Characteristics of Electromagnetic Scattering from Vegetation Models using Random Wire Structures with Applications to Land Imaging SAR Systems

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Abstract. Clouds of both random curly wires and randomly-oriented straight wires with good conductivity are used to construct random volume models to simulate structures found in vegetation areas on the ground surface like naturally cultivated plants involving grass, trees, primary crops and chaff clouds. A variety of such random volumes are then subjected to incident electromagnetic plane wave of specific polarization to study the properties of electromagnetic scattering from such natural objects existing on the earth surface. It is shown that the frequency dependence of the Radar Cross Section (RCS) of such random structures has maxima around the frequencies corresponding to the natural modes of the wire structures constituting the volumetric model. On the other hand, the frequency behaviour of the RCS of these random clouds exhibits sharp peaks or anti-peaks over very narrow intervals of the frequency due to the generation of internal resonant modes between the finite-length pairs of wires constituting the random clouds. It is shown that such maxima, sharp peaks and anti-peaks of frequency behaviour of the backscattered field are very important to extract useful information for construction of microwave images and, also, for the classification of the vegetation areas that appear in earth remote sensing Synthetic Aperture Radar (SAR) images taken for the ground surface. The polarization properties of the fully polarimetric backscattering coefficients collected by a land imaging SAR system are studied through electromagnetic simulation.

1. Introduction

Earth remote sensing using optical imaging is a well-established tool for monitoring vegetation and forested areas and flooded-crops on the earth surface. However, optical imaging can suffer from several limitations, especially where heavy cloud cover occurs. The increased availability of space-borne microwave radar imagery offers additional means for monitoring the dynamics of vegetation and forests. Earth remote sensing with Synthetic Aperture Radar (SAR) has several advantages compared to optical sensing as it provides its own source of illumination in the microwave range and
the independence of atmospheric conditions therefore, guaranteeing the continuity of earth observation [1].

Land imaging SAR systems are the most preferred tool for mapping submerged vegetation areas on the earth surface; smooth open water areas can be easily detected in the SAR data. It is well known that earth remote sensing using SAR systems with multiple polarizations provide more information on inundated vegetation areas than single-polarized SAR. Studies employing multi-polarized data indicate advantages of like-polarization (HH or VV) for the separation of flooded and non-flooded forests and vegetation. The backscatter ratio between flooded and non-flooded vegetation areas is higher at HH polarization than at VV polarization. Backscatter is generally lower for cross-polarization (HV or VH) as depolarization does not make for ideal corner reflectors [2]. The study of agricultural crops using C- and L-band SAR data at different polarization modes revealed that C-band gives better classification results than L-band. However, L-band shows better correlation with the crop growth variables. Furthermore, land-imaging fully-polarimetric SAR systems are found to be better than various modes of hybrid polarimetric SAR systems for crop studies [3].

Wide areas of the ground surface have vegetation and either planted or thrown natural chaff that can be modelled as clouds of randomly oriented straight and curly wires with good electric conductivity. To get important information for signal processing involved in the operation of land imaging SAR systems used for earth remote sensing, it is useful to study the characteristics of polarization of the electromagnetic backscattering form such random volumes over a wide range of the frequency. In the present work, vegetation volumes and natural chaff clouds are modelled as random volumetric structure composed of a number of randomly oriented and distributed straight and curly wires of random lengths separated by random distances.

2. Geometric model of random volumetric wire structures and electromagnetic simulation of PolSAR imaging.

2.1 Geometric modeling of random volumetric wire structures

As discussed above, vegetation volumes and natural chaff clouds can be modelled as random volumetric structure composed of a number of randomly oriented and distributed straight and curly wires of random lengths separated by random distances and placed at random locations.

2.1.1 Generation of random volumetric structure of straight wires

A randomly oriented straight wire can be modelled as shown in Figure 1(a, b) with the following statistical parameters, the random variable \( l \) represents the wire length. The random variables \( \theta, \phi \) represent the angles of orientation of the straight wire, \( \psi \) represents the angle of twist about the local axis of the strip wire, where the plane of the strip wire is normally parallel to the \( x-z \) plane. The four random variables \( l, \theta, \phi, \psi \) are uniformly distributed with mean values \( \mu_l, \mu_\theta, \mu_\phi, \) and, \( \mu_\psi \) respectively and limited by the following pairs of limiting values \((l_{\text{min}}, l_{\text{max}}), (\theta_{\text{min}}, \theta_{\text{max}}), (\phi_{\text{min}}, \phi_{\text{max}}), \) and \((\psi_{\text{min}}, \psi_{\text{max}}), \) respectively.

A random volumetric structure of such randomly oriented straight wires can be constructed up as shown in Figure 1(c, d) by generating a number of these wires each at a location defined by the random variables \((x_o, y_o, z_o)\) which are uniformly distributed with mean values \( \mu_{x_o}, \mu_{y_o}, \) and, \( \mu_{z_o}, \) respectively, and have the following limiting pairs of values \((x_{o\text{min}}, x_{o\text{max}}), (y_{o\text{min}}, y_{o\text{max}}), \) and \((z_{o\text{min}}, z_{o\text{max}}), \) respectively.

2.1.2 Generation of random volumetric structure of curly wires

A randomly curly wire can be modelled as shown in Figure 2(a) with the following statistical parameters. The random variables \( h \) and \( \rho \) represent the height and the distance between a point on the curly wire and its. The random variable \( \phi \) represents the angle of a point on the wire and the \( x \)-axis. The variables \( h, \rho, \) and \( \phi \) are uniformly distributed with mean values \( \mu_h, \mu_\rho, \) and \( \mu_\phi, \) respectively.
respectively and limiting values ($h_{\text{min}}, h_{\text{max}}$), ($\rho_{\text{min}}, \rho_{\text{max}}$), and ($\phi_{\text{min}}, \phi_{\text{max}}$), respectively. The radial distances $\rho$ for the points along the wire axis is spatially correlated with a correlation length $l_{\rho_c}$. Also, the distribution of the angular rotations $\phi$ correlated with a correlation length $l_{\phi_c}$. A random volumetric structure of such random curly wires can be constructed up as shown in Figure 2(b) by generating a number of these wires. A detailed description of generating such a spatially correlated one-dimensional random data is provided in [8].

![Figure 1: Geometry of a randomly oriented strip wire and clouds of randomly oriented straight wires to represent natural plants/chaffs](image)

![Figure 2: Geometry of a random curly wire and clouds of random curly wires to represent natural plants/chaffs](image)

Examples of natural vegetation and chaff that can be modelled as random volumetric wire structures are presented in Figure 3.
2.2 Properties of electromagnetic scattering from volumetric wire structures

Each of the conducting wires in a volumetric model of grown vegetation or chaff clouds has its EM natural resonances [4, 5]. In a natural vegetation or chaff it is frequent to find pairs of nearly parallel adjacent wires of approximately equal lengths. Such a pair may be seen as an open-ended two-wire waveguide resonator. In the present discussions the natural modes of the individual wires constituting the random structure are referred to as the “external resonances”, whereas the waveguide resonator modes of a pair of quasi-parallel wires are referred to as “internal resonances”. Both types of resonances, if excited, contribute a great deal to the RCS of the volumetric model at the corresponding resonant frequencies [6, 7].

2.2.1 Natural resonances of a single wire (external resonances)

The thin straight wire has its EM natural resonances contributing a great deal to the RCS. The complex frequencies of the wire of diameter $D$ and length $L$ can be expressed as,

$$f_{n}^{Nat} = f_{n}^{(r)} + jf_{n}^{(i)}, \quad n = 1, 2, 3, ... \tag{1}$$

For an infinitesimally thin wire ($D/L \rightarrow 0$), one can make the following approximation

$$f_{n}^{(r)} \approx n \frac{c}{2L}, \quad n = 1, 2, 3, ... \quad \text{and} \quad f_{n}^{(i)} \approx 0, \quad n = 1, 2, 3, ... \tag{2}$$

2.2.2 Two-wire waveguide resonator (internal resonances)

A microwave cavity is a special type of resonator, consisting of a closed metal structure that confines electromagnetic fields in the microwave region of the spectrum. The structure is either hollow or filled with dielectric material. The microwaves bounce back and forth between the walls of the cavity. At the cavity’s resonant frequencies they reinforce to form standing waves in the cavity. Therefore, the cavity oscillates preferentially at a series of frequencies, its resonant frequencies. It has been shown that for a cavity-backed aperture, the RCS as, a functions of frequency, has sharp maxima or minima at the resonant frequencies corresponding to the (internal) cavity modes [6, 7]. Like cavity-backed apertures, the finite length open ended two-wire transmission line has (internal) resonant modes. For very thin wires ($D/L \rightarrow 0$), the resonant frequency of the TEM mode of the two-wire waveguide resonator can be calculated as follows

$$f_{n}^{TEM} \approx \frac{c}{\lambda_{n}^{TEM}} \approx \frac{n c}{2L}, \quad n = 1, 2, 3, ... \tag{3}$$

where $\lambda_{n}^{TEM}$ is the wavelength of the two-wire TEM guided mode, $c$ is the velocity of light, $L$ is the length of the two-wire transmission line and $n$ is the order of the resonant mode.

In view of (2) and (3), the resonant frequency of the $n^{th}$ internal resonant mode coincides with that of the $n^{th}$ external resonant mode for a pair of very thin parallel wires ($D/L \rightarrow 0$).
2.2.3 Polarization characteristics of the scattered far field

This section aims to give quantitative definitions for the polarimetric backscattering coefficients associated with fully POLSAR data. As shown in Figure 4, a linearly polarized plane wave is assumed to incident on the ground surface in the direction defined by the angles \( \theta_i \) and \( \phi_i \) and propagation vector \( \hat{k}_i \). The angle \( \psi_i \) identifies the polarization of the incident plane wave (i.e. the direction of the electric field).

The propagation vector
\[
\hat{k}_i = \sin \theta_i \cos \phi_i \hat{a}_x + \sin \theta_i \sin \phi_i \hat{a}_y + \cos \theta_i \hat{a}_z
\]
The vertical and the horizontal vectors are
\[
\hat{h} = \frac{k_i \times \hat{a}_z}{\sin \theta_i} \quad \text{and} \quad \hat{v} = \hat{h} \times \hat{k}_i
\]
Let the angle between the incident electric field vector (\( \hat{E}_i^0 \)) and the horizontal polarization unit vector (\( \hat{h} \)) is \( \psi_i \). Thus, the incident field decomposed of horizontally and vertically polarized components as follows,
\[
\hat{E}_i = \hat{E}_i^0 \cos \psi_i \hat{h} \quad \hat{E}_i^0 = \hat{E}_i^0 \sin \psi_i \hat{v}
\]
\[
S = \begin{bmatrix} S_{hh} & S_{hv} \\ S_{vh} & S_{vv} \end{bmatrix}
\]

**Figure 4**: Horizontal and vertical polarization directions

In vertically polarized wave the magnetic field is parallel to the earth’s surface, while in horizontally polarized wave the electric field is parallel to the earth’s surface. The horizontal and vertical polarization vectors are orthogonal to each other and lie in the same plane.

As described above, the PolSAR operation is simulated to obtain the co-polarized and cross-polarized backscattering coefficients \( S_{hh} \), \( S_{vh} \), \( S_{hv} \), and \( S_{vv} \), defined as,
\[
S_{hh} = \frac{E_i^0}{E_i^0} \left| E_i^i \right|_{\psi = 0}^0, \quad S_{vh} = \frac{E_i^0}{E_i^0} \left| E_i^i \right|_{\psi = 0}^0, \quad S_{vv} = \frac{E_i^0}{E_i^0} \left| E_i^i \right|_{\psi = 0}^0, \quad S_{hv} = \frac{E_i^0}{E_i^0} \left| E_i^i \right|_{\psi = 0}^0
\]
(4)

where the superscripts i and r denotes incident and received simultaneously.

The backscattering of the target can be described by the polarization backscattering matrix, \( S \)

3. Results and discussion

3.1 Generation of random clouds of wire structures

This section is concerned with the generation of volume models composed of structures that include both straight and curly wire/strip elements for modeling natural vegetation and chaff.

3.1.1 Generation of clouds of randomly oriented straight wires

A sample random straight wire model is created according to the method described in Section 2.1.1 and is presented in Figure 5(a). The strip wire has the following dimensional and statistical parameters:
\[ l = 4 \text{ cm}, \ w = 0.4 \text{ cm}, \ \theta_{\text{Max}} = 30^\circ, \ \varphi_{\text{Max}} = 90^\circ \text{ and } \psi_{\text{Max}} = 180^\circ. \]

The random clouds of straight wires representing a chaff are constructed of 100 wires with separation \( d = 1 \text{ cm} \) between the elements. The individual wires have the dimensions: length \( l = 5 \text{ cm} \), width \( w = 0.1 \text{ cm} \). Figures 5(b, c and d) show three models of unbaised, quasi-vertically and quasi-horizontally oriented straight wires. The quasi-vertically structure is suitable to model the many types of grwon crops and ground-implanted natural chaff whereas The quasi-horizontally structure suitable to model many types of shredded or cut stalks of crops and natural chaff collected and thrown to the ground over wide areas.
3.1.2. Generation of a single and clouds of random curly wires
As described in Section 2.1.2, three geometric models are created for curly wires of the same height ($h = 7\, \text{cm}$), and different lengths ($l = 10, 8.65, 7.32\, \text{cm}$) as presented in Figure 6 (a, b and c). It is noticed that the total length of the wire increases with increasing the maximum allowable distance of the points on the wire from the wire axis ($\rho_{\text{max}}$).

A random volume structure is constructed up of 25 curly wires each of height $h = 7\, \text{cm}$, length $l = 8.65\, \text{cm}$, and width $w = 0.1\, \text{cm}$; the statistical parameters $\rho_{\text{max}} = 1.2\, \text{cm}$ and $\phi_{\text{max}} = 90^\circ$. Figure 6(d) shows a model of chaff cloud of $z$-oriented elements of curly wires.

3.2. Characteristics of the electromagnetic scattering from wire structures
To study the RCS of a straight strip wire, its geometric model is subjected to an incident plane wave that the incoming wave from the SAR antenna. The material of the wire is assumed to be a perfect electric conductor (PEC). The frequency dependence of the RCS of a single strip wire is shown in Figure 7(a). The smooth peaks of the RCS-frequency curve correspond to the first four natural
resonances. The resonant frequencies of this wire are 2, 4.1, 6.2 and 8.3 GHz, which agree with the approximate equation (2) for the natural resonant frequencies of a straight wire.

Not only the straight wire has its natural resonances related to its length, but also the curly wire behaves the same. Figure 7(b) presents the frequency dependence of the RCS of a single curly wire of perfect electric conductivity. The curly wire of \( h = 7 \) cm has its first natural resonance at about 2 MHz whereas the wire of \( h = 5 \) cm has its first natural resonance at about 2.5 MHz. The natural frequencies corresponding to the RCS peaks are determined by the total length of the random curly wire and almost obey the rule given by equation (2).

![Figure 7: Variation of RCS vs. frequency (MHz)](image)

As shown in Figure 8, the current distributions on straight and curly wire surface are presented in color scale at the frequencies corresponding to the peaks of the RCS. The change of the surface current magnitude along the wire length presents the same order of the corresponding natural resonance (number of maxima and minima of the current).

![Figure 8: Current distribution on thin straight and curly wires for the first five natural resonances](image)

3.3 Frequency dependence of the RCS of two-wire structures

When two wires are close to each other the mutual coupling may affect the RCS of the entire two-wire structure. In Figure 9(a). The RCS of two parallel wires of the same length \( l = 4 \) cm is plotted against the frequency and is compared with the RCS of a single wire of the same length. As the two parallel wires are far enough from each other \( (d = 3 \) cm), the frequency behavior of the RCS of the two-wire structure has smooth peaks at the same frequencies as that corresponding to the natural resonances of the individual wires (Note the curly wire exhibits the same behaviour).
The current distribution on the surface of the wires and the electric field in the regions between and around the two wires and around them are plotted in color scale at the frequencies corresponding to the first natural resonance as shown in Figure 9(b). It is clear that the electric field is concentrated around each wire rather than in the region between them. It means that no wire affects the other due to the relatively far distances between them.

![Surface Current and Electric Field](image)

(a) RCS versus frequency (MHz)  
(b) 1\textsuperscript{st} resonance $f = 3400$ MHz

**Figure 9:** Two parallel strip wires ($l = 4$ cm and $d = 3$ cm) subjected to a vertically polarized incident plane wave $\theta_i = 45^\circ$ and $\phi_i = 0^\circ$

3.4. Effect of the internal resonances of two-wire waveguide resonator on the RCS of random parallel wire structures

A pair of conducting wires of finite length can act as a waveguide resonator that has its resonant modes occurring at frequencies determined by the waveguide length (length of the two wires). This section is dedicated for discussing the effect of such internal resonances on the RCS of two-wire structures.

As shown in Figure 10(a), the RCS has (smooth) peaks at the frequencies corresponding to the natural modes of the straight wire and has (sharp) peaks at the frequencies corresponding to the internal (two-wire resonator) modes generated between the parallel wires.

The RCS of the parallel wires separated by $d = 0.5$ cm, resonate at $3250$ MHz and $6805$ MHz for the first and second order resonant modes, simultaneously. The sharp peak of the RCS-frequency curve occurring at $3450$ MHz and $6967$ MHz can be attributed to the generation of the first and second-order resonant modes. This may represent useful information not only for the operation of signal processing required in the SAR image formation but also for SAR image classification. This becomes a necessary requirement when the SAR image is taken for natural volumes including scatters like the random wire structures as described before.

In natural chaff composed of nearly straight wires, the angle between two adjacent wires greatly affect the possibility of internal modes excitation at their resonant frequencies. When the angle between the wires is $0^\circ$, they are completely parallel and the RCS-frequency curve in Figure 10(b) shows a sharp peak corresponding to the resonant frequency of the first-order internal mode. As the angle of intersection increases approaching about $45^\circ$, the RCS peak disappears indiciting the absence of the internal mode. When the two wires become perpendicular to each other, the frequency behavior of the RCS of the two wires is nearly identical to that of a single wire.
(a) two parallel wires \( l = 5 \text{ cm}, d = 0.5 \text{ cm} \)

(b) two parallel wires \( l = 5 \text{ cm}, d = 0.5 \text{ cm} \) making angles \( 0^\circ, 20^\circ, 45^\circ \) and \( 90^\circ \)

Figure 10: Variation of RCS vs. frequency (MHz) of 2 wire strips

Figure 11 (a,b), shows the near field distributions in the region between the two straight wires at the natural and the corresponding internal modes. Like the near field distribution between the two parallel straight wires, Figure 11 (c), shows the near field distribution at the first internal resonance mode for two curly wires.

First natural resonance, \( f = 3250 \text{ MHz} \)
(a) Electric field at 1\(^{st}\) resonance

First internal resonance, \( f = 3450 \text{ MHz} \)
(b) Electric field at 2\(^{nd}\) resonance

Second natural resonance, \( f = 6805 \text{ MHz} \)
First internal resonance \( f = 6967 \text{ MHz} \)
(c) 1\(^{st}\) resonance mode

Second internal resonance, \( f = 6967 \text{ MHz} \)

Figure 11: comparison of the field distribution between two parallel wires at natural and internal resonances

At the first-order resonant mode, the \( E_x \) component has a sharp peak whereas the \( E_z \) component has a sharp antipeak where both occur over a very narrow interval of the frequency. This indicates a dramatic change of the near field polarization; that is the electric field between the wires change its direction from being inclined to the wires by about \( 45^\circ \) \( (E_x \approx E_z) \) to be nearly perpendicular to them \( (E_x \gg E_z) \) over very narrow band of the frequency. The effect of such a change of the near field polarization on the far field scattering parameters should be investigated as it should be taken into consideration, if encountered, in the SAR signal processing. It should be noted that from the same frequency behavior curve presented in Figure 12, the same polarization change of the near field occurs at the frequency \( f = 6967 \text{ MHz} \) corresponding to the second-order resonant mode.
3.5 Scattering of electromagnetic waves from clouds of random wire structures

The back scattering coefficients representing the fully-polarimetric imaging SAR data are $S_{vv}$, $S_{hv}$, $S_{hh}$, and $S_{vh}$. For a vegetation/chaff volume modeled as a cloud of quasi-vertically oriented straight wires (quasi-parallel to $z$-axis), the frequency behavior of the four scattering parameters is presented in Figure 13(a). It is clear that the coefficient $S_{vv}$ has the greatest magnitude among the four polarimetric backscattering coefficients whereas the coefficient $S_{hh}$ has the least magnitude among them over a wide frequency range. On the other hand for a quasi-horizontal chaff structure (quasi-parallel to $y$-axis), the coefficient $S_{hh}$ has the greatest magnitude whereas the coefficient $S_{vv}$ has the least magnitude as shown in Figure 13(b). For SAR applications concerned with imaging vegetation/chaff areas on the earth surface, the plots in Figure 13 give useful information about the frequency bands suitable for distinguishing grown (vertical) and thrown (horizontal) straight crop stalks and chaff sticks.

Figure 13: Polarimetric backscattering coefficients for volumetric structures consisting of 9 randomly oriented straight strip wires; $l = 3, 5$ and $7$ cm and $d = 3$ cm.
the frequencies corresponding to the natural resonances of the individual wires constituting the random cloud. Also, the frequency behavior of the RCS of these random clouds exhibits sharp peaks or anti-peaks over very narrow intervals of the frequency due to the generation internal resonant modes between each pair of wires of equal length within the random clouds. It is shown that at the internal resonant frequencies the electric field (between the two wires) changes its polarization from being parallel to the wires to be orthogonal to them. The polarization change occurs over a very narrow interval of the frequency around the resonance. It is shown that such maxima, sharp peaks and anti-peaks of frequency behavior of the backscattered field are very important to extract useful information for the classification of the vegetation areas that appear SAR images taken for the ground surface.

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