Modeling of Multipath Propagation Components Caused by Trees and Forests

F. M. Schubert*, B. H. Fleury†, P. Robertson*, R. Prieto-Cerdeira‡, and A. Steingass*, A. Lehner*
*German Aerospace Center (DLR)
82234 Wessling-Oberpfaffenhofen, Germany
fmschubert@ieee.org, {patrick.robertson,alexander.steingass,andreas.lehner}@dlr.de
†Aalborg University, Institute of Electronic Systems
Fredrik Bajers Vej 7, DK-9220 Aalborg, Denmark
bfl@es.aau.dk
‡European Space Agency ESA/ESTEC
Keplerlaan 1, 2201AZ Noordwijk, The Netherlands
Roberto.Prieto.Cerdeira@esa.int

***Abstract*—The further development of multipath mitigation methods for Global Navigation Satellite Systems (GNSS) depends on the knowledge of the wave propagation circumstances present in various scenarios. The modeling of the multipath propagation properties for land-mobile users play a vital role in modern GNSS receiver algorithm development. This paper proposes a model for the simulation of a vehicle traveling through a rural environment. The canopies of trees and forests cause a strikingly time-variant channel impulse response (CIR). The proposed approach models individual multipath components and the resulting small-scale fading of forests in terms of infinitesimal point scatterers which are spread out in a cuboidal canopy volume. The output of the proposed model is compared with channel sounding measurements.**

I. INTRODUCTION

The performance of global navigation satellite system (GNSS) receivers is strongly dependent on the present underlying propagation conditions in the radio channel between the satellite and the terrestrial receiver. Systematic errors like ionospheric distortions or satellite clock deviations can be compensated for by the use of dual-frequency transmission and differential GNSS techniques. Errors which are not common to a base station providing local corrections and a receiver cannot be corrected by such differential methods. This is the reason why multipath propagation is still responsible for the most dominant errors in GNSS overall performance-based positioning. The situation for long delay multipath components (related to the chip length) will be improved with the advent of ranging signals with higher bandwidths as to be provided by the modernized GPS and Galileo. But these enhancements will not avoid the general issue of GNSS multipath signal reception. Especially paths with small excess distances compared to the line-of-sight (LOS) signal cause high ranging errors. Although a higher number of satellites will be available in the future, the general problem of signal shadowing and blockage persists for example in urban and rural environments.

To be able to develop effective mitigation methods for high-multipath situations which are present for example in urban and rural environments, the radio propagation channel for GNSS has to be properly modeled. Channel models based on broadband measurements in L-band were developed for example for typical urban vehicle [1] and urban pedestrian [2] use cases. The aim of this contribution is to present a newly developed GNSS channel model that describes multipath propagation generated by roadside trees and forests in rural land-mobile scenarios.

Wave propagation effects caused by trees which affect frequencies in the L-band comprise shadowing and attenuation caused by the the leaves and the trunk, scattering caused by branches and forks, and reflection and diffraction mainly caused by the trunk.

The rural environment mainly consist of trees and groups of trees like alleys and forests. The modeling approach presented in this paper focuses on the description of wave propagation induced by single trees and forests. In accordance to available experimental data, the frequency under consideration lies in L-band. This also serves the prospective main application of the model, namely the simulation of GNSS signal propagation in rural settings.

The paper is organized as follows. Section II gives an overview of the wave propagation effects in relation to trees. Section III introduces the modeling approach. Section IV presents channel sounding data of a rural setting and compares these measurements with output generated by the proposed model. The concluding Section V summarizes the findings and provides future prospects to further refine and validate the proposed model.

II. EFFECTS OF TREES ON RADIO WAVE PROPAGATION

Tree canopies can be described as characteristically shaped bodies which depend on the trees' species. For instance, the canopies of deciduous trees resemble ellipsoidal shapes wheras conifer canopies exhibit more of a conical form. The canopy itself consists of branches, forks and leaves of different dimensions, orientations and densities which differ from species to species.

Because canopies consist of a plethora of such branches and forks with arbitrary size and orientation within certain tree-type specific ranges, the exact back-scattering pattern and its angular dependency are unknown. Investigations were made on the scattering of simple tree-like shapes, for example a thin branch attached to a thicker branch [3]: Finite-difference time-domain (FDTD) simulations at 20 GHz were carried out as well as propagation measurements of artificial forks made of metal in an anechoic chamber. Although the frequency of these experiments was much higher than the one considered in this work, the results show that scattering by fork-like structures in the dimension of the wavelength cause characteristic radial star-shaped patterns which point outwards from the scatterer.

The trunk generates scattering and diffraction. It furthermore attenuates impinging waves when it is located between transmitter and receiver. Throughout the seasons, the density of leaves as well as the water content of trees vary.

Simplifications have to be made for the development of a channel model with reasonable computational needs. For the present consideration of trees which are typical for the temperate zone, the following assumptions are made:

- Branches and leaves are uniformly and independently distributed and oriented inside the canopy.
- The leaves in the canopy are mainly responsible for attenuation since they are smaller than the wavelength.
- The dimensions of branches and forks inside the canopy are of the order of the wavelength and cause scattering with a certain three-dimensional pattern.
- Multi-bounce scattering occurs inside the canopy.
- The tree water content stays constant.
- The movement of the tree and its constituent parts due to the wind is negligible.

The scattering behavior observed in [3] can be conveyed to the land-mobile case of a transmitting satellite, a receiving vehicle and a scattering tree canopy. Since a physical simulation of a complete tree similar to the mentioned approach is too complex to conduct, the following section proposes a simplified tree canopy scattering model. The proposed model allows for the efficient yet accurate simulation of the scattering behavior of tree canopies in the context of a satellite to land-mobile scenario.

III. MODEL FOR VEGETATION SCATTERING AND ATTENUATION

A. Model for the Time-Variant Channel Response of Canopies

The proposed model describes the time-variant CIR in rural environments. To account for the frequency-selective characteristics of vegetation scattering in the considered bandwidth, all elements of the signal sum that enter the receiver front-end are modeled as Dirac-impulse-like components weighted by complex coefficients. One CIR at time t consists of an LOS component as well as multipath components caused by the vegetation scattering which imping at the receiver at different excess delays τ_i. The CIR thus reads

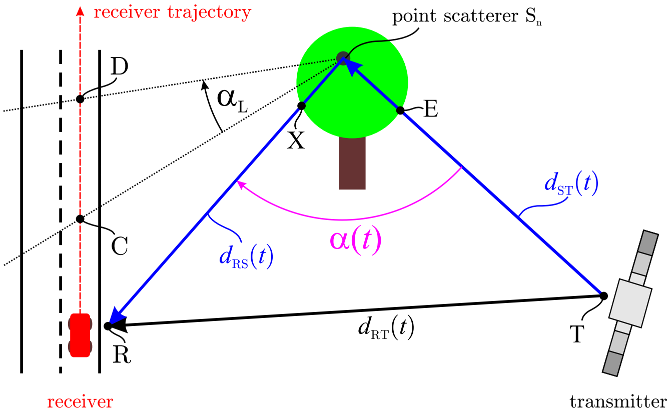

Fig. 1. Geometry of transmitter (satellite), receiver (vehicle), and vegetation object (tree). The creation and desctruction points of the sample point scatterer are denoted by C and D, respectively. The life angle of the scatterer is denoted by α_L. The points E and X are the entry and exit points of the rays which are piercing through the canopy.

$$h(t,\tau) = s_0(t)\delta(\tau - \tau_0(t)) + \sum_{i=1}^{D(t)} s_i(t)\delta(\tau - \tau_i(t)), \qquad (1)$$

where $s_0(t)$, given as

$$s_0(t) = g_0(t)e^{j\varphi_0(t)} \qquad (2)$$

is the complex weight of the LOS signal, and $s_i(t)$, given as

$$s_i(t) = g_i(t)e^{j\varphi_i(t)} \qquad (3)$$

is the complex weight of the multipath components. The $\tau_i(t)$ and $D(t)$ denote the excess delays and the number of multipath components, respectively. The point scatterers can consist of a linked scatterer chain which accounts for multi-bounce scattering inside the canopy. In the proposed channel model, the shape of the canopy volume can be conical and ellipsoidal for trees and cuboidal for forests. Yet, the locations of the scattering elements are not determined using a ray-tracing approach, they are rather drawn from a distribution that range identical to the canopy volume. The following subsections describe how the weights and delays in (1) are determined.

B. Scattering

The objects inside the tree canopies causing multipath propagation and diffuse scattering are modeled as point scatterers inside the canopy which re-radiate the incident wave. As mentioned in Section II, radial scattering patterns which point outwards from the scatterer center are assumed for the point scatterers behavior inside the canopy. A life angle α_L is determined for each point scatterer under which the vehicle receives the signal which is re-radiated by the them, see Fig. 1 The radial scattering pattern emerging from the point scatterer cause a dependency of the received signal on the angle $\alpha(t)$ between the lines transmitter–scatterer $d_{\mathrm{ST}}(t)$ and scatterer–receiver $d_{\mathrm{RS}}(t)$. The creation process of the point scatterers depends on $\alpha(t)$. The life angles of the scatterers are drawn from a truncated exponential distribution $\tilde{p}_e(x)$. The probability density function of an exponential distribution with parameter $b > 0$ is given as

$$p_e(x) = \begin{cases} 0 & \text{for} \quad x \leq 0 \\ be^{-bx} & \text{for} \quad x > 0 \end{cases} \tag{4}$$

Its distribution function is given as

$$P_e(x) = \begin{cases} 0 & \text{for} \quad x \leq 0 \\ 1 - e^{-bx} & \text{for} \quad x > 0 \end{cases} \tag{5}$$

The exponential distribution is truncated at $x = 360°$ and normalized to $P_e(360°)$ resulting in the probability density function

$$\tilde{p}_e(x) = \begin{cases} 0 & \text{for} \quad x \leq 0 \\ \left[1/(1 - e^{-b \cdot 360°})\right] \cdot be^{-bx} & \text{for} \quad 360° \geq x > 0 \\ 0 & \text{for} \quad x > 360° \end{cases} \tag{6}$$

The parameter $1/b = \alpha_E$ can be set in the model configuration. When α changes more than the life angle, the respective scatterer is destroyed and re-created at a different position.

C. Amplitude calculation

The attenuation of canopies and trunks are modeled as constant specific attenuation. This parameter is definable per tree and lies between $0.2\,\mathrm{dB/m}$ and $3\,\mathrm{dB/m}$, typically [4].

The resulting amplitudes are normalized to the free-space loss of the LOS signal, resulting in an amplitude of $|a_0(t)| = 1$ for the case where the LOS signal is unobstructed. The transmitter and receiver antennas are assumed to be omnidirectional antennas with gains $g_t = 1$ and $g_r = 1$, respectively. In this case, the free-space loss can be written as

$$a_{\mathrm{f}}(t) = \frac{P_t}{P_r(t)} = \left(\frac{4\pi d(t)}{\lambda}\right)^2 \tag{7}$$

with distance $d(t)$, wavelength λ, constant transmitted power P_t, and time-dependent received power $P_r(t)$.

The free-space loss for the unobstructed LOS signal amplitudes dependent on the distance d_{RT} from transmitter to receiver thus reads

$$a_{\mathrm{f,RT}}(t) = \frac{\sqrt{P_t}}{\sqrt{P_r(t)}} = \frac{4\pi d_{\mathrm{RT}}(t)}{\lambda}. \tag{8}$$

A transmitted amplitude of $s_{\mathrm{T}} = 1$ is assumed. On the length $d_{\mathrm{ET}}(t)$ from transmitter to the entry point E on the canopy surface, the signal is attenuated by the FSL

$$a_{\mathrm{f,1}}(t) = \frac{4\pi d_{\mathrm{ET}}(t)}{\lambda}, \tag{9}$$

see Fig. 1. Since multi-bounce scattering is considered, the total length traveled inside the canopy is the path from the entry point E over all scatterers $\mathrm{S}_0 \ldots \mathrm{S}_n$ to the canopy exit point X:

$$d_{\mathrm{XSE}}(t) = |\mathrm{E}-\mathrm{S}_0| + |\mathrm{S}_0-\mathrm{S}_1| + \ldots + |\mathrm{S}_{n-2}-\mathrm{S}_{n-1}| + |\mathrm{S}_{n-1}-\mathrm{X}|, \tag{10}$$

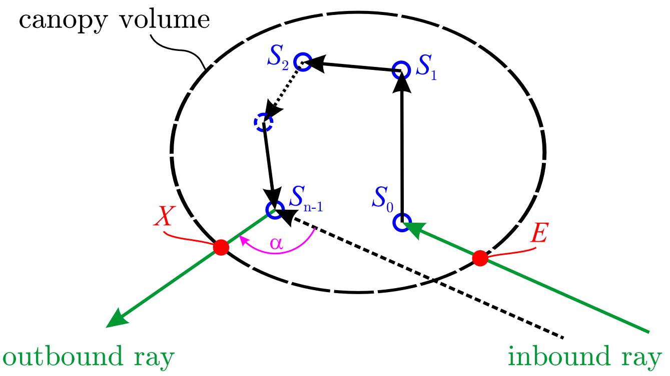

Fig. 2. Geometry of multi-bounce scattering and the respective point scatterers inside the tree canopy. The angle α between scatterer and receiver is determined using the last point scatterer in the scatterer chain.

On this path length the signal is attenuated by the canopy's specific attenuation a_c:

$$a_{\mathrm{b}}(t) = d_{\mathrm{XSE}}(t) \cdot a_c \tag{11}$$

From the canopy exit point X to the receiver R, the FSL attenuates the signal by

$$a_{\mathrm{f,2}}(t) = \frac{4\pi d_{\mathrm{RX}}(t)}{\lambda}. \tag{12}$$

It is assumed that every point scatterer in the multi-bounce scatterer chain has a directional property of re-radiating the incident signal. The amplification factors of the scatterer chains are modeled as normally distributed g_{S_i} for the ith scatterer. The mean value and variance of this distribution are input parameters to the proposed model.

It is furthermore assumed that the point scatterers re-radiate a higher field intensity back into the direction of the incident wave and a smaller intensity for the through scattering. This behavior is modeled as a functional dependency on the angle $\alpha(t)$ between transmitter, scatterer, and receiver, given as

$$a_\alpha(t) = \frac{1}{\cos(\alpha(t)/2)}. \tag{13}$$

In a scatterer chain, α is determined using the last scatterer, see Fig. 2.

Completing the received amplitude for the ith multipath component thus yields

$$g_i(t) = \frac{s_{\mathrm{T}} \cdot g_{\mathrm{S}_i}}{a_{\mathrm{f,1}}(t) a_{\mathrm{b}}(t) a_{\mathrm{f,2}}(t) a_\alpha(t)} \tag{14}$$

before the normalization to the amplitude of the unobstructed LOS signal. The phases of the LOS signal and the multipath components signals are calculated using the traveled distance and the wavelength. Coherent scattering is assumed to be only dependent on the geometrical distances and not on phase changes introduced by the scatterers. Thus a multipath component's phase is solely dependet on the total path length from transmitter over all point scatterers to the receiver:

$$\varphi_i(t) = \frac{2\pi}{\lambda}\left(d_{\mathrm{ET}}(t) + d_{\mathrm{XSE}}(t) + d_{\mathrm{RX}}(t)\right) \tag{15}$$

Fig. 3. The forest as seen from the receiving vehicle's front camera.

When the LOS signal is obstructed by a tree canopy or trunk, its amplitude is attenuated by the canopy's specific attenuation, using the piercing length through the canopy from the entry point to the exit point:

$$a_{\mathrm{p}}(t) = d_{\mathrm{XE}}(t) \cdot a_c. \tag{16}$$

The complex ampltitude of the LOS signal is given by

$$a_0(t) = \frac{s_{\mathrm{T}}}{a_{\mathrm{f,RT}}(t) a_{\mathrm{p}}(t)}, \tag{17}$$

before the normalization to the amplitude of the unobstructed LOS signal is applied. The LOS phase is calculated as

$$\varphi_0(t) = \frac{2\pi}{\lambda} \cdot d_{\mathrm{RT}}(t). \tag{18}$$

IV. EXPERIMENTAL INVESTIGATIONS AND COMPARISON

The German Aerospace Center (DLR) conducted various channel sounding measurements at a center frequency of 1.51 GHz and a bandwidth of 100 MHz in a rural surrounding approximately 30 km south-west of the Munich city center [5]. A zeppelin served as a hovering transmission platform resembling the satellite and a receiving van roamed the rural environment. For the example presented in this section, the elevation of the zeppelin was 62°. To demonstrate the rural channel model's performance, the recordings of a drive past a forest with the approximate length of 29 m, 24 m width, and 15 m height is compared to the model. The picture of the van's front camera just before it passes by the forest can be seen in Fig. 3. The recordings are shown in Fig. 4.

The channel model implementation offers a three-dimensional visualization of the defined scenery. An example situation can be seen in Fig. 5. For the comparison, the same geometrical parameters of the scenery was used as input to the proposed model. In Fig. 3 it can be seen that the forest overhangs over the road. Thus, the simulated receiver is set to the left side of the road to reach as close to the simulated forest as was the case during the example measurements.

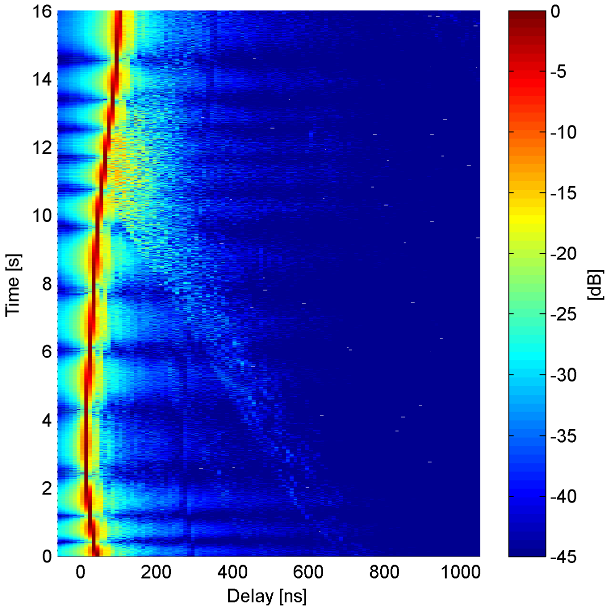

Fig. 4. Measured raw channel impulse response as caused by the forest which is shown in Fig. 3.

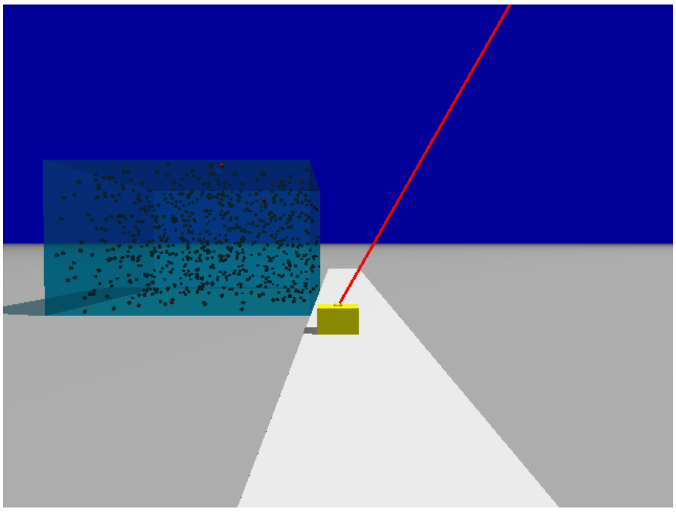

Fig. 5. Visualization of the proposed model. The forest is shown as transparent box on the left which contains the point scatterers shown as small red spheres. The yellow box represents the vehicle's position. The red beam indicates the LOS signal path.

The accuracy of the simulated wave propagation is dependent on the number of scatterers per volume unit. The more scatterers are chosen per cubic meter the more multipath components can be considered. On the other hand, a greater number of point scatterers leads to higher computational needs. The number of point scatterers was chosen to $0.07\,\mathrm{scatterers/\,m^3}$ to achieve good agreement with the measurements with reasonable computational needs. The mean

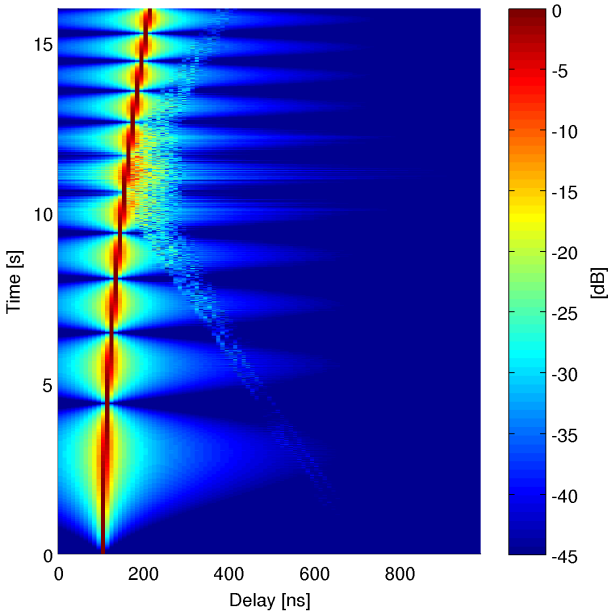

Fig. 6. CIR as generated for the modeled forest which is shown in Fig. 5.

value and the variance of the normal distribution for the point scatterers' amplification factors are set to $\mu = 43$ and $\sigma^2 = 8$ in linear scale, respectively. The specific attenuation of the canopy is set to $a_c = 0.95\,\mathrm{dB/\,m}$. The parameter for the life angle random distribution was set to $1/b = \alpha_E = 1°$. The parameters μ, σ^2, and a_c were chosen to fit the measurement data. Fig. 6 shows the generated CIR. The raw measurements and the model output match well. The raw measurements in Fig. 4 show a larger delay spread than the model in Fig. 6. This is due to the part of the forest that was overhanging over the road during the measurements. This lead to a larger delay range while the van was close to the forest. Another reason is the approximation of the varying specific attenuation of the forest in reality with a constant specific attenuation used in the model. A varying delay spread can be observed when parts of the canopies exhibit a smaller attenuation than other parts.

V. CONCLUSIONS AND OUTLOOK

A channel model for multipath propagation and attenuation as caused by trees and forests has been presented. The proposed model allows for the definition of an artificial scenery in which objects such as trees and forests can be placed. Tree trunks are modeled as cylinders with a constant specific attenuation. Canopies are modeled as geometrical bodies of ellipsoidal, conical, or cuboidal shapes. The multipath propagation behavior as caused by this type of vegetation is mimicked by point scatterers which are distributed inside the canopy volumes. Each scatterer is received during certain life angles which are exponentially distributed. The scatterers' amplitudes follow a normal distribution whereas their phases are solely dependent on the distance traveled by the wave. The scatterers are assumed to exhibit a directional re-radiation pattern. The gain towards the receiver's direction is modeled as being normally distributed. Although simplifications were made compared to real trees, the resulting CIR of the proposed model shows good agreement to channel sounding measurements. Even though vegetation possesses complex propagation properties the proposed approach offers an accurate model with reasonable computational needs.

The whole available set of rural channel sounding measurements will be used to derive the set of parameters which are needed for the model's random distributions. Another approach would be a wave propagation evaluation of typical branch and fork shapes. The hitherto unknown directional pattern of the scatteres could be deduced from this information and serve as refining input to the proposed model.

REFERENCES

[1] A. Lehner and A. Steingass, "A channel model for land mobile satellite navigation," in *Proceedings of the 18th International Technical Meeting of the Institute of Navigation Satellite Division*, Long Beach, California, USA, 2005.

[2] A. Lehner, A. Steingass, and F. M. Schubert, "A location and movement dependent GNSS multipath error model for pedestrian applications," in *Proceedings of the European Navigation Conference GNSS*, Naples, Italy, 2009.

[3] R. F. S. Caldeirinha, "Radio characterization of single trees at micro- and millimetre wave frequencies," Ph.D. dissertation, University of Glamorgan, 2001.

[4] "Attenuation in vegetation," Rec. ITU-R P.833-6, International Telecommunication Union, 2007.

[5] A. Steingass and A. Lehner, "Measuring the navigation multipath channel: A statistical analysis," in *Proceedings of the 17th International Technical Meeting of the Institute of Navigation Satellite Division (ION GNSS 2004)*, Long Beach, California, USA, 2004.