on this assumption, by measured brightness temperature at two frequencies:

\[ B(f_2,f_2) = B_1(f_2,f_2) + B_2(f_2,f_2) \left( \frac{V(f_1)}{V(f_2)} \right) \] (4)

The second method to drive MVI was based on (Eq. 1). At this function the slope and intercept of the linear function of brightness temperature simulation in two adjacent frequencies are \( B_v(f_2,f_2) \) and \( A_v(f_2,f_2) \) respectively. Based on theoretical MVI definition \( B_v(f_2,f_2) \) or (MVI-B) and \( A_v(f_2,f_2) \) or (MVI-A) are independent of underlying soil surface signals and dependent only on vegetation properties (Shi et al. 2008). So calculation of MVI-A and MVI-B are possible in different soil parameters, constant canopy properties and constant temperature. We named them \( \text{MVI}^A \) and \( \text{MVI}^B \) respectively.

Optical depth and single scattering albedo: Optical depth and single scattering albedo are two vegetation parameters that connect observed brightness temperature from zero order model to geophysical variables in Radiative Transfer Model. Also, based on MVI technique the brightness temperature from 0-order model can be expressed as a linear function of soil emissivity with a slope of \( V_1 \) and intercept of \( V_2 \). Based on \( \text{MVI}^A(f_2,f_2) \) and \( \text{MVI}^B(f_2,f_2) \) definition in (Eq. 2) and (3) and their dependency on \( V_1 \) and \( V_2 \) respectively, here is desirable to understand are \( B_v(f_2,f_2) \) and \( A_v(f_2,f_2) \) as a function of optical depth and single scattering albedo respectively or not? Analyzing MVI's and vegetation properties relationships will indicate MVI potential in global vegetation monitoring.
To calculate effective optical depth, matrix doubling model is used because of taking into account multi scattering effects inside the corn canopy. By this method simulated canopy transmissivity of Tor Vergata model is used as a function of the extinction cross section averaged among sub layer scatterers. To calculate effective optical depth by Matrix Doubling Model we used:

\[ \tau^* = -\ln(T^M)\cos\theta \]  

(5)

\( \tau^* \) is effective optical depth, \( T^M \) is the transmissivity of corn canopy and \( \theta \) is observation angle. Effective albedo by matrix doubling model can be derived as:

\[ \omega^* = 1 - \frac{e^\omega M}{1-T^M} \]  

(6)

\( \omega^* \) is effective scattering albedo, \( T^M \) is the emissivity simulated by MD model and \( \theta \) is observation angle (Ferrazzoli et al. 2002).

### 2.3 Result

First MVI in different frequencies based on Matrix doubling model calculated and tried to analysis its behavior in different soil moisture and roughness by different densities of corn canopy to understand how they change. Figure 1(up) is absolute difference of MVI\( _n^1 \) in 0.1 and 0.3 volumetric soil moisture for four types of MVI\( _n^1 \). According to the corn graphs, sensitivity to soil moisture was different in different pair of MVI frequencies. As that figure shows MVI-CX, MVI-SL had the least sensitivity to soil moisture, especially MVI-CX (Shi et al. 2008; Zhao et al. 2011). Figure 1(down) is the absolute difference of MVI\( _n^1 \) in two roughnesses. As it clears from the figure, MVI-CX, MVI-SL and MVI-CL were the most in depended and MVI-CS had the most sensitivity to roughness.

![Figure 1](image1.png)

Figure 1. Absolut difference of MVI\( _n^1 \) for two soil moisture conditions (up), two roughness conditions (down) at 45-degree incident angle.

Although by calculating MVI\( _n^1 \) in different frequencies based on Matrix doubling model (to consider multi scattering effects), sensitivity to soil parameters were minimum (Figure 1) but still the MVI’s behavior compare to soil parameters weren’t ideal according to its definition. Yunging Li calculated MVI based on Matrix Doubling Model and tried to explain its sensitivity to soil moisture and VWC besides other vegetation indexes. She figured out has more stable and smooth trend compared to other microwave vegetation indexes in soil moistures influence but not corresponded completely to theoretical meaning.

The second method to drive MVI was based on the linear function of brightness temperature at two adjacent frequencies (Eq. 1). The slope and intercept of this linear function are respectively. Figure 2 is MVI\( _L^1 \) and MVI\( _H^1 \) in four pairs of frequencies. By increasing canopy height MVI\( _L^1 \) were increased and MVI\( _H^1 \) were decreased in all MVIs(Shi et al. 2008).

![Figure 2](image2.png)

Figure 2, MVI\( _L^1 \) (up) and MVI\( _H^1 \) (down) in four pairs of frequencies

In this study comparing MVI from two methods to optical depth and single scattering albedo has been done. MVI\( _L^1 \) and MVI\( _H^1 \) index in multi frequency (SL, CL, CS and CX) was compared to optical depth at vertical and horizontal polarization and table 3 is the correlation coefficient of comparing them at 45-degree incident angle. The most correlation between MVI\( _n^1 \) and optical depth in V and H polarization (second column) were for MVI-CX and MVI-SL, and they could work well at dense corn (up 2-meter). P-values for MVI-CS were more than 0.05 and the correlation of MVI-CL with optical depth in both polarizations were low. The coefficient of determination between optical depth and all four MVI\( _n^1 \) in both polarizations (third column) generally were more than 90 percent. The important point was higher R2 values in MVI\( _n^1 \) compare to MVI\( _H^1 \). Paying attention to canopy height shows MVI\( _n^1 \) can work well at dense corn (up 2-meter). P-values in all cases were less than 0.05.


