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Modelling radar backscatter from crops during the growth cycle

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Abstract

A radiative transfer model to study the effects of plant shape and dimension on the backscattering from a vegetation layer during the plant growth has been implemented. The model represents vegetation as an ensemble of randomly oriented disks and almost vertical cylinders on a rough surface. The model was used to simulate the growth cycle of wheat and sunflower by using bio-physical data collected during the intensive campaigns on the agricultural test site of RESEDA project as inputs. A comparison with backscattering data obtained from satellite SARs (ERS and Radarsat) and by means of the French airborne Scatterometer has shown that model and experimental results are in reasonable agreement.

1. Introduction

Experimental research has demonstrated that the microwave backscattering coefficient \( \sigma' \) is sensitive to crop biomass, and is affected by the shape and dimensions of plant constituents (leaves and stems) [Wegmuller et al. 1994, Baronti et al. 1995, Ferrazzoli et al. 1997]. At the same time, several models, mostly based on the radiative transfer theory with various approximations [Tsang et al., 1985; Karam and Fung 1988; Ulaby et al. 1990; Touré et al. 1994], have been developed in order to simulate backscattering from canopy-covered soils. In these models, a vegetation layer has usually been represented as an ensemble of cylinders and disks on a homogeneous half-space with a rough interface. The scattering amplitude and the extinction cross section of the scatterers have been calculated by using different approximations, depending on the relative dimensions of the scatterer and on the electromagnetic wavenumber. The disc shape effects have been studied by Karam and Fung [1989], who found that there may be a significant difference between the backscattering from the two types of leaves.

In 1996-97 intensive remote sensing and ground measurement campaigns were carried out on the agricultural fields of the test site Les Alpilles, France, within the framework of the EC Project ReSeDA (Assimilation of
multi-sensor & multitemporal Remote Sensing Data to monitor vegetation and soil functioning). The main objective of the ReSeDA project was to monitor soil and vegetation processes by means of multi-sensor and multitemporal observations. In this paper, simulations of the backscattering coefficient, obtained with a radiative transfer model, were compared with experimental data collected by means of the ERASME airborne scatterometer at C- and X- bands and the ERS-SAR satellite.

2. The model

The model developed for interpreting experimental data is based on the radiative transfer theory and represents vegetation as an ensemble of randomly oriented disks and almost vertical cylinders on a rough surface. It includes the following terms: direct backscattering from soil, direct backscattering from the vegetation layer (leaves and stems), soil-vegetation and vegetation-soil interaction (double scattering), soil-vegetation-soil interaction. The backscattering coefficients $\sigma^{pp}$ and $\sigma^{pq}$ for co- and cross-polarized terms (p,q = V, H and VH = HV) can be expressed as follows [Tsang et al. 1981]:

$$
\sigma^{pp}_{pp} = \sigma_{pp} e^{-2\kappa_{pp} d \sec \theta} + \frac{P_{ppp}}{2\kappa_{pp}} (1 - e^{-2\kappa_{pp} d \sec \theta}) \\
+ 2 r_{pp} P_{ppm} \ d \sec \theta \ e^{-2\kappa_{pp} d \sec \theta} + \\
\frac{r_{pp}^2 P_{ppp} e^{-2\kappa_{pp} d \sec \theta}}{2\kappa_{pp}} (1 - e^{-2\kappa_{pp} d \sec \theta})
$$
\[ \sigma^\theta_{pq} = \sigma_{pq} e^{-(K_{ep} + Keq)d \sec \theta} + \frac{P_{pq}}{K_{ep} + Keq} (1 - e^{-(K_{ep} + Keq)d \sec \theta}) \]

\[ + \frac{r_{sp} P_{pqm}}{-K_{ep} + Keq} e^{-K_{ep}d \sec \theta} (e^{-K_{ep}d \sec \theta} - e^{-K_{ep}d \sec \theta}) \]

\[ + \frac{r_{sq} P_{pqm}}{-K_{ep} + Keq} e^{-K_{ep}d \sec \theta} (e^{-K_{ep}d \sec \theta} - e^{-K_{ep}d \sec \theta}) \]

\[ + \frac{r_{sp} r_{sq} P_{pqm}}{K_{ep} + Keq} e^{-(K_{ep} + Keq)d \sec \theta} (1 - e^{-(K_{ep} + Keq)d \sec \theta}) \]

where:

\[ \sigma_{pq}, \sigma_{spq} = \text{bare soil backscattering at co- and cross-polarization} \]

\[ r_{sp} = \text{soil reflectivity} \]

\[ k_{ep} = \text{average value of the extinction coefficient (m}^{-1})\text{of disks and cylinders weighed according to the densities of the two kinds of scatterers} \]

\[ d = \text{height of the vegetation layer (m)} \]

\[ P_{pq}, P_{pqm} = \text{average values of scattering matrix elements of disks and cylinders for pq polarization, within the reference frame, computed for direct and double scattering, respectively, and weighed according to the densities of the two kinds of scatterers.} \]

The scattering amplitudes and the extinction cross sections of circular and elliptic dielectric disks were computed by using the model proposed by Karam [1998], which establishes a link between the quasi-static and physical optics approximations. It was demonstrated that this approach gives similar results to those of the quasi-static formulation for a very thin disk, and to those of the physical optics approximation for a disk with a radius much larger than its thickness. Since the crop stems considered were much longer and much thinner than the electromagnetic wavelength, scattering from a finite length cylinder was computed by using the infinite
cylinder approximation, i.e. by assuming that the cylinder responds to an incoming wave as though it were infinite in length [Tsang, et al. 1992]. For both types of scatterers, the extinction cross sections were obtained from the scattering amplitude tensor elements by applying the forward scattering theorem [ Karam, 1998]). The scattering amplitudes used in (1) were transformed from local to reference frame by using the relationships given in Karam and Fung, (1989).

Backscattering from soil at HH and VV polarizations was computed by using the single scattering Integral Equation Model for low to moderate roughness [Fung, 1994], while the cross-polarized component was estimated by using the empirical model by Oh et al. [1992]. Surface scattering to account for interaction soil-vegetation was modeled by modifying the Fresnel reflectivity with an exponential term related to surface height standard deviation [Ulaby et al., 1982]. The model was first validated by using a set of data taken from the literature [Chauhan et al., 1994].

3. Comparison of model simulations with experimental data

3.1. Simulation of wheat life cycle

Simulation of the scatterometer data set requires a large number of biophysical data as model inputs. Thus, the first step of this study was to chose fields in which there was an availability of vegetation and remote sensing data for a sufficient period of time. Two fields were chosen for the wheat crop type, whereas only one field had been monitored with the necessary frequency and accuracy for sunflower. Since only a few scatterometer data were available for this field, model analysis for this crop was carried out using satellite data.

Temporal variation in the vegetation parameters and soil moisture for the wheat crop are given in Table I. Soil roughness was assumed to be unaltered during the vegetation growth, with height standard deviation = 0.8 cm, correlation length = 7 cm and exponential autocorrelation function.

Table I: Model Parameters of wheat field ( plant density = 340 p/m\(^2\) )
An example of the comparison between measured and simulated backscattering coefficients at C- and X-band, VV and HH polarizations, 20 and 40 degrees of incidence angle, versus day of the year is given in Figs 1 and 2, which represent the variation from December 01, 1996 to June 19, 1997 for the two wheat fields. We observe that theoretical and experimental data are in reasonable agreement, especially at X-band. The model approximates pretty well the average values of experimental data, and follows the variation of measured backscattering coefficient during the season. Indeed, the simulated backscattering decreases during the growth stage of crop and increases in the senescence stage when the vegetation moisture decreases. The highest discrepancy is at C-band, especially at low incidence angle, VV pol., where the contribution from soil to total backscattering is more important and experimental data are affected by the periodic structure of furrows, which is not taken into account by the model.

### 3.2. The backscattering as a function of leaf area index

As already said, the relationship between backscattering coefficient and vegetation biomass, represented by leaf area index (LAI) depends on the shape and dimension of plant constituents. Thus, in order to investigate this topic we considered two types of crops with very different geometrical characteristics: wheat, characterized by thin stems and long elliptical leaves, and sunflower, characterized by relatively large stems and almost circular leaves.

The analysis of the experimental backscattering $\sigma^\circ$ represented as a function of LAI, showed a significant
amount of dispersion, (e.g., for the same value of LAI, σ varied of about ± 3 dB). Thus, to model the backscattering coefficient of wheat and sunflower versus LAI, for each crop type we selected vegetation parameters of a field with a backscattering coefficient as close as possible to the average trend of all the data. The vegetation parameters as a function of LAI are given in Table II and III.

Table II- Model Parameters of the Sunflower Field (plant density = 6 p/m²)

<table>
<thead>
<tr>
<th>LAI</th>
<th>Crop Height cm</th>
<th>Stem Radius cm</th>
<th>Stem Bmin-Bmax Degr</th>
<th>Stem Moisture %</th>
<th>Leaf Radius cm</th>
<th>Leaf Thickness cm</th>
<th>Leaf Bmin-Bmax Degr</th>
<th>Leaf Moisture %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.26</td>
<td>24</td>
<td>0.4</td>
<td>3-10</td>
<td>40</td>
<td>5</td>
<td>0.02</td>
<td>70-90</td>
<td>40</td>
</tr>
<tr>
<td>0.8</td>
<td>50</td>
<td>0.5</td>
<td>3-10</td>
<td>50</td>
<td>6</td>
<td>0.02</td>
<td>70-90</td>
<td>60</td>
</tr>
<tr>
<td>1.3</td>
<td>90</td>
<td>0.6</td>
<td>3-10</td>
<td>80</td>
<td>7.5</td>
<td>0.02</td>
<td>60-80</td>
<td>80</td>
</tr>
<tr>
<td>2.1</td>
<td>100</td>
<td>0.6</td>
<td>3-10</td>
<td>70</td>
<td>10</td>
<td>0.025</td>
<td>60-80</td>
<td>80</td>
</tr>
<tr>
<td>2.7</td>
<td>110</td>
<td>0.6</td>
<td>3-10</td>
<td>70</td>
<td>11</td>
<td>0.02</td>
<td>60-80</td>
<td>70</td>
</tr>
</tbody>
</table>

Table III- Model Parameters of the Wheat Field (plant density = 340 p/m²)

<table>
<thead>
<tr>
<th>LAI</th>
<th>Crop Height cm</th>
<th>Stem Radius cm</th>
<th>Stem Bmin-Bmax Degr</th>
<th>Stem Moisture %</th>
<th>Leaf Major axis/2 Cm</th>
<th>Leaf Minor axis/2 Cm</th>
<th>Leaf Thickness cm</th>
<th>Leaf Bmin-Bmax Degr</th>
<th>Leaf Moisture %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>8</td>
<td>0.2</td>
<td>3-10</td>
<td>85</td>
<td>4</td>
<td>0.2</td>
<td>0.01</td>
<td>40-70</td>
<td>85</td>
</tr>
<tr>
<td>0.8</td>
<td>20</td>
<td>0.2</td>
<td>3-10</td>
<td>75</td>
<td>5</td>
<td>0.4</td>
<td>0.01</td>
<td>40-70</td>
<td>80</td>
</tr>
<tr>
<td>1.5</td>
<td>50</td>
<td>0.18</td>
<td>3-10</td>
<td>75</td>
<td>6</td>
<td>0.4</td>
<td>0.015</td>
<td>20-50</td>
<td>75</td>
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<tr>
<td>1.8</td>
<td>60</td>
<td>0.18</td>
<td>5-10</td>
<td>70</td>
<td>6</td>
<td>0.5</td>
<td>0.015</td>
<td>20-50</td>
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<td>0.5</td>
<td>0.015</td>
<td>20-50</td>
<td>70</td>
</tr>
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</table>

Figs. 3 and 4 present a comparison between data and model for a single field (top) and for the whole data data set (bottom). We can see that the model fits data for a single field fairly well, but it is also representative of the complete data set.
4. Conclusions

It was found that radiative transfer model developed in this study was able to reproduce with reasonable accuracy the experimental data collected on wheat and sunflower crops at two frequencies, two polarizations and two incidence angles. The two crops, which have different geometrical characteristics have shown completely different behaviour of backscattering coefficient as a function of LAI. Indeed, as vegetation growth, backscattering increases in the case of sunflower and decreases in the case of wheat. This result confirms the sensitivity of backscattering to the dimension and shape of plant constituents, and suggests the possibility of discriminating the two crops categories.

ACKNOWLEDGEMENTS

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References


Karam M. A., “Bridging the quasi static and the physical optics approximations: an elliptic disk case,”


Fig. 1 - Simulated (— HH, - - - VV) and experimental backscattering coefficient at C-band, $\theta = 20^\circ$ (top) and $40^\circ$ (bottom), of wheat crop as a function of day of the year.
Fig. 2 - Simulated (— HH, - - - VV) and experimental backscattering coefficient, at X band, $\theta = 20^\circ$ (top) and $40^\circ$ (bottom), of wheat crop as a function of day of the year.
Fig. 3 - Simulated and measured backscattering coefficient versus Leaf Area Index of wheat for a single field (top) and all fields (bottom)
Fig. 4 - Simulated and measured backscattering coefficient versus Leaf Area Index of Sunflower for a single field (top) and all fields (bottom).