Modeling the GNSS Rural Radio Channel: Wave Propagation Effects caused by Trees and Alleys

F. M. Schubert[1,2,3] (*ION member*), A. Lehner[1], A. Steingass[1], P. Robertson[1], B. H. Fleury[3], R. Prieto-Cerdeira[2]
[1]German Aerospace Center (DLR), Institute of Communications and Navigation
[2]European Space Agency, ESA/ESTEC
[3]Aalborg University, Department of Electronic Systems

BIOGRAPHIES

F. M. Schubert studied Electrical Engineering and Information Technology at the University of Karlsruhe, Germany. Since 2007 he is member of the scientific staff at the Institute of Communications and Navigation, German Aerospace Center (DLR). During his studies, he was involved in a research project concerning inertial measurement unit (IMU) calibration at the Delft University of Technology, Delft, The Netherlands, and he developed a simulation software for a robust powerline communication system at the Massachussetts Institute of Technology, Cambridge, USA. Since 2007, F. M. Schubert is participating in the European Space Agency's Networking/Partnering Initiative (NPI) together with DLR and the University of Aalborg working towards his Ph.D. He is working on topics such as radio channel modeling for satellite navigation and the influences of harsh multipath environments on satellite navigation receiver performance.

A. Lehner studied Mechatronics at the Johannes Kepler University in Linz. Since 2001, he is a research scientist at the German Aerospace Center. In 2007 he received a Ph.D. in Electrical Engineering from the University of Erlangen-Nuremberg, Germany. His research and project work focuses on the analysis of multipath and interference effects in satellite navigation systems and the design of inter-vehicle communication systems.

A. Steingass received his Electrical Engineering diploma in 1997 from the University of Ulm, Germany. Since then he has been a research scientist at the German Aerospace Center. He has been involved in several projects in the area of satellite navigation and location-dependent mobile services. In 2002 he received his doctoral degree from the University of Essen.

P. Robertson received a Ph.D. from the University of the Federal Armed Forces, Munich, in 1995. He is currently with DLR, where his research interests are navigation, sensor based context aware systems, signal processing, and novel systems and services in various mobile and ubiquitous computing contexts.

B. H. Fleury received the diploma in Electrical Engineering and Mathematics in 1978 and 1990 respectively, and the doctoral degree in Electrical Engineering in 1990 from the Swiss Federal Institute of Technology Zurich (ETHZ), Switzerland. Since 1997 B. H. Fleury has been with the Department of Electronic Systems, Aalborg University, Denmark, as a Professor in Communication Theory. He is the Head of the Section Navigation and Communications, one of the eight labs of this department. Since April 2006 he has also been affiliated as a Key Researcher with Forschungszentrum Telekommunikation Wien (FTW), Austria. B. H. Fleury's current areas of research include stochastic modelling and estimation of the radio channel, especially for multiple-input multiple-output (MIMO) applications and in fast time-varying environments, and iterative information processing with focus on efficient, feasible advanced receiver architectures.

R. Prieto-Cerdeira received his Telecommunications Engineering degree in 2002 from the University of Vigo, Spain, and followed postgraduate studies on Space Science and Radioastronomy in Chalmers University of Technology, Gothenburg, Sweden. Since 2004, he has been with the European Space Agency (ESA/ESTEC) in the Wave Interaction and Propagation Section where he is responsible of the activities related to radiowave propagation in the ionosphere and local environment for Global Navigation Satellite Systems (GNSS) such as Galileo and EGNOS projects, satellite mobile communications, and remote sensing and planetary radio science projects.

ABSTRACT

Among the various physical influencing factors with the potential to degrade the overall performance of a global navigation satellite system (GNSS), the behavior of the radio wave propagation channel occupies doubtlessly a cen-

tral role. Especially multipath propagation and signal shadowing cause high ranging and hence positioning errors in current receivers.

Although new signals and ranging codes with higher bandwidths become available, the principal issues inherent to the time-varying GNSS radio channel cannot fully be eliminated. Detailed analysis and knowledge of the radio channel characteristics under realistic conditions are essential to identify and eventually be able to mitigate such disturbances.

The goal of the presented work is to establish an understanding of the propagation conditions in rural settings for vehicular land-mobile users.

As a contribution to a comprehensive GNSS rural channel model, the effects caused by single trees are examined. Even though individual trees spaced afar from each other along a road do not evoke much harm to the smoothing tracking algorithm of a delay-lock-loop (DLL), an alley can profoundly impact a GNSS receiver's tracking performance.

1 INTRODUCTION

Compared to radio channel modeling in the digital communication domain, channel modeling for satellite positioning, and especially for GNSS positioning applications is still in its beginnings. Only since recent years realistic channel models, for example for urban [2] [4], sub-urban [5] and pedestrian [3] scenarios, have been developed. The wave propagation effects caused by roadside trees and alleys are very pertinent to channel modelling aspects for GNSS applications.

Trees close to the road cause periodic deep fades in the order of -10 to -30 dB of the signal when the line of sight (LOS) signal is shadowed by a tree's canopy. In addition, the trees' canopies show strong reflective and scattering behaviour that can even exceed the power of the direct signal path when the receiver is approaching a tree.

Both effects, i.e. the deep fades and the strong reflections of the satellite signal in close proximity of the vehicle, happen frequently and repetitively in rural settings which imposes GNSS receivers to a demanding situation in surroundings dominated by tree vegetation. Consequently, the modeling of the GNSS rural radio channel presented in this paper will focus on shadowing and scattering of single trees along a road. To demonstrate the effect an alley has on a GPS receiver's performance, recorded channel measurements of a ride through an alley is used in a time-domain simulation.

The paper is organized as follows: Section 2 describes the definition of the scenario including the user vehicle trajectory, the tree positions, and the geometric parameters for the tree trunk and the canopy. Section 3 introduces the signal model and illustrates how the incoherent scattering caused by trees is being approximated. Section 4 includes a comparison of model output to channel sounding measurement data. The imposed stress of a ride through an alley on a GPS tracking loop is examined in Section 5. The concluding Section 6 summarizes the main features that were found from the measurements and how they were converted to model properties.

Figure 1. Picture of the example tree.

2 MODEL INPUT

Physically, a treetop consists of a heterogeneous multitude of attenuating and scattering elements. Leaves cause mainly attenuation due to their water content whereas structures at wavelength scale such as branches and forks induce scattering at *L*-band. To analyze these phenomenas in their full complexity one would have to conduct a finite-difference time-domain (FDTD) simulation. Due to the high amount of processing power and memory needed to carry out such simulations it has only been done for small tree-like structures consisting of few branches and leaves [1]. To establish a model that is suitable for GNSS simulation, the complex physical features of a tree is drastically simplified. Tree trunks are modeled by cylinders with given radii and heights and the canopy is approximated by a spherical volume.

Channel sounder measurements at a center frequency of 1.51 GHz and a bandwidth of 100 MHz, which were taken in a rural environment, are available to determine the model parameters. An example of raw channel impulse responses (CIR) are shown in Fig. 3. The transmitter was located at an elevation angle of 44°. The incoherent scattering components can be seen as reflections coming closer from a delay of $\tau = 400\,\mathrm{ns}$ until the vehicle is right below the tree and the LOS signal gets blocked at $t = 596.8\,\mathrm{s}$.

The proposed model approximates the tree canopies scattering by sphericals volumes which contain a plethora of point scatterers. The scatterers' positions are uniformely distributed. These point scatterers reproduce the characteristic speckle-like reflective behaviour caused by the trees' heterogeneous composition that can be seen in Fig. 3. To

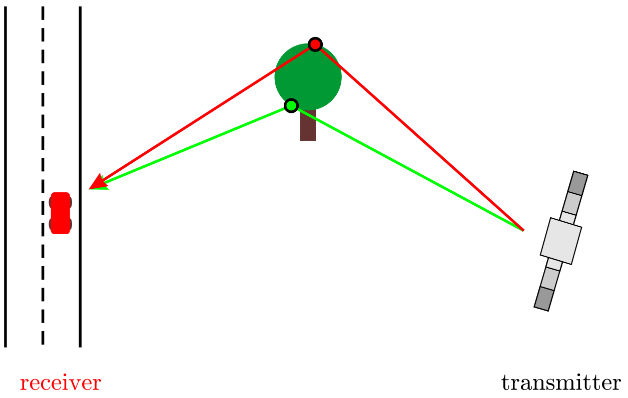

Figure 2. Minimum and maximum excess distance of a single reflector on the treetop surface.

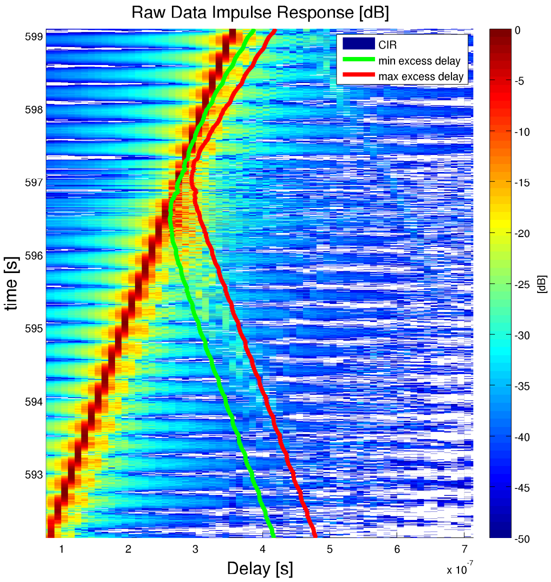

Figure 3. Raw channel impulse measurements of a ride by a single tree.

determine the delay spread under which the reflected components of the treetop scatterers appear, a spherical tree canopy with a radius of 5.5 m is assumed. The minimum and the maximum excess delays that a scatterer that is located on the canopy sphere's surface can exhibit is computed. Fig. 2 shows an example of this minimum and a maximum excess distances in principle. The result for the analyzed tree is shown as a green and a red line in the example record of raw channel impulse responses in Fig. 3. It can be seen that the delay spread of the tree scattering can be limited well by the minimum and maximum excess distance of a single scatterer on the treetop. However, when the vehicle comes close to the tree at time $t = 596$ s until $t = 597.5$ s, the delay spread becomes much larger. This is assumed to be due to multiple scattering inside the tree's canopy. The presented model utilizes thus scattering over multiple bounces up to the order of three. Since the scattering fluctuations become more rapid the closer the vehicle approaches the tree, the positions of the scatterers are redrawn whenever α changes more than 1°.

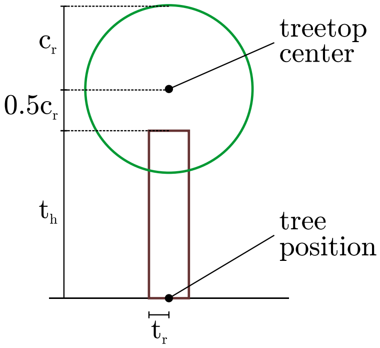

Figure 4. Tree parameters.

The attenuation of trunk and the treetop are modeled using a constant specific attenuation. The proposed model generates a virtual scenery and allows the definition of the vehicle trajectory, the stationary transmitter location, and a number of trees. They are parameterized by their position, the trunk height t_h, the trunk radius t_r, and the canopy radius c_r. The trunk reaches half way into the canopy. The ground is assumed to be flat. Fig. 4 shows a sketch with all relevant parameters.

Once the position of transmitter, receiver, and trees are defined the following parameters can be determined according to Fig. 5:

- the antenna height,
- the distance transmitter – tree $d_{\text{tx-tree}}(t)$,
- the distance tree – receiver $d_{\text{tree-rx}}(t)$,
- the total path length from the transmitter over a reflector to the receiver

$$d_{\text{ref}}(t) = d_{\text{tx-tree}}(t) + d_{\text{tree-rx}}(t), \tag{1}$$

- the excess distance for a given reflector

$$d_{\text{exc}}(t) = d_{\text{ref}}(t) - d_{\text{LOS}}(t), \tag{2}$$

- the excess delay

$$\tau_{\text{exc}}(t) = \frac{d_{\text{exc}}(t)}{c_0}, \tag{3}$$

- and the angle α between transmitter, treetop scatterer, and receiver. For multiple scattering, α is determined for the last scatterer.

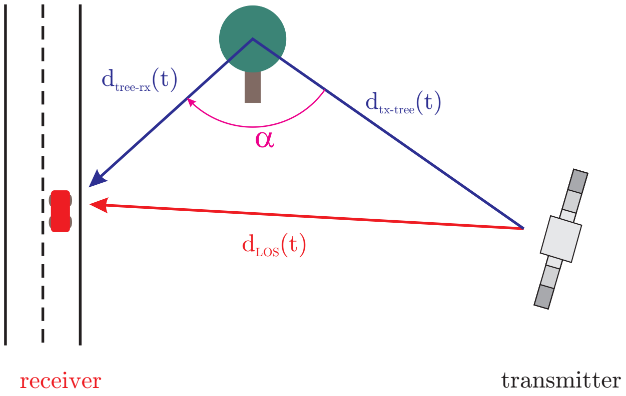

Figure 5. Transmitter, receiver, and reflector geometry.

3 SIGNAL MODEL

All elements of the signal sum that enter the receiver front-end are modeled as Dirac-impulses. The LOS signal is modeled as single Dirac-impulse with

$$s_{\mathrm{LOS}}(t,\tau) = a_{\mathrm{LOS}}(t)\delta(\tau) \qquad (4)$$

The scattering components of a treetop are modeled as a number of reflectors inside the spherical canopy due to the tree canopy's random nature. These reflective components generated by a tree at time t are modeled as a number of $D(t)$ distinct paths with excess delay $\tau_{\mathrm{exc},i}(t)$ and complex amplitude $a_i(t)$:

$$s_{\mathrm{tree}}(t,\tau) = \sum_{i=1}^{D(t)} a_i(t)\delta(\tau - \tau_{\mathrm{exc},i}(t)) \qquad (5)$$

The resulting signal is the coherent sum of (4) and (5):

$$s(t,\tau) = a_{\mathrm{LOS}}(t)\delta(\tau) + \sum_{i=1}^{D(t)} a_i(t)\delta(\tau - \tau_{\mathrm{exc},i}(t)). \qquad (6)$$

All amplitudes are normalized to the LOS signal which exhibits $|a_{\mathrm{LOS}}(t)| = \sqrt{P_{\mathrm{LOS}}(t)} = 1$ for the unobstructed case. The phase of each component is solely dependent on the distance to its origin. Thus, the complex amplitudes of the LOS component and the scatterers read

$$a_{LOS}(t) = \sqrt{P_{\mathrm{LOS}}(t)} \cdot e^{j \cdot 2\pi \frac{f_c}{c_0} \cdot d_{\mathrm{LOS}}(t)}, \qquad (7)$$

and

$$a_i(t) = \sqrt{P_i(t)} \cdot e^{j \cdot 2\pi \frac{f_c}{c_0} \cdot d_{\mathrm{exc},i}(t)}, \qquad (8)$$

respectively.

A total maximum power of $P_{\mathrm{tree,max}}$ for the sum of all treetop scatterers is assumed. From the measurements it can be observed that the scatterers reflected signal energy is higher when α is smaller. When the vehicle is entering the treetop's shadow, and the angle α thus approaches 180°, the re-radiated energy reaches its minimum. This behavior of the radiated scatterer power is modeled with a dependency on $\cos(\alpha/2)$.

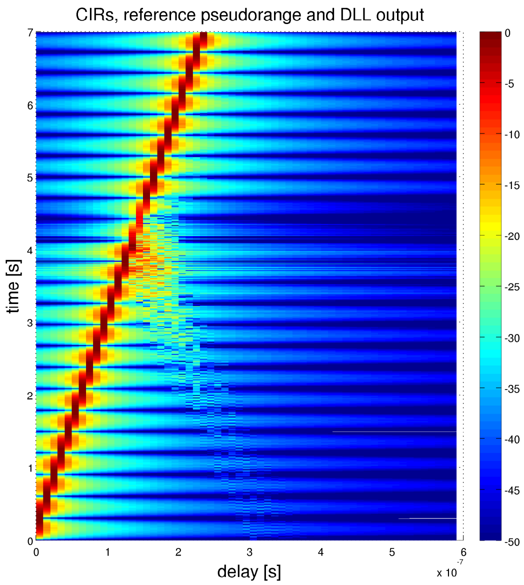

Figure 6. CIR model output.

4 MODEL OUTPUT

The model can be queried at arbitrary frequencies, yet the maximum Doppler frequency shift caused by the vehicle speed must suffice Nyquist's sampling theorem.

The Doppler frequency for a carrier frequency f_c, a vehicle speed v, and the speed of light $c_0 = 3 \cdot 10^8\,\mathrm{m/s}$ is given by

$$f_D = f_c \cdot \sqrt{\frac{c_0 + v}{c_0 - v}}. \qquad (9)$$

For a maximum vehicle speed of $v = 30\,\mathrm{m/s}$ and a carrier frequency of $f_c = 1.51\,\mathrm{GHz}$ the Doppler frequency offset is given by

$$f_{D,\Delta} = f_D - f_c = f_c \cdot \sqrt{\frac{c_0 + v}{c_0 - v}} - f_c = 151\,\mathrm{Hz} \qquad (10)$$

The minimum rate at which the channel can be sampled yields

$$f_{\mathrm{CIR,min}} = 2 f_{D,\Delta} = 302\,\mathrm{Hz} \qquad (11)$$

for this case. Conditions such as speed, tree parameters, and transmitter elevation, which were present for the sample CIR measurement of Fig. 3, were entered into the model for comparison. The number of scatterers inside the canopy was set to $0.11\,\mathrm{scatterers}/m^3$ for this example tree. The output of the channel model was then interpolated to the same bandwidth as the original measurements in Fig. 3 and can be seen in Fig. 8.

5 SIMULATION OF A RIDE THROUGH AN ALLEY

It can be argued that a DLL copes easily with the temporary shadowing and scattering of a single tree, especially at

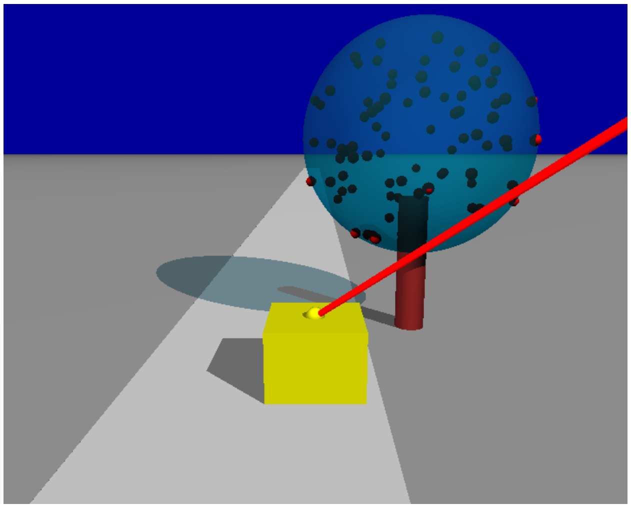

Figure 7. Visualization of the rural channel model's virtual scenery.

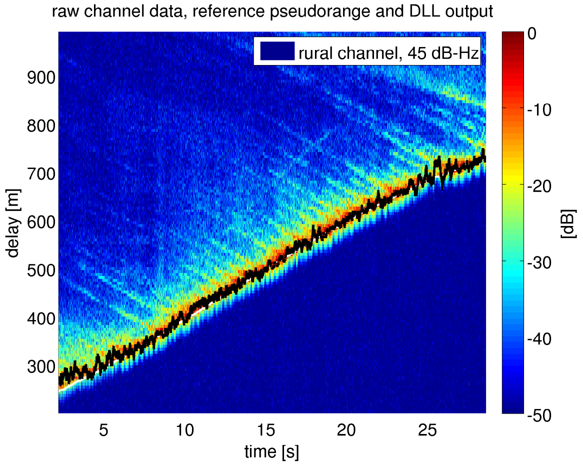

Figure 8. SNACS simulation run of raw channel sounding measurements of a ride through an alley. The black line shows the DLL tracking result and the white curve in the background represents the reference range.

usual speeds of up to 100 km/h in rural areas. Yet, such events pose high stress on the GNSS receiver algorithm when they happen frequently. This happens when a vehicle drives below a row of trees or an alley. Fig. 8 shows raw CIR measurements of a 30 s ride on a road which is lined by trees. A simulation with the GPS C/A code was conducted, the discriminator chip-spacing was set to 1 chip, the noise level was set to 45 dB-Hz. The rms error of the simulated situation is 32.4 m.

6 CONCLUSIONS AND OUTLOOK

A wide-band model for tree reflection and tree canopy scattering was introduced. Its purpose is the usage in signal level simulation in navigation and synchronization applications for the land-mobile case. The model takes the highly variant incoherent scattering caused by tree canopies in land-mobile situations into account and models it with a number of point scatterers inside the treetop. The attenuation is determined by specific attenuations for treetop and trunk. The transmitter position can be defined and different elevations can thus be evaluated. The re-radiated power and the speed of the scatterers' variations are dependent on the distance to the tree and the incident angle from transmitter over the tree to the receiver. Although its comparably simplicity, the proposed model of single trees' scattering shows good agreement to CIR measurements of rides of a vehicle past free-standing trees. The severity of rides past an alley on GNSS receiver performance was shown by means of a simulation with CIR measurements.

It is planned to include further features into the GNSS rural channel model such as electricity poles, buildings, and forrests, to obtain a realistic and comprehensive channel model of rural settings.

REFERENCES

[1] R. F. S. Caldeirinha. *Radio Characterization of Single Trees at Micro- And Millimetre Wave Frequencies*. PhD thesis, University of Glamorgan, 2001.

[2] 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.

[3] A. Lehner, A. Steingass, and F. Schubert. A location and movement dependent gnss multipath error model for pedestrian applications. In *Proceedings of the 13th European Navigation Conference*, Naples, Italy, 2009.

[4] F. Perez-Fontan, M. Vazquez-Castro, C. E. Cabado, J. P. Garcia, and E. Kubista. Statistical modeling of the lms channel. *IEEE Transactions on Vehicular Technology*, 50, 2001.

[5] A. Steingass and A. Lehner. Navigation in multipath environments for suburban applications. In *Proceedings of the 20th International Technical Meeting of the Institute of Navigation Satellite Division*, Fort Worth, Texas, USA, 2007.