Electromagnetic Simulation of Volume Scattering for Monitoring the Height of Natural Grass using PolSAR Radar Vegetation Index

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Abstract. The present work proposes a new method for monitoring the natural grass height through the fully polarimetric synthetic aperture radar (PolSAR) data. For electromagnetic simulation, the grassland area is modelled as a cloud of random curly strips with high conductivity. The physical problem of electromagnetic scattering of plane waves of vertical and horizontal polarizations from ensemble of random structures representing the grasslands are solved using the electric field integral equation (EFIE) with the method of moments (MoM). The ensemble average of the fully polarimetric backscattering coefficients is calculated and the corresponding radar vegetation index (RVI) is estimated. It is shown that the ensemble average of the RVI is strongly correlated to the average height of the grass model. It is found that the relation between the grass height and the corresponding RVI can be approximated to either linear or quadratic dependence with 95% confidence level.

1. Introduction
Grasslands cover approximately one quarter of the world’s land surface. Grassland contributes to carbon storage and animal feed production. The maintenance of grasslands is an essential requirement for ecosystem balance, which, in turn, requires continuous monitoring of the grass height [1]. Earth remote sensing employing optical sensors have been efficiently used for grassland biomass estimation. However earth remote sensing with polarimetric synthetic aperture radar (PolSAR) has several advantages when compared to optical sensing due to the following reason: Unlike an optical sensor which requires the sun light, a SAR sensor provides its own source of illumination in the microwave range. Therefore, it is characterized by near all-weather/day-night imaging capabilities independent of atmospheric conditions. This guarantees continuous observation of the earth. Moreover, due to the forming of a synthetic aperture, which grows with an increasing distance, the resolution SAR image is nearly independent of the distance [2].

Previous studies have used optical remote sensing data for grassland biomass estimation, but only a few studies have focused on PolSAR remote sensing approaches for this purpose. The present work introduces a new method for monitoring the natural grass height through the PolSAR radar vegetation index (RVI). For this purpose the grassland areas are modelled as random clouds of curly strip-wires of high conductivity. Electromagnetic simulation using the method of moments (MoM) is applied to estimate the volume scattering from ensembles of grassland models with different grass heights. The electromagnetic simulation shows that the ensemble average of the RVI is strongly dependent on the
average height of the grass model. The relation between the grass height and the corresponding RVI can be approximated to either linear or quadratic dependence with very high confidence level.

2. Grassland modelling and electromagnetic simulation of PolSAR imaging

For estimation of backscatter coefficients during PolSAR imaging of vegetation areas through electromagnetic simulation, a cloud of randomly oriented very thin wire scatterers have been used in literature to model grasslands and forest canopies [3]. In this section the geometric model used in the present work for representing the grasslands and the applied electromagnetic simulation technique are briefly described.

2.1. Modelling of natural grassland as cloud of conductive random curly strips

Three common types of natural grass are shown in Figure 1. The branches constituting the grass cloud are not usually straight. Therefore, instead of using randomly oriented thin straight wires for electromagnetic simulation of volume scattering from vegetation, the present work proposes a random curly strip model for a single branch of the grass cloud. Since vertical orientation of a branch is rather dominant for most of the grassland types, the angle between the branch and the gravity direction should have Gaussian probability distribution function. Assuming no wind conditions, the mean value of this angle is zero whereas its variance is arbitrary and depends on the specific grassland type.

![Figure 1: Three types of grasslands that can be modeled as clouds of random curly strips](image)

For obtaining the backscatter coefficients, it is required to deduce the current flowing on the strip surface due to a plane wave incident on the strip. As shown in Figure 2, the surface is divided into a number of triangular patches, each has three edges; an edge which belongs to only one triangular patch is called a boundary edge. Such an edge exists only on the rim of the surface and hence, it has no electric current component flowing normal to it. An edge which belongs to two adjacent triangular patches is a non-boundary edge. The current flowing on the conducting surface is expressed as a summation of vector basis functions (defined only at the non-boundary edges) with unknown amplitudes. The most suitable basis function is the Rao-Wilton-Glisson basis function [4]. Figure 3 provides a brief description of such a basis function and the current distribution on the strip surface. Once the EFIE is formed it can be solved using the MoM to get the unknown current distribution on the strip surface. Consequently, the backscattered far field can be evaluated giving rise to the coefficients $S_{hh}$, $S_{hv}$, $S_{vh}$ and $S_{vv}$.
Surface current: \( \mathbf{J} = \sum_{n=1}^{N} I_n \mathbf{f}_n \)

\( I_n \) is the magnitude of the current crossing the edge \( L_n \).

Basis function: \( \mathbf{f}_n = \begin{cases} \frac{l_n}{2S_n^+} \mathbf{p}_{n+}, & \mathbf{r} \in P_{n+} \\ \frac{l_n}{2S_n^-} \mathbf{p}_{n-}, & \mathbf{r} \in P_{n-} \\ 0, & \text{otherwise} \end{cases} \)

\( \mathbf{p}_{n+} = \pm (\mathbf{r}_{n+} - \mathbf{r}_f), \)

\( S_n^\pm \) is the area of \( P_{n^\pm} \)

2.2 Electromagnetic simulations of POLSAR imaging and estimation of radar vegetation index

A grassland model can be generated as a cloud of random curly strips each of which has a location defined by the randomly distributed variables \((x_o, y_o, z_o)\) with their mean values and variances arbitrarily determined according to the horizontal density of the natural grass. Both the parameters of the geometric model of each strip and the statistical parameters that control the distribution of the strips within the random cloud should be set to match the type of grass. Figure 4 (a) shows a random curly strip-wire which can be an element of a random cloud. Figure 4 (b) shows a cloud of such random curly strips to simulate natural grass. A single strip or a cloud of strips can be subjected to incident plane wave of specific polarization to simulate the PolSAR operation during land imaging. The operation of land imaging through monostatic side-looking PolSAR can be simulated as a spaceborne (satellite) antenna moving in the azimuth direction at altitude \( H \) as shown in Figure 4(c). This antenna continuously transmits electromagnetic pulses at a specific rate. Each pulse can be considered as a pulsed plane wave incident on the ground at an angle \( \theta_i \) with the satellite nadir. The ground range direction is parallel to the ground surface and normal to the azimuth direction. As described in Section 2.1, an EFIE is formulated and then solved by the MoM for the assessment of the backscatter coefficients \( S_{hh}, S_{hv}, S_{vh} \) and \( S_{vv} \) by simulation of two cases: (i) the incident plane wave is horizontally polarized \( (E^i_v = 0) \) and (ii) the incident plane wave is vertically polarized \( (E^i_h = 0) \).

2.2.1. Estimation of backscattering coefficients and covariance matrix

As described above, the PolSAR operation, Figure 4(c), is simulated to obtain the co-polarized and cross-polarized backscattering coefficients \( S_{hh}, S_{hv}, S_{vh} \) and \( S_{vv} \) defined as,

\[
S_{hh} = \frac{E^r_h}{E^i_h} \big|_{E^i_v=0}, \quad S_{hv} = \frac{E^r_v}{E^i_h} \big|_{E^i_v=0}, \quad S_{vh} = \frac{E^r_v}{E^i_v} \big|_{E^i_h=0}, \quad S_{vv} = \frac{E^r_v}{E^i_v} \big|_{E^i_h=0}
\]

where the superscripts \( i \) and \( r \) denotes incident and received simultaneously.

The covariance matrix can be assessed as follows, where the operator \( \langle \rangle \) denotes the ensemble average, while the superscript * denotes complex conjugate.
\[
\langle [C] \rangle = \begin{bmatrix}
\sigma_{hh}^2 & \sigma_{hh,hv} & \sigma_{hh,vv} \\
\sigma_{hv,hh} & \sigma_{hv}^2 & \sigma_{hv,vv} \\
\sigma_{vv,hh} & \sigma_{vv,hv} & \sigma_{vv}^2
\end{bmatrix} = \begin{bmatrix}
\langle |S_{hh}|^2 \rangle & \frac{1}{2}\langle S_{hh}S_{hv}^* \rangle & \frac{1}{2}\langle S_{hv}S_{hh}^* \rangle \\
\frac{1}{2}\langle S_{hv}S_{hh}^* \rangle & \langle |S_{hv}|^2 \rangle & \frac{1}{2}\langle S_{hv}S_{vv}^* \rangle \\
\frac{1}{2}\langle S_{hv}S_{hh}^* \rangle & \frac{1}{2}\langle S_{hv}S_{vv}^* \rangle & \langle |S_{vv}|^2 \rangle
\end{bmatrix}
\] (2)

\[4\]

(a) Single random curly strip

(b) Cloud of random curly strips

(c) Operation of grassland imaging using PolSAR system

**Figure 4:** Assessment of backscatter coefficients for land imaging PolSAR system through electromagnetic simulation of grassland model subjected to incident plane waves.

2.2.2. Estimation of the RVI

The normalized difference vegetation index (NDVI) and the radar vegetation index (RVI) are used to monitor vegetation growth. The former is used by land-imaging systems using optical sensors whereas the latter is used by spaceborne PolSAR systems for earth remote sensing. In recent literature [5], the RVI has been introduced as an alternative to the commonly used NDVI for the purpose of vegetation monitoring. The RVI is superior to the NDVI as it is independent of the day time and has low sensitivity to environmental condition effects. The RVI has been proposed for monitoring the level of vegetation growth. An increase in the height of grass creates more volume scattering. The RVI is sensitive to the biomass, vegetation water content and generally ranges between 0 and 1, where it is near zero for a smooth bare surface and increases as crop grows (up to a point in the growth cycle). The RVI can be considered as a measure of randomness of back scattering and can be expressed as:

\[
RVI = \frac{8\sigma_{hv}}{\sigma_{hh} + \sigma_{vv} + 2\sigma_{hv}}
\] (3)

3. Results and discussions

It should be noted that the results presented in the present section are obtained through electromagnetic simulation for a PolSAR operating in the L-band at a frequency of 1.27 GHz.
3.1. Scattering coefficients of grass models using random volumes of curly strip-wires

Geometric models for grassland areas each of dimensions 1m × 1m are generated, as described in Section 2.1, for grass heights of 20, 40, 60, 80, and 100 cm. An ensemble of 10 samples of random curly clouds for each of the indicated heights is created. The electromagnetic simulation is performed for each of the 50 samples of grassland models, as described in Section 2.2. The backscattering coefficients $S_{hh}$, $S_{vh}$, $S_{hv}$, and $S_{vv}$ are evaluated for different values of the aspect angle $\theta_A$, which is the angle between the direction of incidence of the plane wave and the mean direction of orientation of the strips of each grassland model. The variation of the scattering coefficients with the grass height is presented in Figures 5(a) through 5(d), where it is clear that $S_{vh} = S_{hv}$ due to reciprocity of the monostatic radar cross section. The averaged values of the scattering coefficients, for a SAR look angle of 40°, are plotted versus the grass height as shown in Figure 5(e). The corresponding covariance matrix is calculated and, hence, the RVI is plotted against the grass height as presented in Figure 5(f) with some fitted relations.

Figure 5: Variation of the backscatter coefficients with the grass height for different values of the aspect angle ($\theta_A$) and the corresponding Gaussian weighted average of the RVI

3.2. Estimated relation between the RVI and the grass height

The ensemble averaged RVI, for a SAR look angle of 40°, is plotted in Figure 5(f) against the grass height. Curve fitting is used to get simple relation from which the grass height can be estimated using the measured RVI. Both of the following linear and quadratic relations can be used to monitor the grass height using the RVI with confidence level not less than 95%.

$$L_g = 99.93 \text{ RVI} - 1.347, \quad 20 \text{ cm} \leq L_g \leq 100 \text{ cm} \quad (4-a)$$

$$L_g = 113.8 \text{ RVI}^2 - 24.26 \text{ RVI} - 26.15, \quad 20 \text{ cm} \leq L_g \leq 100 \text{ cm} \quad (4-b)$$

3.3. Recovery of grass height from PolSAR images of grassland

For more demonstration of the applicability of the method proposed in the present work to monitor the grass height using the RVI measured by PolSAR systems, a model of inhomogeneous square (100 m × 100 m) grassland area composed of four quarters of different average grass heights (20, 40, 60, 80 cm) is constructed using clouds of curly strips as shown in Figure 6(a). A four-channel PolSAR image with resolution of 1m × 1m is constructed with the aid of the results obtained in Section 3.1 through EM simulation as described in Section 2.2. The corresponding image of the RVI is
constructed using (3) and is visualized using the color map presented in Figure 6(b). A comparison between Figures 6(a) and 6(b) shows a strong correlation between the grass height and the RVI value for each pixel. It should be noticed that grass height corresponding to each pixel value of the RVI can be obtained using (4-a) or (4-b). Figures 6(c) shows a plot for the grassland heights estimated using the quadratic relation given by (4-b). Comparing Figure 6(c) to 6(a), it becomes clear that the estimated grass heights are almost identical to the original heights at all the positions within the modelled grassland area. Figure 6(d) shows a plot for the percentage error of the estimated grass height at each pixel of the image. It is clear that the errors are very low and can be negligible. The percentage error in the grass height averaged over the image pixels is about 0.7%. Such low percentage error in the estimated grass height reflects the accuracy and efficiency of the proposed method to estimate the grass height using the RVI data measured by a PolSAR system.

Figure 6: Monitoring grass height using RVI obtained by simulation of land imaging PolSAR

4. Conclusion
A method for monitoring the natural grass height through the RVI data collected by PolSAR systems is proposed. This method is validated through electromagnetic simulation. The grassland area is modelled as a cloud of highly conductive random curly strips. The electromagnetic scattering of plane waves form random structures representing the grasslands are solved using the EFIE with the MoM. The ensemble averages of the backscattering coefficients $S_{hh}$, $S_{vh}$, $S_{hv}$, and $S_{vv}$ are calculated and the corresponding RVI is estimated and shown to be strongly correlated to the average height of the grass model. It is found that the relation between the grass height and the corresponding RVI can be fitted to linear or quadratic dependence with 95% confidence level. The percentage error in the estimated grass
height averaged over the image pixels is shown to be very small, which reflects the accuracy and efficiency of the proposed method to estimate the grass height using the RVI data measured by a PolSAR system.

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