*Progress In Electromagnetics Research, Vol. 114, 33–49, 2011*

# ELECTROMAGNETIC SCATTERING FROM A CORN CANOPY AT L AND C BANDS

**Y. Du and W.-Z. Yan**

Department of Information Science and Electronic Engineering
Zhejiang University, Hangzhou, Zhejiang 310027, China

**J. C. Shi**

Institute of Remote Sensing Applications
Chinese Academy of Sciences, Beijing 100101, China

**Z.-Y. Li and E.-X. Chen**

Institute of Forest Resources Information Techniques
Chinese Academy of Forestry, Beijing 100091, China

**Abstract**—Extraction of vegetation water content and soil moisture from microwave observations requires development of a high fidelity scattering model. A number of factors associated with the vegetation canopy and the underlying bare soil should be taken into account. In this paper, we propose an electromagnetic scattering model† for a corn canopy which includes coherent effect due to the corn structure and takes advantage of recently advanced scattering models for dielectric cylinder of finite length, for thin dielectric disk with elliptical cross section, and for rough surface. The model results are validated at both L and C bands. At C band we acquired some RADARSAT-2 data of several test fields of corn canopy in Jiangsu Province, China, in 2009, and carried out simultaneous measurement campaigns to collect the *in situ* ground truth. A comparison is made between theory and RADARSAT-2 data. At L band because high quality AIRSAR measurement data are available along with detailed ground truth in the literature, a comparison is also made between theory and AIRSAR data.

*Received 21 November 2010, Accepted 17 January 2011, Scheduled 17 February 2011*
Corresponding author: Yang Du (zjuydu03@zju.edu.cn).

† The material in this paper was presented in part at the 2010 IEEE International Geoscience and Remote Sensing Symposium (IGARSS10), Honolulu, Hawaii, USA, July 25–30, 2010.

## 1. INTRODUCTION

The ability to retrieve and monitor soil moisture and vegetation water content (VWC) is of great importance (e.g., [1–3]). Soil moisture is often the limiting factor in transpiration of plants and evaporation from soil surface, which in turn has a significant impact on the energy cycle. Soil moisture is also a key determinant of the global carbon cycle. Detection of VWC is useful to monitor vegetation stress and important for irrigation management and yield forecasting. Microwave remote sensing has demonstrated itself a powerful tool for monitoring of soil moisture and VWC. Yet accurate retrieval of such information from microwave observations presents a big challenge, which calls for the development of high fidelity scattering models.

In the literature, a "discrete scatter" approach was usually deployed, which attempted to determine first the scattering behavior of the individual constituent of the canopy, then that of canopy as a whole by summing up either incoherently [4–7] or coherently [8–12].

To simplify the problem, constituents of the canopy are modeled as canonical geometrical objects. For corn canopy, the stalks are modeled as dielectric circular cylinders with finite length, and the leaves are represented as thin dielectric disks with elliptic cross section. Since scattering from each of the canonical object serves as the base for further "assembling", it is expected to be accurately determined. However, mush is still desired in this regard.

For a dielectric cylinder of finite length, in studying its scattering behavior the generalized Rayleigh-Gans approximation (GRGA) [13] is usually applied, which approximates the induced current in a finite cylinder by assuming infinite length. This method is valid for a needle shaped scatterer with radius much smaller than the wavelength. Yet caution must be taken even at L band when EM scattering from the stalk of a corn plant is to be evaluated using GRGA. As an example let us consider a cylinder which is 62.5 cm in length and 2.5 cm in diameter, with relative dielectric constant of $29.1 + i8.9$. The data set is taken from [4] and is typical of corn stalk. Thus the length to radius ratio is 50, and the length is 2.7 wavelengths at L band of 1.3 GHz. This kind of dimension indicates that it is inappropriate to use GRGA to analyze EM scattering from such cylinder. Fig. 1 shows that it is indeed the case, where magnitudes of both HH and VV bistatic scattering amplitude at L band are obtained using the method of moment (MoM) and GRGA, respectively, where the incidence angle is $130^\circ$, and the scattering angles are in the forward incidence plane ranging from $0^\circ$ to $180^\circ$. We observe that while HH results of GRGA capture the typical scattering behaviors, VV results are appreciably different from that

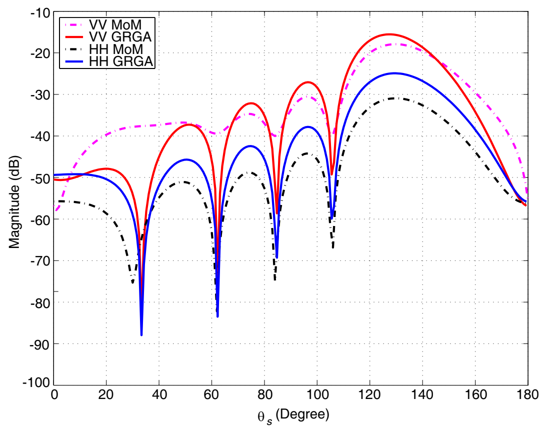


**Figure 1.** Comparison of magnitudes of both HH and VV bistatic scattering functions at L band between GRGA and MoM. Incidence angle is 130°.

of MoM. Such discrepancy partly helps explain why a coherent model employing GRGA for cylinder scattering performs better at HH than VV. Moreover, GRGA fails to satisfy the reciprocity theorem [8].

One alternative approach is the $T$-matrix method which is based on the extended boundary condition method [1]. Yet a straightforward application of the $T$-matrix method for scattering from corn stalks will not work, since it has been well known that for scatterers with extreme geometry, for instance, dielectric cylinders with large aspect ratios, this approach may fail. To deal with such difficulty, recently we proposed a method based on an extension of the $T$-matrix approach, where a long cylinder is hypothetically divided into a cluster of identical sub-cylinders, for each the $T$ matrix can be numerically stably calculated. Special care was paid to fulfill the boundary conditions at the hypothetic surface of any two neighboring sub-cylinders. The resultant coupled equations are different from that of multi-scatterer theory. The model results were in good agreement with experiment data available in the literature [14] and MoM results [15]. Its validity region has been characterized by extensive comparison with MoM results.

In the evaluation of scattering amplitude of leaves, the GRGA method is usually used. One condition for GRGA to be applicable is that $kh(\sqrt{\varepsilon_r} - 1) \ll 1$, where $k$ is the host medium wave number, $h$ is the thickness of the leave, and $\varepsilon_r$ is the leave relative dielectric constant. At C band, assuming some typical values such that $h$ is 0.3 mm, $\varepsilon_r = 29$, a quick calculation shows that the left side takes value of 0.14, which implies the condition is coarsely satisfied. However, caution must be taken here. At C band the wavelength is 5.6 cm, which is comparable to the length of minor axis of corn leaves, which presents an unfavorable condition in applying GRGA and thus appreciable error is expected in the predicted scattering amplitude.

When corn canopy is at its early stage of growth, or when the incidence angle is not large, contribution from the underlying ground is appreciable and thus its accurate prediction is important. Yet this roughness effect has not been adequately addressed in canopy scattering models, where what is typically applied is conventional analytical method such as Kirchhoff approximation (KA), or the small perturbation method (SPM) [1], or the more advanced yet still improvement-needed integral equation method (IEM) [16]. In this study, we choose to apply a more rigorous treatment of the rough surface contribution using the recently advanced EAIEM model by the authors [17].

With the advancement of several scattering models of dielectric cylinder and disks and of rough surfaces, it is the aim of this paper to investigate if a coherent combination of these constituent models can improve predictive power of the resultant canopy scattering model. As such, the model results will be validated at both L and C bands.

## 2. MODEL

### 2.1. Main Scattering Mechanisms and General Considerations

There are five major scattering mechanisms for a corn canopy: 1) direct backscatter from the underlying rough surface; 2) direct backscatter from corn canopy; 3) single ground bounce: from scatterer to ground; 4) single ground bounce: from ground to scatterer; and 5) double ground bounce. These scattering mechanisms are illustrated in Fig. 2.

To evaluate the absorption and scattering effects caused by the canopy, the Foldy's approximation [1] is employed in this model, in accordance with the majority work in the literature (e.g., [8, 9]).

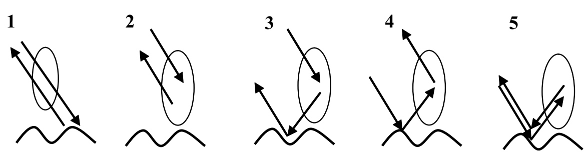


**Figure 2.** Major scattering mechanisms for a corn canopy.

To obtain scattering amplitude of a single corn plant, we sum the scattering amplitude of all the elements as

$$S_{pq} = S_{0pq} + \sum_{j=1}^{N_l} S_{jpq}^L + S_{pq}^F \qquad (1)$$

where the subscripts $p$ and $q$ are unit polarization vectors for the incident and scattered wave, respectively. The three terms in the right side of (1) represent contributions of the stalk, leaves, and maize (if any), respectively.

The backscattering coefficient is defined as:

$$\sigma_{pq} = \frac{4\pi}{A_0} \langle S_{pq}^t S_{pq}^{t*} \rangle \qquad (2)$$

where $A_0$ is the illuminated area, and the superscript $t$ refers to the total scattering amplitude that is the sum of that of single plant within the illuminated area.

## 2.2. Scattering from Stalks

The stalks are modeled as dielectric cylinders of finite length. As seen from the Introduction Section, the GRGA method is not appropriate for determination of scattering amplitude of typical stalks at L band. Moreover, this method is not appropriate at C band either, since its predicted phase of the scattering amplitude can be appreciably different from that of MoM, as a comparison of Fig. 3 for GRGA and

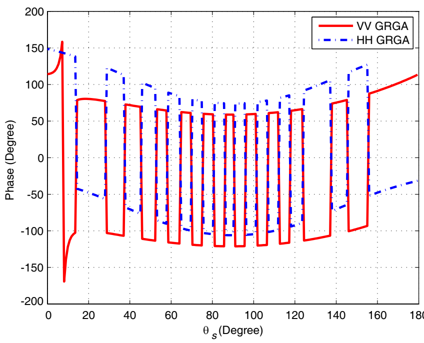


**Figure 3.** Phases of both HH and VV bistatic scattering functions at C band by GRGA. Incidence angle is 130°.

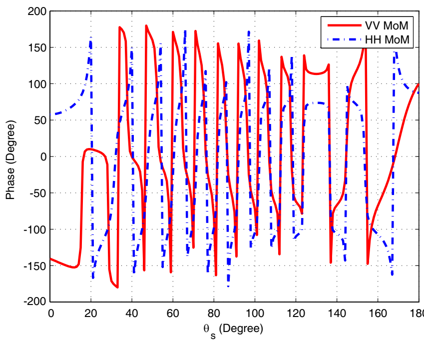


**Figure 4.** Phases of both HH and VV bistatic scattering functions at C band by MoM. Incidence angle is 130°.

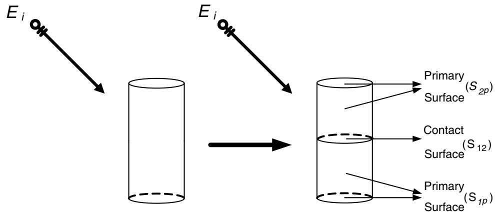


**Figure 5.** Division of a cylinder into two identical sub-cylinder.

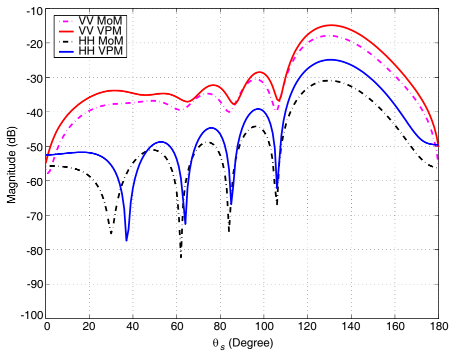


**Figure 6.** Comparison of magnitudes of both HH and VV bistatic scattering functions at L band between VPM and MoM. Incidence angle is 130°.

Fig. 4 for MoM clearly demonstrates, where the same cylinder as in the Introduction section is considered.

In our new approach for single cylinder scattering [14], a long cylinder is divided into a cluster of $N$ identical sub-cylinder by using $N-1$ hypothetic surfaces, for each the $T$ matrix can be calculated stably in the numerical sense. Fig. 5 provides an illustration of two sub-cylinder division. The boundary conditions at the hypothetic interface are treated carefully. A system of equations is set up for each sub-cylinder, and the overall system of equations is coupled and linear, thus can be solved by appropriate iterative method. For notational convenience, we shall denote this proposed method for cylinder scattering as VPM (virtual partition method). To demonstrate the high fidelity of the VPM method, it is applied to the scattering problem of the same cylinder as in the Introduction section. Fig. 6 shows the model results of the proposed VPM method and compares favorably with that of MoM.

Moreover, the VPM method is found to be applicable to dielectric cylinders of arbitrary length as long as the $T$ matrix is attainable for the elementary sub-cylinder. The applicable relative dielectric constant can go up to 70 (real part), which is normally the upper bound for corn stalks at C band. The radius of the cylinder can be as high as 5 wavelengths, a feature of the model that is expected to be useful for forest applications [15].

### 2.3. Scattering from Leaves

Leaves are modeled by thin dielectric disks of elliptical cross section. With typical thickness of 0.3 mm, which is significantly smaller than the wavelength at either L or C band, the assumption about "thin" leaves is valid. What differentiates the different analytical models for determination of the scattering amplitude of leaves is the specific treatment of the fields internal to the leaves when the dimension of the cross section is at varying relative magnitude to the wavelength. A seemingly encouraging alternative to GRGA is the method proposed by Koh and Sarabandi (K-S method) [18], where the fields internal to a leaf is more rigorously treated, and RGA is shown to be one form of its approximation. However, in applying this method there is still technical difficulty to be dealt with. This stems from the fact that determination of the far field involves an integral which contains the product of two Bessel functions as shown below.

$$\iint dk_x dk_y f(k_x,k_y) \frac{J_1\left(\sqrt{a^2\left(k_x-k_{ix}\right)^2+b^2\left(k_y-k_{iy}\right)^2}\right)}{\sqrt{a^2\left(k_x-k_{ix}\right)^2+b^2\left(k_y-k_{iy}\right)^2}} \cdot \frac{J_1\left(\sqrt{a^2\left(k_x-k_{sx}\right)^2+b^2\left(k_y-k_{sy}\right)^2}\right)}{\sqrt{a^2\left(k_x-k_{sx}\right)^2+b^2\left(k_y-k_{sy}\right)^2}} \tag{3}$$

where $a$ and $b$ are the major and minor axis respectively; $J_1(\cdot)$ is the Bessel function of the first order; $f(\cdot,\cdot)$ is an analytical function in its two arguments; $k_{ix}$ and $k_{iy}$ are the horizontal components of the propagation vector of the incidence wave; and $k_{sx}$ and $k_{sy}$ are of the scattered wave. In the forward scattering direction, propagation vectors of the incidence wave and scattered wave coincidence, and evaluation of the above integral presents no difficulty despite of the oscillating behavior of the Bessel function, because in essence one only needs to deal with the oscillation of one Bessel function. However, when the scattering is of bistatic nature, propagation vectors of the incidence wave and scattered wave no longer coincide, and the centers

**Figure 7.** Photo of corn canopy at the male tetrad stage in one test field.

of the oscillation of the two Bessel functions are separated. So far a numerical method that can evaluate this kind of integral reliably is still unavailable.

In this study, we propose a new approach that compromises GRGA and the K-S method. That is, in calculating the bistatic scattering amplitude from a leaf, the GRGA method is still used, however, the result is to be "corrected" by a correcting coefficient, which is determined using the K-S method from forward scattering.

Another issue in treating scattering from leaves arises from the fact that a considerable number of leaves is curved, as depicted in Fig. 7. There are approximate method for treating scattering from curved leaves in the literature, however, here the applicability of these methods is not quite clear since the curvatures show different features and readily go beyond the canonical assumptions of these methods. Moreover, quantification of the curvatures is not an easy task either. Hence curvature effect is not considered in this study, as is the case often found in the literature (e.g., [4]).

## 2.4. Scattering from Rough Surfaces

Scattering from rough surface is treated using the EAIEM model [17], which is a unifying model recently developed by us for electromagnetic scattering from a Gaussian rough surface with small to moderate heights. It is based on the integral equation formulation where the spectral representations of the Green's function and its gradient are in complete forms, a general approach similar to those used in the advanced integral equation model (AIEM) [19] and the integral equation model for second-order multiple scattering (IEM2M) [20]. Yet this new model can be regarded as an extension to these two models on two accounts: first it has made fewer and less restrictive assumptions in evaluating the complementary scattering coefficient for single scattering, and second it contains a more rigorous analysis by the inclusion of the error function related terms for the cross- and complementary scattering coefficients, which stems from the absolute phase term in the spectral representation of the Green's function.

## 3. MODEL RESULTS AND DISCUSSIONS

In this section, we present radar backscattering coefficients predicted by the proposed coherent scattering model at both L and C bands. At C band we acquired some RADARSAT-2 data of several test fields of corn canopy in Jiangsu Province, China, in 2009 on the dates of the 30th of July, 23rd of August, and 23rd of September, respectively. Simultaneous measurement campaigns to collect the *in situ* ground truth were carried out on the dates of the 28th of July, 22nd of August, and 17th of September, respectively. We shall present model results and comparison at the male tetrad stage (at around 30th of July) since comparison at other two dates shows similar behavior and is not illuminating. At L band because high quality AIRSAR measurement data are available along with detailed ground truth [4], hence a comparison is also made between theory and AIRSAR data. We shall start with L band.

The AIRSAR data were collected over several corn fields in Mahantango Creek watershed during the summer of 1990, as part of the Multisensor Aircraft Campaign, MACHYDRO [4]. The data collection was taken on four different days, namely, on the 10th, 13th, 15th, and 17th of July, 1990, when there was raining event in between. The corn data were calibrated and averaged using about 1200 pixels to come up with the backscattering coefficients.

Figure 8 shows comparison of our theoretical results of HH backscattering coefficients with measurements. Also compared are the model results of Chauhan et al. [4], where the distorted Born approximation was employed. Both theories show good agreements with measurements. What is surprising is the highly overlapped results of both theories.

We further compare VV results in Fig. 9. It is seen that our theory is closer to measurements than that of Chauhan et al. We also

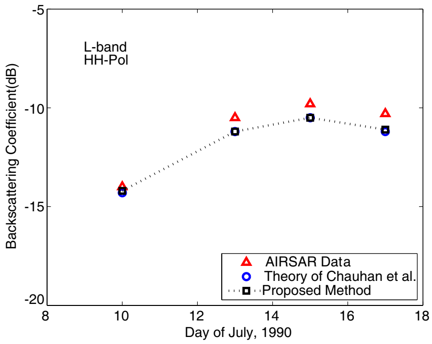


**Figure 8.** Comparison of HH backscattering coefficients between theories and measurements.

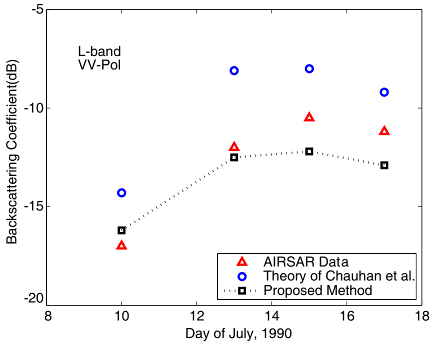


**Figure 9.** Comparison of VV backscattering coefficients between theories and measurements.

observe with interest that while the distorted Born theory uniformly overestimates the VV backscattering coefficients, our model shows opposite behavior by mostly underestimating results.

To study the radar behavior of corn canopy at C band, it is important to have detailed knowledge of the ground truth. In the *in situ* ground truth collection in Jiangsu Province, 16 sites were selected, and a $2\,\text{m} \times 2\,\text{m}$ square within each site was used for the detailed determination of plant parameters, which included length, radius, and gravimetrical water content of the stalks, length of major and minor axes, gravimetric water content of leaves, number of leaves per plant, and plant density. Average values of plant parameters for the corn canopy are shown in Table 1. Inclination angles were not measured directly, but were estimated from numerous photos taken during the ground truth measurement. The gravimetric water content of leaves can be determined from their wet and dry weights, and the dielectric constants can be determined using the Ulaby and El-Rayes model [21]. The same procedure is applied to stalks. As to the underlying ground, measurements of the gravimetric soil moisture and soil bulk density were made, from which the soil dielectric constant was determined [22]. The roughness was estimated from the readings of a grid board that was inserted in the ground. A *rms* height of 0.9 cm was estimated and used in the calculation. A correlation length of 9.4 cm was also estimated from the ground measurements. For each measurement, 80 height points were recorded along a profile, which may not be sufficient for an accurate estimation of the correlation length.

In the following theoretical calculation, the thickness of leaves is unavailable from the ground truth, so for the current study it is set

**Table 1.** Corn canopy parameters.

| | |
|---|---|
| **Canopy Parameters** | |
| Canopy height (cm) | 172.3 |
| Plant density ($m^{-3}$) | 6.15 |
| **Stalk Parameters** | |
| Length (cm) | 80.9 |
| Diameter (cm) | 2.1 |
| Density ($m^{-3}$) | 6.15 |
| Gravimetric water content (%) | 91.63 |
| **Leaf Parameters** | |
| Semi-major axis (cm) | 46.45 |
| Semi-minor axis (cm) | 4.4 |
| # per plant | 12.3 |
| Gravimetric water content (%) | 80.3 |
| **Soil** | |
| Soil volumetric moisture ($V/V\%$) | 29 |
| bulk density ($g/cm^3$) | 1.53 |
| rms height (cm) | 0.9 |
| correlation length (cm) | 9.4 |

to 0.35 mm similar to that in [4]. The bole positions of leaves are assumed to follow uniform distribution over a range along the main stalk. Its azimuthal angle is assumed uniformly distributed in $[0, 2\pi]$, whereas there is uncertainty in determining the distribution of the inclination angle. This stems from the curvature of the leaves. For instance, a curved leaf could be approximated by a chain of consecutive planar sections, each with its own inclination angle. In this case, a more rigorous treatment would use portion of measured length of corn leaves instead of full length leaves when applying to the model. However, this treatment means different shape of the leaves is needed as opposed to an elliptical one, along with a wide range of sizes, which makes the problem much more complicated. A compromise can be made in this regard, where the full length leaves are still used in the calculation, yet to weigh the count of the inclination angle for the portion in characterizing its distribution. The problem is that how to weigh it in the overall distribution does not permit a unique answer. Such uncertainty has significant impact on model results as we shall demonstrate shortly.

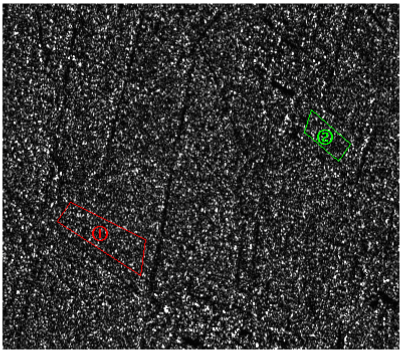


**Figure 10.** RADARSAT-2 HH data of corn canopy at the male tetrad stage.

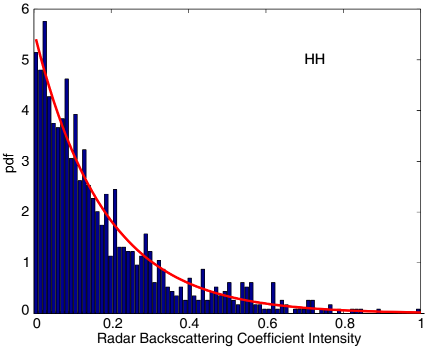


**Figure 11.** Histogram of the RADARSAT-2 HH intensity of corn canopy. Blue bar: histogram of observations; Red line: simulated exponential distribution.

We present here RADARSAT-2 data for corn canopy at the male tetrad stage. The data are fine quad polarization C band single look complex data, with central latitude of 33.77 degrees, longitude of 117.79 degrees, and incident angle of 39.2 degrees at the near range and 40.7 degrees at the far range. Fig. 10 shows the HH data, where two fields #1 and #2 are chosen as marked within which some *in situ* ground truth was collected. Corn field #1 contains about 2600 pixels and #2 about 1400 pixels. Histogram of the HH backscattering intensity of field #1 is shown in Fig. 11, where the intensity is presented in natural scale. We observe that it closely follows an exponential distribution (simulated and depicted in red), with an estimated parameter of 0.1793, which is within the 95% confidence interval of [0.1687, 0.1908]. This result is expected, since corn canopy can be approximated by a homogeneous medium. The backscattering coefficients are approximated by the average values for the corn fields. The backscattering coefficients for the two regions are $-7.13$ dB and $-7.47$ dB respectively for HH, and are $-8.14$ dB and $-8.15$ dB respectively for VV.

Figure 12 shows the theoretical results of HH and VV backscattering coefficients as functions of incidence angle. The frequency is set to 5.405 GHz. At the incidence angle of RADARSAT-2 which is 40 degrees, the theoretical prediction is $-7.01$ dB for HH and $-5.56$ dB for VV. It is seen that theory is in good agreement with RADARSAT 2 data for HH, yet there is around 2.5 dB error in VV. Also VV is lower than HH in the data yet theory shows the opposite.

There might be a number of factors contributing to this discrepancy, including: 1) The attenuation for VV may be underestimated in the Foldy approximation where multiple scattering is not considered; 2) Curvature effect of leaves is not included; 3) The stalks are assumed to be vertical, yet in reality their inclination angles are randomly distributed, although within a small range; and 4) There is uncertainty in the inclination angle distribution of the leaves. The last point can be illustrated as follows. If we change the inclination angle distribution, which is assumed the same as in [4] in Fig. 12, to that of Gaussian distribution, with mean of 28.9 degrees and standard deviation of 9.7 degrees, while all other configurations remain the same as before, then the theoretical results for HH and VV backscattering coefficients (see Fig. 13) change appreciably, and over a wide range of incidence angles, HH backscattering coefficients are larger than that of VV. A brief explanation of the change in the pattern across the incidence angle is as follows. First one observes that the inclination angle has wide distribution with a peak at the bin centered at 52.5 degrees for the distribution in [4], whereas for Gaussian distribution the peak is at the mean of 28.9 degrees and the distribution is much narrower, with very small magnitude at 50 degrees and beyond. When incidence angle approaches the peak distribution, for an appreciable portion of the inclination angles, the wave is incident at a direction almost tangential to the leaf surface, with the resulting scattering almost negligible. The overall effect is a drop in the backscattering coefficient, as is evident

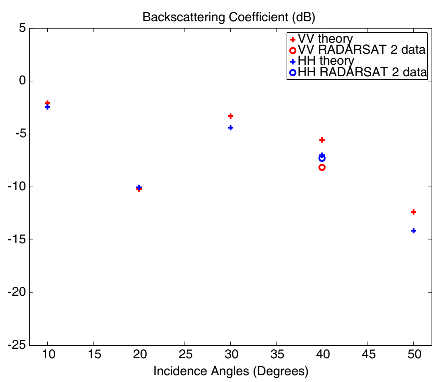


**Figure 12.** Comparison of backscattering coefficients between theory and RADARSAT-2 data.

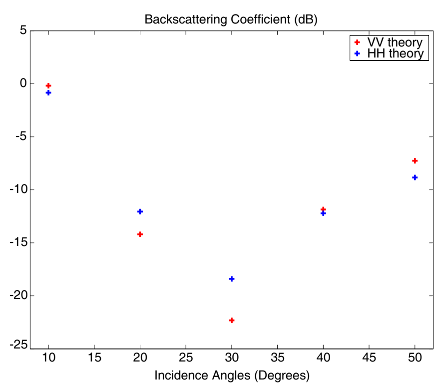


**Figure 13.** The effect of inclination angle distribution of corn leaves on backscattering coefficients at C band: Normal distribution is assumed.

in Fig. 13 where a deep valley appears at 30 degrees (close to 28.9). Other forms of distribution for corn leave inclination angle were also suggested in the literature (e.g., the ellipsoidal distribution [23]). The corresponding results are different from above (not shown here) as expected.

It should be mentioned that volume fraction of the corn plants is less than 1% based on the ground truth as given in Table 1, which means that the corn canopy is not a dense medium yet, and Foldy approximation is applicable to determine the extinction rate. Otherwise, more rigorous methods should be called for in analyzing wave propagation in the dense medium (e.g., [24]).

Further investigation reveals the following additional points: 1) scattering from stalks is appreciable at L band, yet is dominated by that from leaves at C band; 2) modification of the scattering amplitude of leaves using the K-S method elicits insignificant change at L band, yet becomes important at C band.

## 4. CONCLUSION

In this paper, we proposed an electromagnetic scattering model for a corn canopy which includes the coherent effect due to the corn structure and takes advantage of recently advanced scattering models for dielectric cylinder of finite length, for thin dielectric disk with elliptical cross section, and for rough surface. The model results were validated at both L and C bands.

At L band, it was found that for HH, both the proposed coherent model and an incoherent model based on distorted Born approximation by Chauhan et al. showed good agreements with measurements, while for VV, our theory was closer to measurements than that of Chauhan et al.

At C band, we found that the incoherent model by Chauhan et al. showed significant discrepancy with RADARSAT-2 data, hence no attempt was made here in including this theory for comparison. The proposed coherent model was found to be in good agreement with RADARSAT-2 data for HH, yet there was error around 2.5 dB in VV. The true cause for such a discrepancy is currently under investigation.

## ACKNOWLEDGMENT

The authors would like to thank Prof. Bing-Bo Li for carrying out the campaign of *in situ* ground truth collection in Jiangsu Province, 2009, Miss Yin-Hui Wang for processing the ground truth, Mr. He-Jia Luo for processing the RADARSAT-2 data, and the anonymous reviewers for their helpful reviews and suggestions. This work was supported by National High Technology "863" Programs of China under Grant No. 2009AA12Z113 and 2006AA120108, National Basic Science Research and Development Grants (973) under Grant No. 2007CB714404, and Open Fund of China State Key Laboratory of Remote Sensing Science under Grant No. OFSLRSS201007.

## REFERENCES

1. Tsang, L., J. A. Kong, and R. T. Shin, *Theory of Microwave Remote Sensing*, Wiley-Interscience, New York, 1985.
2. Singh, D. and A. Kathpalia, "An efficient modeling with GA approach to retrieve soil texture, moisture and roughness from ERS-2 SAR data," *Progress In Electromagnetics Research*, Vol. 77, 121–136, 2007.
3. Mudaliar, S., "On the application of the radiative transfer approach to scattering from a random medium layer with rough boundaries," *Journal of Electromagnetic Waves and Applications*, Vol. 20, No. 13, 1739–1749, 2006.
4. Chauhan, N. S., D. M. Le Vine, and R. H. Lang, "Discrete scatter model for microwave radar and radiometer response to corn: comparison of theory and data," *IEEE Trans. Geosci. and Remote Sensing*, Vol. 32, 416–426, Mar. 1994.
5. De Roo, R., Y. Du, and F. Ulaby, "A semi-empirical backscattering model at L-band and C-band for a soybean canopy with soil moisture inversion," *IEEE Trans. Geosci. and Remote Sensing*, Vol. 39, No. 4, 864–872, Apr. 2001.
6. Singh, D., V. Srivastava, B. Pandey, and D. Bhimsaria, "Application of neural network with error correlation and time evolution for retrieval of soil moisture and other vegetation variables," *Progress In Electromagnetics Research B*, Vol. 15, 245–465, 2009.
7. Jiang, W.-Q., M. Zhang, and Y. Wang, "CUDA-based radiative transfer method with application to the EM scattering from a two-layer canopy model," *Journal of Electromagnetic Waves and Applications*, Vol. 24, Nos. 17–18, 2509–2521, 2010.
8. Yueh, S. H., J. A. Kong, J. K. Jao, R. T. Shin, and T. Le Toan, "Branching model for vegetation," *IEEE Trans. Geosci. and Remote Sensing*, Vol. 30, No. 2, 390–401, Mar. 1992.
9. Chiu, T. and K. Sarabandi, "Electromagnetic scattering from short branching vegetation," *IEEE Trans. Geosci. and Remote Sensing*, Vol. 38, No. 2, 911–925, Mar. 2000.

10. Du, Y., Y. Luo, W.-Z. Yan, and J. A. Kong, "An electromagnetic scattering model for soybean canopy," *Progress In Electromagnetics Research*, Vol. 79, 209–223, 2008.
11. Lim, K.-S., J.-Y. Koay, V.-C. Koo, H.-T. Ewe, and W.-L. Kung, "High angular resolution measurements of the monostatic backscattering coefficient of rice fields," *Journal of Electromagnetic Waves and Applications*, Vol. 23, No. 1, 1–10, 2009.
12. Koay, J. Y., C. P. Tan, K. S. Lim, S. Bahari, H. T. Ewe, H. T. Chuah, and J. A. Kong, "Paddy fields as electrically dense media: Theoretical modeling and measurement comparisons," *IEEE Trans. Geosci. and Remote Sensing*, Vol. 45, No. 9, 2837–2849, 2007.
13. Karam, M. A., A. K. Fung, and Y. M. M. Antar, "Electromagnetic wave scattering from some vegetation samples," *IEEE Trans. Geosci. and Remote Sensing*, Vol. 26, 799–808, Nov. 1988.
14. Yan, W.-Z., Y. Du, H. Wu, D. Liu, and B.-I. Wu, "EM scattering from a long dielectric circular cylinder," *Progress In Electromagnetics Research*, Vol. 85, 39–67, 2008.
15. Yan, W.-Z., Y. Du, Z. Li, E.-X. Chen, and J.-C. Shi, "Characterization of the validity region of the extended $T$-matrix method for scattering from dielectric cylinders with finite length," *Progress In Electromagnetics Research*, Vol. 96, 309–328, 2009.
16. Fung, A. K., Z. Q. Li, and K. S. Chen, "Backscattering from a randomly rough dielectric surface," *IEEE Trans. Geosci. and Remote Sensing*, Vol. 30, No. 2, 356–369, Mar. 1992.
17. Du, Y., "A new bistatic model for electromagnetic scattering from randomly rough surfaces," *Waves in Random and Complex Media*, Vol. 18, No. 1, 109–128, Feb. 2008.
18. Koh, I. S. and K. Sarabandi, "A new approximate solution for scattering by thin dielectric disks of arbitrary size and shape," *IEEE Trans. Antennas and Propagation*, Vol. 53, 1920–1926, Jun. 2005.
19. Chen, K. S., T. D. Wu, L. Tsang, Q. Li, J. C. Shi, and A. K. Fung, "Emission of rough surfaces calculated by the integral equation method with comparison to three-dimensional moment method simulations," *IEEE Trans. Geosci. and Remote Sensing*, Vol. 41, No. 1, 90–101, Jan. 2003.
20. Alvarez-Perez, J., "An extension of the IEM/IEMM surface scattering model," *Waves in Random Media*, Vol. 11, 307–329, 2001.

21. Ulaby, F. T. and M. A. El-Rayes, "Microwave dielectric spectrum of vegetation — Part 11: Dual dispersion model," *IEEE Trans. Geosci. and Remore Sensing*, Vol. 25, 550–557, 1987.
22. Dobson, M. C., F. T. Ulaby, H. Hallikainen, and M. A. El-Rayes, "Microwave dielectric behavior of wet soil — Part 11: Four components dielectric mixing models," *IEEE Trans. Geosci. and Remote Sensing*, Vol. 23, 35–46, 1985.
23. Campbell, G. S., "Extinction coefficients for radiation in plant canopies calculated using an ellipsoidal inclination angle distribution," *Agricultural and Forest Meteorology*, Vol. 36, 317–321, 1986.
24. West, R., D. Gibbs, L. Tsang, and A. K. Fung, "Comparison of optical scattering experiments and the quasi-crystalline approximation for dense media," *J. Opt. Soc. Am. A*, Vol. 11, 1854–1858, 1994.