A Practical Deconvolution Antenna Method to Retrieve Scattering Profile in Complex Random Media - A Vegetation Case Study at 28 GHz

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***Abstract*—This paper presents a method to improve the extraction the *Radiative Energy Transfer* (RET) theory input parameters for application in vegetation attenuation modeling. The input parameters for this model, which are extracted from specific measurement data, are normally influenced by the radiation pattern of the receiver antenna. A new method to improve the accuracy of the scattering function parameters obtained from measurements is presented. This method is based on the prior analysis of the antenna's radiation pattern distortion while measuring the scattering function, allowing the development of calibration curves, to correct the distorted propagation parameters. The proposed method was tested with measurements conducted inside an anechoic chamber, using real small indoor trees, mimicking a forest scenario using various different receiver antennas at 28 GHz, and the model accuracy improvement was assessed at various vegetation depths.**

***Index Terms*—Propagation modeling, vegetation, trunk layer, millimeter waves.**

I. INTRODUCTION

The phenomena inherent to radiowave propagation through vegetation areas have raised particular interest among researchers in the past decade [1]. In the particular case of terrestrial mobile networks, vegetation may influence the propagation of radiowaves, causing its attenuation, scattering and/or depolarization [2]. Noteworthy, the irregular shapes, the inhomogeneous and the time variant properties of trees yield to one of the most complex topics of research in radiowave propagation [3].

The Radiative Energy Transfer theory (RET) has been reported in the literature [4] as a model leading to more accurate predictions of the signal attenuation in vegetation media in the microwave and millimeter wave bands. In [3], this model has been extensively compared with measurements over the 1 to 60 GHz frequency range, leading to the adoption of ITU-R recommendation for attenuation in vegetation [1].

The RET model relies upon four input parameters, which are vegetation dependent and must be extracted from specific attenuation and scattering measurements. The radiation pattern of the receiver antenna is known to have a major influence on measured signal strength levels [1] and consequently on the input parameters extracted from the measured data. Although various methods to extract these parameters have been reported in the literature [3], none of them appears to have considered the effects of the radiation pattern of the receiver antenna on the estimated values of the extracted RET input parameters.

In this paper a method to reduce the dependency of the scattering function estimated parameter values on the receiver antenna is presented. The method will be assessed with measurements performed in an anechoic chamber using an idealized small scale forest formation made of *Ficus Benjamina* plants.

II. THE RET PROPAGATION MODEL

The RET model [4] is a theoretical model for attenuation in vegetation media, that relies on the assumption that the radio path is a random and homogeneous medium of scatterers, randomly distributed and with an infinitesimal size ds. In this model, each scatterer is characterized by a set of input parameters, including an absorption coefficient (σ_a), which describes the amount of the incoming radiation that is absorbed by the scatterer, the scattering cross section per unit of volume (σ_s), which describes the amount of signal scattered by the medium element volume and the phase function or ($\rho(\hat{s}, \hat{s}')$), which is the scatter directional profile of each scatterer, where $\hat{s}'$ and $\hat{s}$ are the direction of incoming and outgoing radiation, respectively.

The RET model provides the specific intensity $I(\hat{r}, \hat{s})$ at a given point within the vegetation medium $(\hat{r}, \hat{s})$, as a sum of a coherent component I_{ri}, which is reduced in intensity due to absorption and scatter of the incident wave, and an incoherent (diffuse) component I_d, generated due to the multiple scattering occurring within the vegetation volume [4]. The RET mathematical formulation is expressed as

$$s\Delta I(\hat{r}, \hat{s}) = I_{ri} + I_d \tag{1}$$

where

$$\begin{cases} dI_{ri} = -(\sigma_a + \sigma_s) I(\hat{r}, \hat{s}) dl \\ dI_d = \frac{1}{4\pi} \sigma_s \iint_{4\pi} \rho(\hat{s}, \hat{s}') I(\hat{r}, \hat{s}') d\Omega' dl \end{cases} \tag{2}$$

As far as scatterers' phase function is concerned, the RET model assumes that all tree constituents are relatively large when compared to the signal wavelength at micro- and millimeter wave frequencies. Hence, a strong forward scattering is expected and $\rho(\hat{s}, \hat{s}')$ is assumed to be expressed by means of a narrow Gaussian forward lobe superimposed over an isotropic background [5]. Such scattering function is therefore expressed as

$$\rho(\gamma) = \alpha \left(\frac{2}{\beta}\right)^2 e^{-\left(\frac{\gamma}{\beta}\right)^2} + (1-\alpha), \tag{3}$$

where γ is the angle between incident and scattered waves, expressed as $\gamma = cos^{-1}(\hat{s}, \hat{s}')$, α is the ratio of the forward scattered power to the total scattered power and β is the beamwidth of the forward lobe.

Various methods to measure the phase function of a forest formation have been reported in [6], [7]. In these, the receiver is placed inside the vegetation medium and rotated around its vertical axis. For each angular position of the receiver antenna, the signal power is measured and recorded, producing a directional signal profile which is considered to be similar to that of the phase function reported in [3] and [7].

III. PHASE FUNCTION MEASUREMENT DISTORTION ANALYSIS AND PARAMETRIZATION

In transport theory, it is assumed the various scattered wave trains are uncorrelated in phase and can be added in power [2]. The receiver antenna, when placed inside the vegetation medium, gathers the scattered signal from the surrounding trees as shown in Fig. 1. The received signal level can be calculated by summing the directional contributions due to the scattered signal after conveniently weighted by the radiation pattern of the receiver antenna. If the specific scenario presented in Fig. 1 is taken into account, the received signal level will be given by Eq. 4.

$$\begin{aligned} P_{RX}\left(\theta_{RX}\right) &= I\left(\theta_1\right) G_{RX}\left(\theta_1 - \theta_{RX}\right) \\ &+ I\left(\theta_2\right) G_{RX}\left(\theta_2 - \theta_{RX}\right) \\ &+ \ldots \\ &+ I\left(\theta_n\right) G_{RX}\left(\theta_n - \theta_{RX}\right) \\ &= \sum_{\theta_i} I\left(\theta_i\right) G_{RX}\left(\theta_i - \theta_{RX}\right) \end{aligned} \tag{4}$$

where P_{RX} is the received directional spectrum, G_{RX} is the radiation pattern of the receiving antenna (representing the relative directional gain of the antenna) and $I(\theta_i)$ is the directional intensity profile which depends only on the vegetation medium propagation characteristics (*i.e.* independent of the receiver antenna radiation pattern). Some authors [4], [7] suggest that when an homogeneous vegetation volume is considered, the specific intensity directional profile, $I(\theta_i)$, can be used as an approximation for the RET phase function. Using this approximation and recognizing that Eq. 4 represents a discrete convolution, the relation between the received directional spectrum P_{RX}, the effective vegetation phase function $p(\theta)$ and the receiver antenna radiation pattern G_{RX}, can be written as (5), where $*$ denotes a convolution [8].

$$P_{RX}\left(\theta\right) = p\left(\theta\right) * G_{RX}\left(\theta\right) \tag{5}$$

In Eq. 5, both G_{RX} and P_{RX} can be obtained with sufficient accuracy. The radiation pattern of the receiver antenna can be measured inside an anechoic chamber or calculated from simulations whereas the received directional spectrum can be measured by placing the receiver antenna inside the vegetation volume and rotating the receiver antenna over its vertical axis. Consequently, the only unknown in Eq. 5 is the scattering phase function $p(\theta)$ [9].

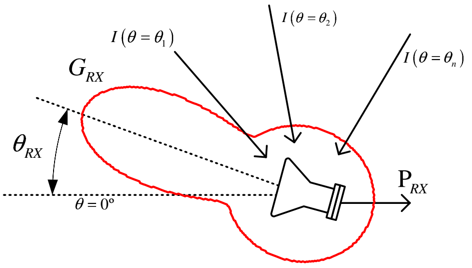


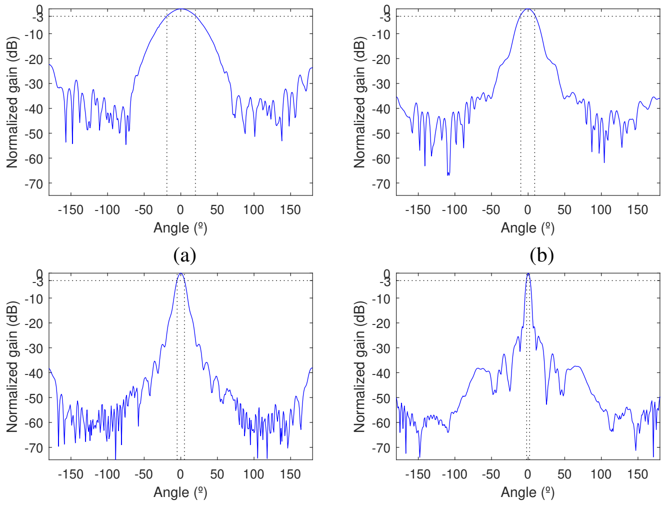
Fig. 1: Phase function measurement through directional spectrum.

At this point, several simulations were conducted to study and analyze the influence of the antenna's radiation pattern G_{RX} on the $p(\theta)$ extraction. This study consisted of using a known antenna radiation pattern, and calculate its convolution with a phase function with pre-established α and β values. Subsequently use the resulting P_{RX} function to extract the α' and β' parameters using RMS error minimization criteria and finally, evaluate the parameter distortion caused by the antenna pattern. This procedure was repeated for several combinations of α and β values and using four different antennas with gains of 10, 20, 25 and 33 dBi, corresponding to a half-power beamwidth (HPBW) ranging from 40° to 5°. The radiation patterns of the antennas used during this study are depicted in Figure 2.

The results of α and β distortion obtained for the 10 dBi standard horn antenna are depicted in Figure 3. In Figure 3a) it is possible to observe the distortion found for the α parameter, for various values of α_{RX}, i.e. α values extracted from P_{RX} function, and for various values of β. These results tell us that if we are measuring a P_{RX} function that is characterized by an α_{RX} of 0.5, and the β value is 10°, we are getting a measurement error of 0.1 and the correct α value should be 0.6. Similar behavior is depicted in Figure 3b) which depicts the β distortion. For β it was found that the distortion caused by the antenna convolution is not dependent on the α value yet, if the P_{RX} function that is characterize by a relatively low β value, the distortion observed becomes pronounced.

The distortion analysis results obtained for the remaining antennas are depicted in Figures 4 to 6. Ideally, the directional spectra measurements for phase function parameter extraction would be conducted with pencil sharp antenna. This would eliminate any distortion caused by the convolution process. However, the results obtained for the 33 dBi antenna, depicted in Figures 6, prove that relatively narrow antennas, exhibiting HPBW around 5°, yield to reduced distortion on the phase function parameter extraction, since the distortion values were found below the 0.015 and 5° for α and β parameters, respectively.

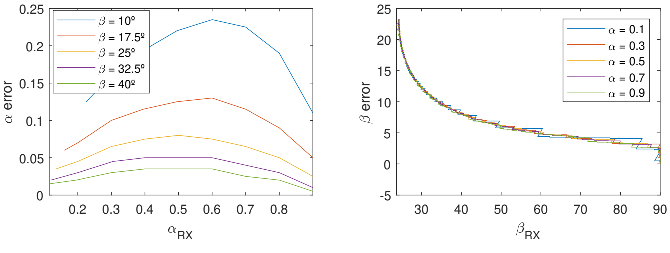
Distortion analysis results depicted in Figures 3 to 6 allow



(a) (b)

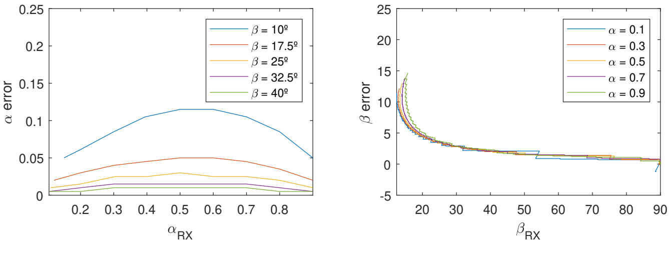
(c) (d)

Fig. 2: Normalized antennas' radiation patterns: a) 10 dBi, b) 20 dBi, c) 25 dBi and d) 33 dBi.



(a) (b)

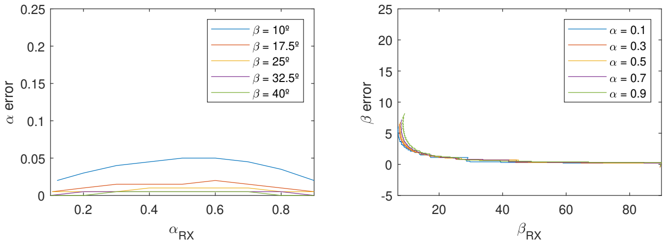
Fig. 3: Phase function distortion by 10 dBi antenna: a) α and b) β.



(a) (b)

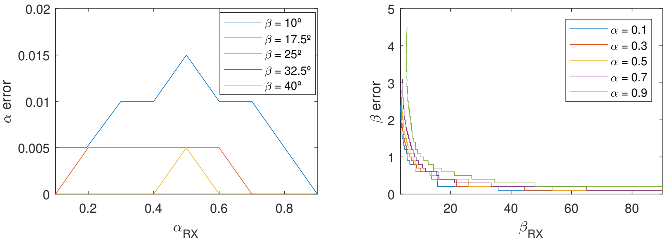
Fig. 4: Phase function distortion by 20 dBi antenna: a) α and b) β.

the development of calibration curves to each antenna taken into consideration. In the next section, these antennas will be used to extract the relevant phase function parameters inside an idealized forest scenario, and the proposed calibration curves will be used to correct the extracted parameter values.



(a) (b)

Fig. 5: Phase function distortion by 25 dBi antenna: a) α and b) β.



(a) (b)

Fig. 6: Phase function distortion by 33 dBi antenna: a) α and b) β.

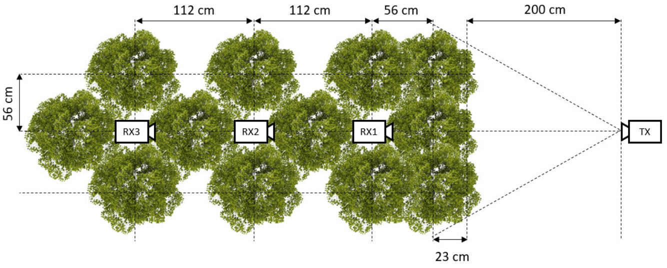
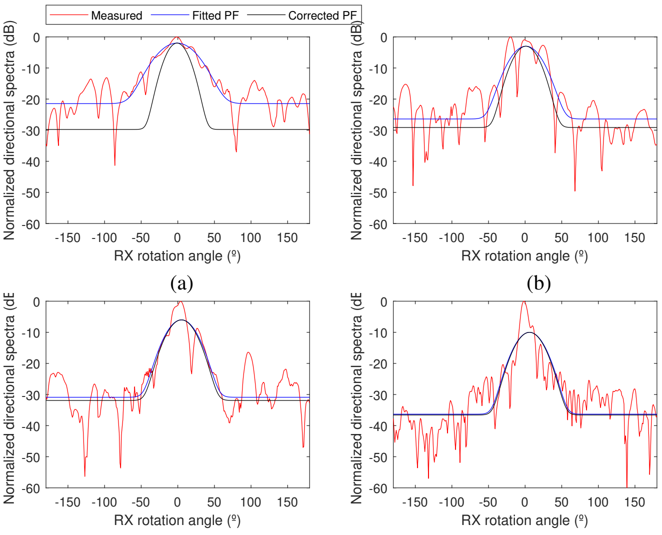


Fig. 7: Anechoic chamber measurement setup.

IV. INPUT PARAMETER EXTRACTION IN TREE FORMATION SCENARIOS

Following the development of the calibration curves for the antennas taken into consideration in this paper, the proposed method for phase function parameter extraction was assessed under an idealized forest environment. To this extent, the tree formation scenario depicted in Figure 7, was assembled in a controlled environment, inside an anechoic chamber, in which 12 Ficus benjamina trees were placed in a regular matrix, providing a quasi homogeneous vegetation media for depths ranging from 0 to 3.3 m. The transmitter was located at a distance of 2 m from the air to vegetation interface and the receiver (RX1) was located behind the first row of trees. Additionally, the receiver antenna was rotated around its vertical axis, from $-180°$ to $180°$ in $1°$ steps, recording the directional spectra in that position. A picture of the measurement scenario is presented in Figure 8.

Fig. 8: Idealised forest setup.



(a) (b) (c) (d)

Fig. 9: Directional spectra measurements for PF parameter extraction: a) 10 dBi, b) 20 dBi, c) 25 dBi and d) 33 dBi antennas.

These measurements were repeated using all the antennas taken into consideration, that is, 10, 20, 25 and 33 dBi standard horn antennas. Subsequently, the measured P_{RX} function was used to extract the α and β parameter values using the RMS error minimization criteria. The measurement results obtained for P_{RX} and the fitted $p(\theta)$ using the optimized α and β values are depicted in Figure 9, in red and blue, respectively.

Additionally, the α and β values fitted from measured P_{RX} are depicted in Table I. In this, it is possible to observe the distortion effect of the antenna while extracting the relevant input propagation parameters. Given that the forest scenario and the signal frequency are not changed, the forest α and β parameters should remain constant, regardless the antenna used for parameter extraction. However, the parameter values obtained from P_{RX} are considerably different from antenna to antenna, specially from 10 dBi to 33 dBi antenna, considering the usual range of values found for α and β parameters [1].

TABLE I: Scattering parameters obtained 28 GHz.

Antenna	$P_{RX}(\theta)$		$p(\theta)$	
	α_{RX}	β_{RX}	α_f	β_f
10 dBi	0.85	29.2°	0.92	15.9°
20 dBi	0.89	22.1°	0.91	18.0°
25 dBi	0.91	20.8°	0.92	19.7°
33 dBi	0.93	20.2°	0.93	19.6°
Mean	0.90	23.1°	0.92	18.3°
Standard Dev	0.03	4.16°	0.01	1.8°

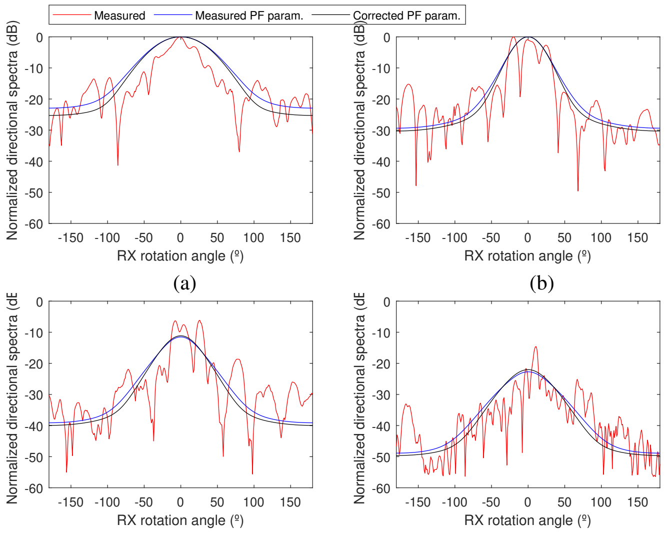
Subsequently, the antenna calibration curves, developed in the previous section of this paper, were used to correct the fitted α and β values, obtained from measured P_{RX}, for all the antennas under test. The corrected α and β values are depicted in Table I, under the $p(\theta)$ column, in which can be observed that the corrections performed using the antennas' calibration curves, yield to more consistent α and β values, since they are now relatively constant, regardless the antenna used for extraction. Additionally, as the antennas' HPBW is reduced, the corrections applied to the α and β parameters extracted are less pronounced, which is in line with the consideration that a pencil sharp antenna would not cause distortion on the phase function measurement and its parameter extraction. This can be observed by comparing the corrections made to measurements using the 10 and 33 dBi antennas.

V. VALIDATION OF THE PARAMETER EXTRACTION CORRECTION METHOD

The proposed method for correction of the measured α and β, which is based on the prior knowledge of the antennas' calibration curves, was able to provide consistent values for the input propagation parameters of the idealized forest scenario. In this section, the overall RET model results accuracy improvement, i.e. using corrected α and β parameters, is evaluated at various vegetation depths. To this extent, the directional spectra measurements conducted at receiver position RX1, using various receiver antennas and at a vegetation depth of 80 cm, were repeated at receiver positions RX2 and RX3, also depicted in Figure 7, corresponding to vegetation depths of 192 and 304 cm, respectively.

Additionally, the idealized forest scenario was modeled with the RET model using both sets of input propagation parameters, i.e. the α and β fitted from the measured P_{RX}, and the corrected values using the antennas' calibration curves. The remaining RET input propagation parameters, i.e., σ_a and σ_s, are not affected by the antenna radiation pattern hence, their extraction was based on the available measurement data acording to the method presented in [9] and kept constant for all the RET simulations.

Measurement and RET simulation results using both sets of input propagation parameters are depicted in Figure 10 a) in receiver position RX1 using the 10 dBi antenna, b) in receiver position RX1 using the 20 dBi antenna, c) in receiver position RX2 using the 25 dBi antenna and d) in receiver position RX3 using the 33 dBi antenna.



(a) (b) (c) (d)

Fig. 10: Directional spectra results at: a) RX1 with 10 dBi antenna, b) RX1 with 20 dBi antenna, c) RX2 with 25 dBi antenna and d) RX3 with 33 dBi antenna.

This first remark to these measurement results is that the both measured and simulated results are normalized with respect to the signal level obtained at receiver position RX1 when pointing directly at the transmission. This indicates that the idealized forest is correctly parametrized by the RET model since the simulated directional spectra results are not only able to predict the amount of scattering in the side and back scattering regions, but also to account for the excess attenuation caused by the increasing vegetation depth.

Since the RET accuracy enhancement while using the corrected input propagation parameter set may not be clearly observed in Figure 10, the RMS error between the directional spectra measurement results and the RET simulation using both sets of α and β was evaluated. The results of this quantitative assessment are depicted in Tables II and III, for measured and corrected parameters, respectively. Despite the accuracy enhancement is not as pronounced as it might be expected, Tables II and III proved that the overall model accuracy is improved when using the corrected values obtained for α and β parameters. Additionally, the idealized forest used for validation purposes was composed by relatively small indoor trees and provided a relatively short vegetation depth. The authors believe that the effect of using this enhanced method for input parameter extraction will be more pronounced at larger vegetation depths, in which the coherent (direct) component becomes severely attenuated and the diffuse scattering becomes predominant.

VI. CONCLUSIONS

This paper presents a method to obtain the scattering parameters from vegetation media which is independent of the receiver antenna used. This method is based on the prior analysis of the antenna's radiation pattern distortion while measuring the scattering function, which can be used latter to develop the calibration curves, to correct the distorted input propagation parameters.

TABLE II: RMS error obtained with measured PF parameters.

Position	Measured PF parameters				
	10 dBi	20 dBi	25 dBi	33 dBi	Mean
RX1	5.0	4.9	5.5	4.9	5.1
RX2	10.4	5.3	6.5	7.0	7.3
RX3	5.2	9.8	4.4	5.5	6.2
Mean	6.9	6.7	5.5	5.8	6.2

TABLE III: RMS error obtained with corrected PF parameters.

Position	Measured PF parameters				
	10 dBi	20 dBi	25 dBi	33 dBi	Mean
RX1	5.2	4.9	5.4	4.9	5.1
RX2	9.3	5.3	6.5	7.0	7.0
RX3	5.3	8.9	4.3	5.6	6.0
Mean	6.6	6.4	5.4	5.8	6.0

The proposed method was tested with measurements conducted inside a forest scenario using various different receiver antennas at 28 GHz, and the overall model accuracy improvement was assessed at various vegetation depths.

Further work will be considered in an effort of extending and validating the input propagation parameter correction method in real outdoor forest scenarios, in order to evaluate its impact at larger vegetation depths.

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