Simulating the Radar Cross Section of a Bare Tree: From Megahertz to Terahertz

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Abstract—An approach to estimate a radar cross section (RCS) of a tree through numerical simulations is studied. As an initial work, this paper covers bare trees with a trunk and branches and without leaves. Recent advancements in three-dimensional (3D) modeling of trees and electromagnetic solvers allow simulation of field scattering from a whole tree. There are however open issues in performing the simulations, i.e., 1) obtaining 3D models of tree trunks and branches, especially whether they have to be multilayered or not; 2) knowing dielectric parameters of tree trunks and branches, especially for higher frequencies than 10 GHz; and finally, 3) using a right field solver depending on the electrical size of a tree. In response to the open issues, we propose suitable 3D models of tree trunks and branches, show our present knowledge of dielectric parameters of living trees, and finally demonstrate impacts of branches in addition to a trunk on the estimated RCS through numerical simulations at 1000 MHz to 0.1 THz.

Keywords—Propagation, measurements, terahertz, channel modelling.

I. INTRODUCTION

The applications of wireless systems that are based on electromagnetic (EM) wave propagation and scattering have a tendency of increasing the frequency, as the need for new applications, higher resolution, and availability of interference-free spectrum, along with the development of wireless systems and enabling technologies. There are already existing and well-known methods for the design and development of transceivers in the microwave (MW) or the millimeter wave (MMW) regimes. Different frequency bands are usually used for specific applications. An example is the field of remote sensing, where the frequency range shifted from the MW regime, e.g., around 1 GHz for the earth observations, to the MMW regime e.g., 77 GHz for the automotive radar. In both applications, knowledge of a radar cross sections (RCS) is essential. An RCS of objects is obtained by experiments and numerical simulations of wave incident on objects. We study RCS of a tree in this paper, which is a relevant problem both from remote sensing and automotive radar applications. Experimental studies of EM wave scattering from trees at MMW are found at, e.g., [1], [2], where live trees are cut and measured in an anechoic chamber, while [3] measures a live Bonsai-tree. On the other hand, a simulation-based study of trees are more scarce because the EM model construction and simulations become more complicated as the frequency increases. It would be inevitable for us to simplify the EM models and approximate simulation methods to obtain a reasonable RCS estimate in a feasible time. For the low frequency regime full-wave methods can be used as the wavelength is still in the range of the tree’s dimensions [4]. However, as the frequency increases to the MW and MMW regime, new approaches are necessary, such as the Ray Tracing method [5]. Further model simplifications are introduced in [6] at MW frequencies for a pine tree model. In the present paper, we focus on RCS estimation from a living tree through numerical simulations at MW and MMW bands. To this end, this paper first defines a more precise approximation model of a living tree for electromagnetic scattering simulations in Section II. Then, Section III describes bold estimates of complex permittivity of a tree at MMW based on measured ones at MW band. Having simulated RCS at the two bands, using different solvers due to a changing scale of a tree with respect the wavelength of radio waves, we summarize future works in Section V. In this paper, we consider a simple bare tree model only, and leave a full tree model with foliage as future works. Bare trees are a relevant object to detect in the winter time.

II. STRUCTURAL MODELING OF A BARE TREE

This section describes structural models of a tree at MW and MMW regimes. The 3D model of the tree is constructed by a tool called Tree Generator, which creates a surface mesh of a tree through a set of parameters [7]. A post-processing is required on the generated model to make sure that the mesh is closed and contains any self intersections. Exemplary tree models are illustrated in Fig. 1 which include the trunk and the branch system, but not the foliage.
The cut section of the trunk of a birch tree is depicted on Fig. 2, showing the characteristic layers of the wood material. The core part called the xylem is built up from an inner layer of heartwood and an outer layer of sapwood, which consists of further sub-layers of early and late woods that are all distinct in a moisture content and density. Hence, the core part of the trunk and branches has inhomogeneous material properties, which makes it challenging to model accurately. The thicker layer surrounding the core is called the phloem, and characterized by its homogeneity in the millimeter-scale, and high moisture content, as it has a crucial role in the water transport of the tree. Hence this layer has much higher conductivity than the core. Finally, the outermost layer is called the periderm (cork), and has the purpose to protect the inner parts of the tree. This layer is characterized by its low moisture content [8].

The construction of a structural tree model for EM simulations always is subject to some approximations, such as homogenization or simplification of the structure. Otherwise, the mathematical model would be over-complicated, and sometimes such precision is not necessary for improving the accuracy of scattered field simulations. The required structural details of the model depend on the wavelength of incident radio waves. For wavelengths that are several times longer than the diameter of the trunk and branches, a homogenized model is usually sufficient [9], [10]. For wavelengths that are in the range of the diameter of the branches and the trunk, a more complex model is required, which considers the inhomogeneity of the inner volume [11]. As the wavelength of the radio wave shrinks, the spatial variation of material properties will result in distinct behaviors, as the wood is structured with cell blocks of varying size. For the MW and MMW regimes, the following structural models can therefore be used:

- **MW regime:** The structural model of the MW regime consists of two layers, such as the high conductivity phloem, and the lower conductivity xylem as a homogenized structure.
- **MMW regime:** The structural model of the MMW regime assumes that the outer phloem layer absorbs and scatters most of the incident EM field. Thus, the inner xylem part is not needed in the model, allowing its simplification that is free from the inhomogeneous and anisotropic behavior. The outermost dry periderm layer is considered to have a low impact on absorption and scattering, as the permittivity is much lower than the other layers. Therefore the tree structural model at MMW regime can be homogeneous representing only the outer phloem layer.

### III. Dielectric Models of a Tree Trunk and Branch

Following the structural model, it is also necessary to define dielectric parameters. This section explores them at MW and MMW regimes.

#### A. MW regime

A reference measurement of the homogenized permittivity of a birch phloem (inner bark layer) and xylem at the MW regime is available in [12] for a living birch, whose plot is reproduced on Fig. 4. The data are used in this paper for scattering simulations on tree trunks at MW regime.

#### B. MMW regime

1) **Our permittivity estimates:** In contrast, for over MMW frequencies, such permittivity measurements for wood are not available. The possible reason is that inhomogeneity of the xylem (core) of the tree will be comparable with the wavelength, and will change tree by tree. Thus, an estimate of surface impedance is used for the MMW model, based on the extrapolation of MW measurements.

The dielectric behavior of wood depends mainly on two parameters, the moisture content and the density [13]. This means, that there is no distinctive behavior between different species of trees. As a general observation oven-dry wood has a similar dielectric constant to the air for the real part, and small conductivity according to the imaginary part, which makes it inert to the incident EM field as shown in Table I and Fig. 3. The data are used in this paper for scattering simulations on tree trunks at MW regime.

<table>
<thead>
<tr>
<th>Freq. [GHz]</th>
<th>0.001</th>
<th>0.01</th>
<th>0.1</th>
<th>1</th>
<th>3</th>
<th>10</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re{ε}</td>
<td>2</td>
<td>0.05</td>
<td>0.01</td>
<td>1</td>
<td>1</td>
<td>1.7</td>
<td>1.6</td>
</tr>
<tr>
<td>Im{ε}</td>
<td>0.053</td>
<td>0.03</td>
<td>0.0045</td>
<td>0.039</td>
<td>0.037</td>
<td>0.029</td>
<td></td>
</tr>
</tbody>
</table>

In this paper, complex dielectric parameter estimates of a wood trunk and branch at MMW is based on the assumption that they mostly depend on the water bound in the material. The permittivity of water can be described by the Debye model [14] on the MW and MMW regimes as

\[
\varepsilon_r(\omega, T) = \varepsilon_\infty(T) + \frac{\varepsilon_r(20 \degree C) - \varepsilon_\infty(T)}{1 - j \omega \tau(T)},
\]

where the temperature of water is \( T = 20 \degree C \), the relative permittivity at the direct current is \( \varepsilon_r(20 \degree C) = 80.0 \), the relative optical permittivity is \( \varepsilon_\infty(20 \degree C) = 6.0 \), and the relaxation time is \( \tau(20 \degree C) = 9.4 \text{ ps} \) [15]. Fig. 3 plots the complex permittivity of water, showing that

1) the imaginary part of the complex permittivity takes the same value for the pairs of lower and higher frequencies, e.g., at 3 and 100 GHz and
2) the real and imaginary parts are close to each other for around 100 GHz.

Assuming that the permittivity of wood is defined mainly by the properties of water and that it is known for the lower frequency, the permittivity of wood at the higher frequency can be estimated by the above-mentioned two heuristic relationship of the Debye model at 20 °C. As it reads from Fig. 4 that \(\varepsilon'' \approx 5.5\) at 3 GHz, based on the analogy between 3 GHz and 100 GHz (relationship 1), the coarse estimation for the relative permittivity of the birch phloem at 100 GHz is \(\varepsilon'' \approx 5.5\). Furthermore, since Fig. 3 shows that the relative permittivity and the loss factor have similar values around 100 GHz (relationship 2), the approximation of \(\varepsilon'' \approx \varepsilon'\) at 100 GHz. Henceforth, the complex permittivity of the birch phloem at 100 GHz is estimated to be \(\varepsilon_r \approx 5.5 + j5.5\). This is a heuristic and rough estimate of permittivities, and hence measurements still are required. Still, the following discussions of the penetration depth and surface model of a tree trunk and branch is applicable to any permittivity estimates.

2) Surface model of a tree trunk and branch: The large loss factor (\(\varepsilon''\)) of the phloem material suggests the shallow penetration of the EM field to it. The penetration depth \(\delta\) is given by, e.g., [16]

\[
\delta^{-1} = \omega \frac{\varepsilon' \mu}{2} \sqrt{1 + \left(\frac{\sigma}{\varepsilon' \omega}\right)^2} - 1, \tag{2}
\]

where \(\sigma\) is the conductivity which can be related to the imaginary part of the permittivity by

\[
\varepsilon_r = \varepsilon' + \frac{\sigma}{j\omega\varepsilon_0} = \varepsilon' + j\varepsilon'', \tag{3}
\]

leading to \(\delta_{\text{phloem}} = 0.447 \text{ mm}\) for the phloem at 100 GHz. Whether this depth applies to an arbitrary birch tree or not, requires a statistical knowledge of the phloem layer thickness. The cross-sectional area of the phloem layer is proportional to the diameter of the trunk or the branch [17]. Assuming circular cross-sections, the thickness \(T\) of the phloem layer can be calculated by

\[
T = D - \sqrt{D^2 - \frac{4}{\pi}A}, \tag{4}
\]

where \(D\) is the diameter of the branch/trunk, and \(A\) is the cross-sectional area of the phloem layer. Let us consider a tree model, where the thinnest branches considered are \(D_{\text{min}} = 1 \text{ cm}\) thick, and then the cross-sectional area of the phloem can be estimated to be \(A_{\text{min}} = 20 \text{ mm}^2\) [17]. Hence, the thinnest considered phloem layer in the model is \(T_{\text{min}} = 1.37 \text{ mm}\) according to (4), which is more than twice thicker than the estimated penetration depth of the the phloem layer. Thus, such a surface model can be used to describe an EM properties of tree trunks and branches. It is important to note, that the surface model cannot be used at the MW regime usually, as the penetration depth of the EM field is much deeper than the thickness of the phloem layer. For example, at 3 GHz, the skin depth is 2.5 cm for \(\varepsilon' = 20\) according to Fig. 4. Thus, a layered model is preferred in those situations.

IV. ELECTROMAGNETIC SIMULATIONS OF SCATTERING FROM A BARE TREE

Having established the structural and electrical models of a bare tree in the previous sections for MW and MMW, its scattering simulations with a plane wave incidence are introduced in this section. Specifically, we evaluate an RCS, which is defined as a measure of the scattered field to a given direction normalized by an isotropic scatterer [18]. The received power of a scattering measurement is given by the Radar equation:

\[
P_t = \left( P_t G_t \frac{1}{4\pi R_1^2} \right) \sigma \left( \frac{1}{4\pi R_2^2} \right) A_r, \tag{5}
\]

where the first term gives the power density at a target object at \(R_1\) [m] distance from the transmit antenna with \(P_t\) power fed to its port and \(G_t\) is its gain. The level of interception and scattering of the incident wave by the target is defined by \(\sigma\) [m²], which is called RCS and characterize the properties
of the target itself and changes its value as orientation with respect to the transmit and receive antennas vary. Finally, the scattered field is received by an antenna in $R_2$ [m] distance from the target, with an effective capture area of $A_r$ [$m^2$] of a receive antenna. The case, when the receive and transmit antennas are collocated is called monostatic where $R_1 = R_2$, while the more general case may be a bistatic case, when the receiver antenna is revolved around the target, while the transmit antenna is fixed. In this work, the bistatic RCS is observed to gain insights into scattering for channel modeling in automotive radar applications, where the horizontal cut of the RCS is more relevant than the vertical cut.

A. MW regime

At MW regime, a two layer model of tree trunk and branches was used. Having created volumetric meshes of the bare tree, scattered fields due to the illumination of a vertically polarized plane wave were solved by the Finite Element Method (FEM). For simplicity of the simulations, the ground was considered as a perfect electric conductor (PEC) sheet. We compare the fully branched tree model and the simplified model without the branches as illustrated in Fig. 1. The observed EM field property is RCS for vertically polarized scattered fields. Figure 5 shows the RCS estimates at 1 GHz.

The RCS of the branchless tree trunk on Fig. 5 can be related to the RCS of a electrically long dielectric cylinder [19]. However, the addition of the branches alters the RCS properties, which can be noticed mainly on the back-scattering region at 270° of Fig. 5. The increased back-scattering can be explained with increased scatterer surface of the model. It is important to notice that the side- and forward-scattering are altered as well, which can be explained with multiple scattering due to the branch system. As it seems, the simplified branchless tree model is not adequate for accuracy on the MW regime at 1 GHz. The full branch system is needed to be taken into consideration.

B. MMW regime

The surface model of a tree trunk and branch, justified in Section III-B2 for MMW regime, is used to solve a scattered field when a vertically polarized plane wave is incident. The surface impedance boundary condition (SIBC) assumes that the incident field is totally absorbed in the material apart from the back-scattered field. Hence, the material can be considered through a boundary condition, where the tangential components of the electric and magnetic fields are defined by their ratio, known as the wave impedance. In case of the linearly polarized incident wave, this ratio is given by

$$Z = \frac{E_1}{H_n} = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\varepsilon}}. \quad (6)$$

Thus, the impedance applied on the surface is estimated to be $Z = (120 + 50i)$ $\Omega$ at 100 GHz. Having meshed the surface model using 26 million mesh cells, the scattered fields were solved by the Ray Tracing method of the CST Studio Suite 2021. The tree model is pruned in a way that the diameter of the branches is minimized for 1 cm, which is important for the coherency of the surface mesh. Fig. 6 shows the RCS estimates at 100 GHz.

Fig. 6 shows that the side-scattering has significant differences between the branched and branchless cases, which can be explained by the appearance of additional branches as scatterers. Peculiarily, the back-scattering has close RCS levels for the two cases. This phenomenon can be explained by the dominant scattering of the incident wave by an electrically large and irregular surface of branches, which scatters the wave into several directions, but less probably backwards. This observation suggests that for MMW radar applications, where the back-scattering is of the main interests, bare trees may be modelled without the branches, and can be approximated with a cylindrical shape of the same radius of the trunk.

It must be noted that the comparison of the present results with other studies is difficult, because tree geometries are, in general, so complex that small differences between compared models can lead to considerable change of the RCS estimates.

V. SUMMARY AND FUTURE OUTLOOK

To calculate the EM scattering caused by a tree is a computationally demanding process as the wavelength increases. A bare birch tree model is considered in this work to find out the effects of the branches, whether they are redundant or necessary for an accurate model. The investigations covers an MW, e.g., 1 GHz, and an MMW, e.g., 100 GHz band. At 1 GHz, a two layer volume mesh is used with material parameters based on measurements. The numerically simulated RCS shows that the branches have a significant impact on the scattering and cannot be avoided. At 100 GHz, a novel tree model is introduced, along with the dielectric parameters extrapolated through the coarse analogy between the MW and MMW behavior of the complex permittivity of water. This analogy could give the dielectric parameter estimates above...
20 GHz. The novel tree model is a surface impedance model, which significantly reduces the model complexity. The RCS estimates show that the branches have a negligible impact on back-scattering, and they can be omitted from the model. At MMW regime, therefore, a simplified model of the trunk as a cylindrical body can be used. The right choice of the tree trunk model and numerical solver between 1 and 100 GHz is subject to further study, depending on the penetration depth of the waves into tree trunk and the physical scale of the tree trunk with respect to the wavelength. The highest frequency, where the FEM must be applied, and the lowest frequency, where the Ray-Tracing method is valid, is not known. Consistency of RCS estimates from the two methods at the frequency between 1 and 100 GHz would also be of interest.

It is noteworthy that bare trees are only an approximation of a rare foliage of thin leaves, or of deciduous trees on autumn or winter seasons. The numerical modeling of the foliage requires further research, both from structural and dielectric modelling and simulation points of view. It is also necessary to consider realistic dielectric and conductive parameters of the ground using, e.g., the surface impedance boundary condition, but at the expense of excess complexity for the calculations. Besides, the RCS simulation results should be validated through measurements of the scattering of a whole tree. In case, the model and simulation methods of this work proves to be correct, they serve for modelling various species and shapes of trees, creating generalized statistical models that can be used as references, or as data-sets for the training of artificial intelligence algorithms.

ACKNOWLEDGMENT

This work was supported by the European Commission through the H2020 project Hexa-X (Grant Agreement no. 101015956). The authors would like to thank the guidance of Mr. Pasi Koivumäki for the possibility of 3D modeling of trees using point clouds.

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