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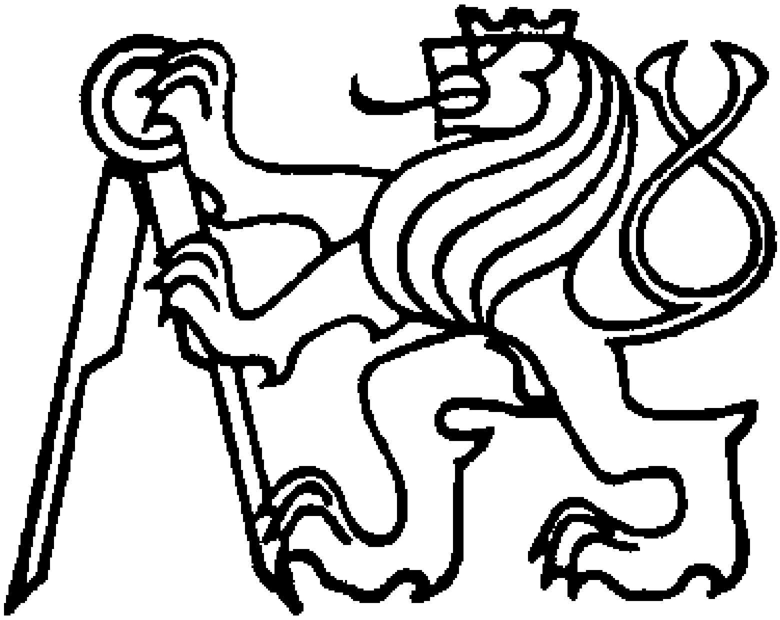

DOCTORAL THESIS STATEMENT

Czech Technical University in Prague

Faculty of Electrical Engineering

Department of Electromagnetic Field

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PROPAGATION MODELING OF SHADOWING BY VEGETATION FOR MOBILE SATELLITE SERVICES

Ph.D. Programme: Electrical Engineering and Information Technology

Branch of study: Radioelectronics

Doctoral thesis statement for obtaining the academic title of “Doctor”,
abbreviated to “Ph.D.”

Prague, October 2011

The doctoral thesis was produced in full-time manner Ph.D. study at the department of Electromagnetic Field of the Faculty of Electrical Engineering of the CTU in Prague.

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CONTENTS

1 CURRENT SITUATION OF THE STUDIED PROBLEM

1.1 Introduction

Satellite communication is one of many conceivable examples of wireless communication systems proposed for radio and television broadcasting, mobile and cordless telephones, military services, government purposes, weather forecasting, environmental and scientific research, establishing positioning, etc. A satellite is an object revolving around another object so in terms of communication systems, a satellite is a platform carrying communication equipment orbiting Earth while another terminal is based on the ground. Satellite communication has evolved greatly over the past few decades since Sputnik, the first satellite, was launched by the Soviet Union on October 4, 1957. It was the size of a basketball and transmitted signals over two frequencies over 20 and 40 MHz. At present, satellites are used in many different designs and sizes, have many uses and are located at three general orbits. All satellite systems are utilized for a variety of purposes and have become an indispensable component of our current life.

Nevertheless, with new requirements imposed on wireless communication systems (wider range of services, increased mobility, more availability, etc), there is a demand for an investigation into outdoor propagation channels for communication. One of the most frequently complex outdoor environmental features is vegetation and the appearance of a forested medium in the path of a satellite, terrestrial or any microwave communication link has a significant effect on the quality of the received signal. The vegetation appears to a passing signal as an ensemble with discrete scatters formed by randomly distributed leaves, branches and tree trunks that cause attenuation, scattering, diffraction and absorption. These factors can severely constrain the utility, performance or endurance of the system as a whole. In general, an accurate electromagnetic description of the tree geometry, including its branches and leaves, valid over a wide range of frequencies, is required for an accurate modeling of radiowave propagation through tree foliage. This is why an understanding of models dealing with the propagation of microwave and millimeter wave through vegetation is essential for the planning and design of radio systems.

Extensive measurement trials and modeling of the effects of vegetation have been performed over the past forty years. Some of these works deals with common attenuation measurement some with statistical characteristics. The measurement trials can be categorized according to utilized frequency, measurement scenario, equipment, goals, etc. For this work the most important categorization is if work is for terrestrial or satellite systems. The models available in the literature are described in the paragraphs below, and these can be separated into three main parts:

Empirical models - these models have one main advantage but also some drawbacks. Their advantage is the simplicity of the mathematical expressions. On the other hand they have a number of drawbacks, including a strict dependence on specific measured data and their failure to relate to the physical processes involved. Dependence on the model parameters, such as frequency, angles and path length through vegetation, is usually determined through regression curves fitted to measured data.

Semi-empirical models - these models combine the features of empirical and analytical models. The main advantage of semi-empirical models lies in the simplicity of their application. They are relatively new and mainly use data that has already been measured. The models are proposed in order to give the best fits to the measured data.

Analytical models - in contrast to the models mentioned above, this kind of model offers an insight into the physical processes involved in radiowave propagation through vegetation. Unfortunately, most of them have complicated mathematical expressions (using numerical analysis methods).

1.2 Empirical and Semi-empirical Models

Empirical models are based on experimental investigations that were performed in various frequency bands, for various measurement scenarios, different vegetation type, etc. One of the most general is Weissberger´s model [Weis82] developed reviewing several exponential decay models and was based on several sets of available measured attenuation data carried out at frequencies from 230 MHz to 96 GHz. In addition this model establishes the difference in path loss for trees with and without leaves from 3 to 5 dB in the frequency range of 450 - 950 MHz. The International Telecommunication Union developed several models: [CCIR86] from measurements performed mainly at UHF, then the optimization [StAl95] utilizing data from measurements performed at 11.2 and 20 GHz and finally [Rec.833-6] including two models for radiowave propagation through vegetation. The first is for terrestrial paths with one terminal in woodland and the other for a case where two terminals are separated from the vegetation (single vegetation obstruction) following a semi-empirical approach. The empirical model COST 235 [COST235] provides general estimates of the amount of excess attenuation caused by a particular vegetation medium, which were proposed based on measurements carried out in a frequency band from 9.6 GHz to 57.6 GHz through a small ($d < 200$ m) grove of trees. The models based on measurement trials performed by Vogel and Goldhirsh belong to the most common [VoGo86], [VoGo87], [VoGo88], [VoGo89], [VoGo93]. These measurements were focused on high elevation link investigation exploiting remotely piloted aircraft, helicopter, balloon or roof of a high building as a carrying platform, however were performed only for several elevation angles in frequency bands UHF, L and K. A very interesting experimental investigation was described in [SoCo04] considering elevation angles ranging at between 20-40 and 10-20 degrees for transmitter located on the building about 41-m high and receiver placed at distances varying from 50 to some hundreds of meters.

Two general models have been selected in this thesis as semi-empirical models. The first, Non Zero Gradient Model (NZG), has been developed to accommodate a dual slope attenuation function seeking to follow the dual gradient of the measured attenuation curve [AlHa93]. The first of these slopes describes the loss experienced by the coherent component and the second slope looks at that mainly experienced by the incoherent component. The model takes into account both of these components and optimizes the parameters to give the best fit in a frequency band between 11.2 and 20 GHz. The second, Gradient Model, is an improvement of the previous (NZG) model, which takes into account the difference in the received signal levels when different antenna beamwidths are used to obtain data [Sevi97].

1.3 Analytical Models

A number of analytical models have been proposed, however in this thesis only four basic groups are presented.

Geometrical and Uniform Theories of Diffraction (GTD/UTD)

The first of these [MaLi99] and [LiYe98] uses a ray-tracing method suitable for high-frequencies and the illuminated object must be placed in the far field region of the source. The next model [LeWe99] for the frequency range 300 MHz – 90 GHz, considers vegetation as a single homogeneous dielectric slab and the scattering has been modeled deterministically depending on the electrical density of the vegetative medium. The resulting model [SaWy68] was proposed by the experimental propagation data over a wide range of parameters in the jungle and is applicable to frequencies of up to 100 MHz. Another ray-based model is based on the Uniform Theory of Diffraction and associates a double-diffracted component over the canopy. This model has been proposed [MaLi99] by propagation measurements at 1.9GHz (in a wooded cross road configuration). In this thesis only three general approaches are mentioned.

The Radiative Energy Transfer Theory (RET)

The RET describes vegetation as a statistically homogeneous random medium of scatters ds, characterized by the absorption cross-section per unit volume σ_a, the scatter cross-section per unit volume σ_s and the scatter function of the medium $p(\hat{s},\hat{s}')$ [AlHa94], [JoSch85] and [Ishi78]. The scatter function can be characterized by two main features: a narrow forward lobe and an isotropic background, where $\hat{s}'$ and $\hat{s}$ indicate the incidence and scatter direction, respectively. The model based on this theory can be used to predict the attenuation curves and directional spectra due to propagation of a microwave signal through vegetation. This model considers a plane wave incident from an air half space upon the planar interface of a vegetation half space.

Full Wave Solution

Three main models are involved here [Seke00], [EwChu00] and [HiSa00]. The first of these was developed by using geometric models of tree (leaves as disks, needles / trunks / branches as cylinders), but such methods are computationally extensive. The latter models show how to compare the wavelength in terms of near field scattering and electrical density. And the last one has shown that at millimetric frequency (where RET has proved good for modeling the bulk properties of vegetation) is much less computationally expensive than the full wave models at millimetric frequencies.

Physical Optics

Another theoretical model [ToBe98] has been developed to describe the effect of propagation loss through the trees in residential areas. This model can be characterized by three main properties: the mean field, the attenuation, and the phase delay. The model takes into account an ensemble full of leaves and branches (these parts have a prescribed location and orientation statistics). There has been found that the wave propagation parameter has both real and imaginary components. The main idea behind this stance is that the specific attenuation for vertically polarized electromagnetic waves is higher than that for horizontal polarized. This is due to the statistical distribution of leaves and branches with respect to the incident angle of the incoming wave. In this model the properties involved the following parts: the probability density functions of the scatters, the electromagnetic characteristics of the scatters, and their dimensions.

2 AIMS OF THE DOCTORAL THESIS

This doctoral thesis is focused on investigating the influence of vegetation on wireless communication links for land mobile satellite (LMS) services. The previous chapter dealt with the current state of research and presented the majority of available models in the literature that can be categorized as empirical, semi-empirical and analytical. Further, it has been shown that a huge number of experimental investigations focused on terrestrial services were performed covering many effects (season, frequency, measurement scenario, type of vegetation, etc.). In contrast to terrestrial investigation, only a small number of performed works were focused on a scenario for high elevation angle links, and only for a limited scenario. The models obtained for terrestrial scenarios are usually applied for high elevation links as well since no experimental results are available for high elevation angles considering a wide range of elevation angles, multiple frequencies, different measurement scenarios and various seasons.

The limitation of terrestrial model applications for high elevation links lies firstly in the fact that different propagation mechanisms appear for individual scenarios. A typical example is to have one terminal located within a woodland, where the maximum total additional attenuation due to vegetation in a radio path, as limited by the effect of lateral-wave propagation over the top of the vegetation medium and forward scatter within it, in contrast to satellite services where different propagation mechanisms appear.

There are no available models in the literature for high elevation links covering a wide frequency range, seasonal influences and different measurement scenarios. Based upon these implications, the targets of this thesis were defined:

- Propose new measurement trials to investigate the influence of vegetation shadowing for high elevation links. The measurement trials should cover different measurement scenarios, relevant frequency bands and different seasons.

- Develop a new model for high elevation links introducing one terminal within woodlands (not measured scenario yet - typical for forested environment) and covering a wide range of elevation angles and frequency bands when vegetation is full in leaf and defoliated.

- Develop a model for high elevation links where the radio path is obstructed by a single vegetative obstruction where both terminals are outside the vegetative medium (typical for ray-tracing tools) and with the model taking into account different frequency bands, seasons and shapes of tree canopy.

3 WORKING METHODS

As noted in the previous chapter dealing with the current state of research, it is clear that extensive measurements have been performed primarily on terrestrial services and less frequently on satellite services. The measurement trials focused on terrestrial links mostly utilizing one terminal located within a woodland or similarly extensive vegetation, and covered a wide range of frequency bands including different types of vegetation and measurement equipment. In contrast to terrestrial link investigations there is still an insufficient number of experimental results available in the literature for high elevation angles considering a wide range of elevation angle and multiple frequencies. Most available measurement trials focused on high elevation angle links were taken at a single frequency and for only a limited range of elevation angles. It is obvious, for terrestrial and high elevation angles links, that different propagation mechanisms are found that cause multipath and establish different total field. As seen from previous research, there is a demand to investigate vegetation attenuation for high elevation angles for different measurement scenarios.

3.1 Basic Concept

Due to the aforementioned reasons, new measurement trials were proposed to investigate the influence of vegetation on high elevation angle services. The fundamental concept is as follows: a fixed transmitter on a platform capable of moving or flying at the required height and trajectory interacts with a receiver located on the ground with a vegetation configuration. For this purpose a remote-controlled airship was chosen as the carrying platform. In addition, two basic measurement scenarios were utilized while the frequencies, ranging from 2.0 to 6.5 GHz, i.e. covering L, S, and C bands, were selected with respect to land mobile and navigation satellite services. The frequency bands are also relevant for future High Altitude Platform Systems where, for example, the 6.0 GHz band is under consideration by the ITU [Res.734]. The measurement scenarios were proposed to obtain relevant data for the larger range of elevation and azimuth angles while taking different seasons into account.

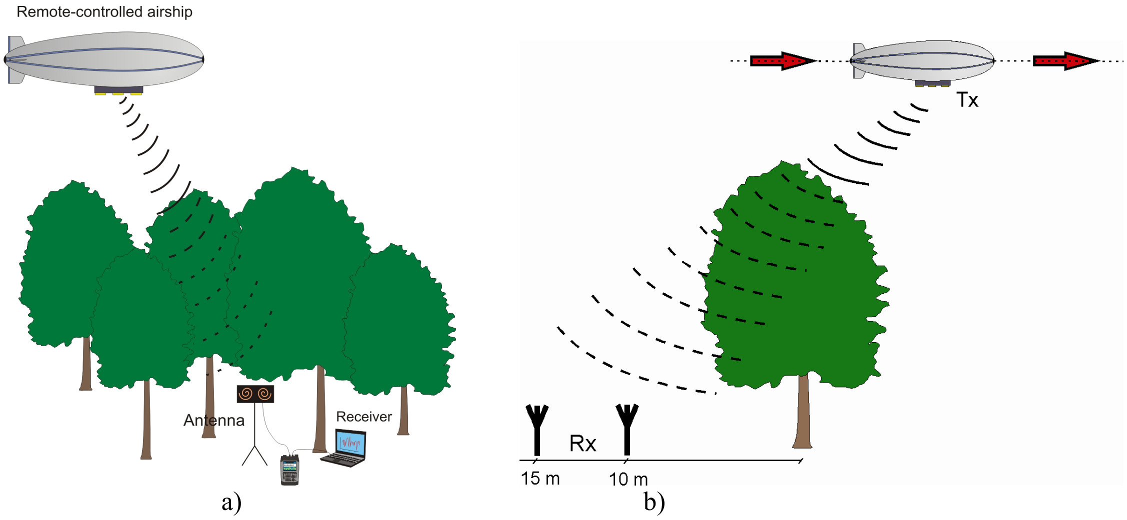
3.2 Measurement Scenarios

The measurement scenarios utilized for vegetation investigation describe, above all, the geometrical arrangement of receiving and transmitting stations and investigated a forested medium. The flyovers and airship positions are precisely established for each measurement location and define the vegetation attenuation based on different parameters. Each selected scenario defines the direction, length, height and number of individual flyovers, and the position of the receiving station to the forested medium investigated. In total, two different measurement scenarios were selected in order to establish vegetation attenuation for forested areas and single trees.

The first selected measurement scenario featured a receiving antenna located inside the vegetation so that the antenna was totally surrounded by the vegetation and the forested medium was fully blocking the experimental radio link. The receiving antenna was attached to a tripod at a default height while the airship flew to predefined directions and distances. At least four flyovers, in a star pattern above the receiving station (see Fig. 3.1a), were planned for each measurement position to obtain statistically relevant data for a sufficient range of elevation and azimuth angles. This scenario led to an elevation angle (from the measurement location perspective) range from about 20 to 90 degrees.

In contrast to the forested areas scenario, the single tree scenario places the receiving antenna at varying distances from the tree investigated and it is obvious from Fig. 3.1b that two different situations occur. Firstly, a line-of-sight (LOS) situation, where the link was not shadowed by the tree and only free space loss can be measured. The second situation occurred when the link was shadowed by a forested medium resulting in a non-line-of-sight (NLOS) situation and vegetation attenuation could be measured. An evident threshold between LOS and NLOS is visible for each measurement position which is given according to the geometrical arrangement. For this scenario two different distances from the tree in question were utilized, namely 10 and 15 meters. The flyovers were planned so that the receiver, the tree under investigation and the airship were kept in line.

In order to obtain reference data a large, open, flat field was chosen as a calibration location where series of flyovers in a star pattern above the receiving antenna were performed. Data were collected for the largest range of elevation and azimuth angles.



a) b)

Fig. 3.1: Schematic diagram of measurement scenarios for a) woodlands and b) single tree

3.3 Measurement Equipment

A 9m-long remote-controlled airship was utilized as a carrying platform to simulate a satellite for high elevation angle measurements (see Fig. 3.2). The airship was developed and operated by the CTU Prague, the Faculty of Mechanical Engineering. Helium filled the airship hull thus allowing for a maximum payload of 7 kg and an operating speed of about 2 – 6 m/s. The airship was equipped with a number of sensors to track position, flight direction, pressure, temperature and the pitch and roll of the airship. These data were collected on the ground using a wireless connection to the airship. The data were subsequently synchronized with other datasets using GPS time stamps. For the precise determination of the airship position, a separate lightweight Differential GPS (DGPS) receiver was used as an additional payload. The external GPS antenna was placed on the top of the airship hull.

Fig. 3.2: The airship utilized for measurements

The transmitting site was fixed on bottom of the airship, supplied from the battery pack and consisted of three basic parts continuous wave generators at 2.0, 3.5, 5.0 and 6.5 GHz, power amplifiers and left hand circular polarized planar antennas (LHCP). Four wave generators provided signals to four amplifiers while only three antennas transmitted electromagnetic waves due to multiplexing two frequencies at 2.0 and 3.5 GHz , while a 12 V power supply was required for all electrical components. A self-complementary structure was utilized for transmitting antennas with input impedance close to the theoretical value of 60π.

The receiving station used a left-handed circularly polarized (LHCP) wideband antenna and a right-handed circularly polarized (RHCP) wideband antenna as a receiving antenna which was attached to a tripod at a default height of 1.5 m above the ground at each measurement position. The received signal strength was measured by a sensitive receiver (PR100 made by Rohde&Schwarz) controlled by computer via its LAN interface. PR100 is a 3.5 kg weight portable receiver and enables the user to detect signal levels from -137 dBm to 0 dBm while working in a band from 9 kHz up to 7.5 GHz. Only the LHCP antenna was utilized for the measurement trials.

In total fourteen measurement positions were chosen in order to investigate the influence of vegetation for high elevation link and can be separated into three locations: Stromovka Park, Tursko and Točná. These locations were selected in order to cover different vegetation type, different arrangement of vegetation and both measurement scenarios.

3.4 Basic Data Processing and Analysis

Raw data obtained throughout the measurement trials can be divided into two main sources: the received signal strength data and flight data from the airship sensors. The signal strength data were obtained from a portable Rohde&Schwarz PR100 receiver located on the ground and remotely controlled via LAN interface by a computer where data for each measurement position were stored into separate files. The flight data were obtained from sensors, attached to the airship gondola, which determined primarily position but also direction, pressure, temperature, height, wind speed, pitch and roll. The position data were collected by a portable GPS device which was located on the hull of the airship during the measurements. Both datasets were subsequently synchronized and processed for each frequency and position. The synchronization resulted in a new dataset. No data for the airship pitch and roll higher than 5 degrees were considered in order to avoid extreme deviations and turns of the airship due to wind gusts.

4 RESULTS AND PROPAGATION MODELING

4.1 Woodlands

For further analyzing data for the elevation angle lower than 25 degrees were discarded to avoid situations when airship turned in the end of flyovers. Then the data were averaged at each frequency over elevation angle intervals of 10 degrees to eliminate multipath fading. For the woodland scenario and its given geometrical arrangement, attenuation seemed to vary erratically with over the whole range of elevation angle and ranged between 6.5 and 13.5 dB. The biggest differences were found in location S1 where values range from 7.5 to 12 dB. While the measurement system accuracy differs by about 1 dB, all interval averages run around “mean value”. Indeed, the vegetation is a heterogeneous medium and gaps cause deviation.

In addition, no straightforward dependence on the elevation angle was derived. This independence can be explained by propagation mechanisms in our scenario of high elevation links when the received signal is given by scattering in a large volume of vegetation rather than by the direct path itself.

Differences of approximately 4 dB and 8 dB between summer and winter measurements were observed for deciduous woodlands at 2.0 and 6.5 GHz, respectively. As expected, only a negligible difference was recorded for the conifer trees in location S1. For the same reason, the mixed woodland in location T4 also shows a smaller difference, see Fig. 4.1a.

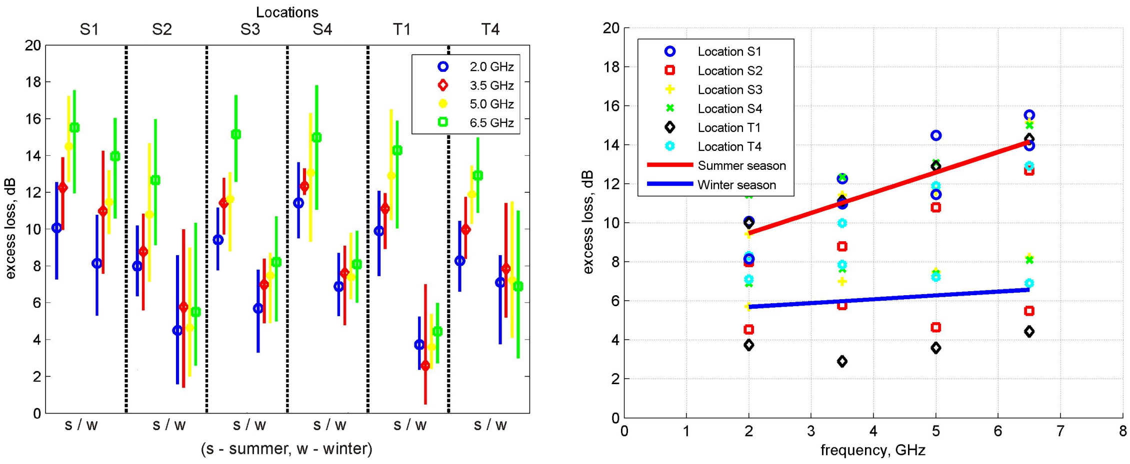
For modeling purposes the averages from Fig. 4.1a were plotted as a function of the frequency (Fig. 4.1b). If the summer and winter results are processed separately, an almost ideal linear fit can be applied. The winter data for location S1 with evergreen vegetation were not considered. The additional attenuation *L* (dB) can then be expressed as a function of the frequency *f* (GHz) by:

$$L = 1.1f + 7.5 \tag{4.1}$$

for the summer season, i.e. vegetation in full leaf, and

$$L = 0.2f + 5.3 \tag{4.2}$$

for the winter season, i.e. vegetation out of leaf.



a)

b
)

Fig. 4.1: a) The average, minimum and maximum vegetation attenuation for individual locations for (s) summer and (w) winter, b) The average vegetation attenuation with appropriate linear models

The standard deviation of the measured data from the model is 4.2 dB and 3.7 dB for summer and winter, respectively. To eliminate the fact that different amounts of data were available at each elevation, the standard deviation was first calculated separately for the 10 degree-elevation angle intervals and then averaged. It was observed that it does not significantly depend on elevation angle. The standard deviation is relatively high in comparison to the additional attenuation values due to the variety of our measurement locations, especially during winter time measurements where, in some cases, line of sight almost had to be considered, while relatively high attenuation was observed in other cases due to the shadowing of the branches and trunks.

Any comparison to results reported in the literature is somewhat complicated since most works considered different scenarios. However, a comparison is possible at certain frequencies and selected elevation angles. The results at 2.0 GHz can be compared to [SoCo04] where the tree attenuation at 2.5 GHz is reported around 10 dB in most cases for elevation angles between 20 - 40 degrees.

4.2 Single Tree

The data, obtained from single tree measurement scenario, were further processed as a function of the elevation angle. No data for an elevation angle lower then 20 degrees were considered. In contrast to the data obtained from the woodland scenario where data lower then 25 degrees were discarded, data for lower elevation angles were processed due to longer flyovers introduced in this scenario. The data was then filtered using a moving averaging window of 10 degrees for each separate flyover and for all data for the same scenario and receiver position at each frequency.

Fig. 4.2 shows an example of the resulting excess loss as a function of elevation angle for multiple frequencies at one position during both seasons. It is obvious that two situations can be distinguished: the line-of-sight (LOS), when the link is not shadowed by the tree, and the non-line-of-sight (NLOS), when the link is shadowed. The border between the two conditions, with an elevation angle of about 60 degrees shown here, is given by the actual geometrical arrangement. The similar behavior of excess loss as a function of elevation angle is observed for each measurement position of the single tree scenario, however, a different border between LOS and NLOS is found.

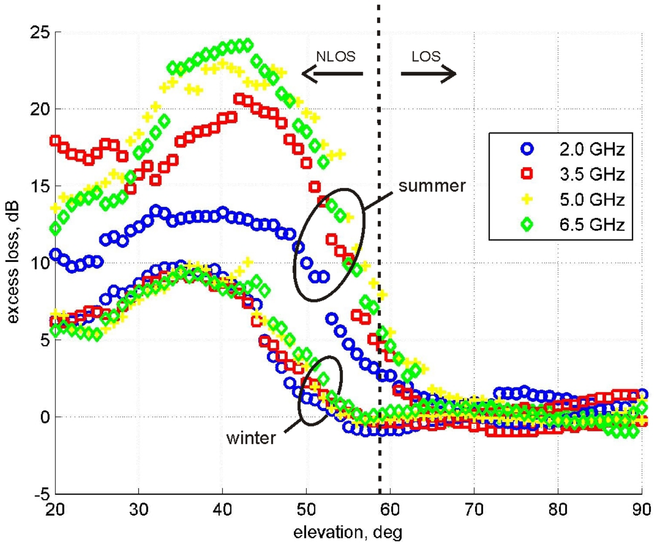


Fig. 4.2: Sample of excess loss during both seasons at multiple frequencies for location T2

As a fundamental concept of signal propagation through a single tree we adopted the same approach as in [Rec.833-6] by considering the tree as a shadowing obstacle introducing two propagation mechanisms: attenuation of the direct signal due to scattering and attenuation within the tree canopy and diffraction over the top and sides of the canopy. Due to our definition of excess loss, we did not consider the ground bouncing ray as in [Rec.833-6] since it is already implicitly included in our reference. Each path presents a different contribution and the sum of these parts establishes the total field which can be expressed in a form of excess loss by:

$$L_{total} = -10\log\left\{10^{\left(\frac{-L_{dir}}{10}\right)} + 10^{\left(\frac{-L_{top}}{10}\right)} + 10^{\left(\frac{-L_{sidea}}{10}\right)} + 10^{\left(\frac{-L_{sideb}}{10}\right)}\right\} \tag{4.3}$$

where L_{total} stands for total excess loss, L_{dir} is attenuation of the direct signal through the tree canopy, L_{sidea} and L_{sideb} are the sides, and L_{top} is top diffraction loss parts, all in dB.

To construct the four paths of the actual tree shape, which can be irregularly shaped, the canopy needs to be approximated by a geometrical solid. Various solids were used to model the tree tops, such as a sphere, cone and cylinder [CheFo11], [ToBe98] and [JoHe04]. We employed an ellipsoid which proved to be the best fit for the trees in our investigation. The height and width were accurately obtained by theodolite in summer.

In [Rec.833-6], the tree volume is modeled by a block and the side and top diffractions are treated as a double isolated knife-edge using the ITU-R Rec. P.526 [Rec.526-11] calculating method. This suits terrestrial link geometry as both antennas were approximately the same height and distance from the forested medium. For the high elevation angle link, ground terminal near the tree, the situation is different and single knife edge diffraction is more appropriate.

In order to derive appropriate dependence, excess loss has to be accounted for with respect to vegetation depth which is a fundamental parameter and is defined as the length of the path within the tree top [Rec.833-6], [Wies82], [COST235]. Then the vegetation depth was established as a function of elevation angle and could be found for individual given geometry. To address this excess loss separately we derived L_{dir} from (4.3) by calculating the diffraction components as described above. The existing empirical models, established through vegetation path loss available in the literature, take different forms. For our study we used the most common general form [Weis82], [COST235]:

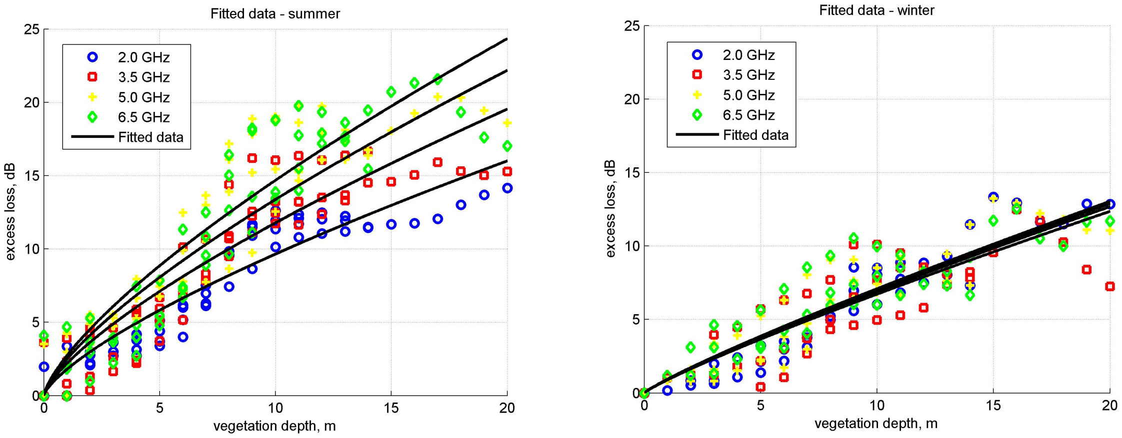
$$L_{dir} = A \cdot d^{B} \cdot f^{C} \tag{4.4}$$

where L_{dir} is attenuation from (4.3) in dB, f is frequency in GHz and d stands for vegetation depth in meters. A, B and C are the fitted empirical parameters of the model.

Based on the overall processed data of four trees at multiple frequencies, the excess loss of the direct path was analyzed for each tree and season separately. Only the NLOS data were considered to obtain L_{dir} as a function of vegetation depth. Then the data were averaged using an averaging window of 1 m of vegetation depth. To derive the empirical parameters, nonlinear data fitting was solved by the least squares method. The resulting parameters are clearly summarized in Table 4.1. Fig. 4.3 demonstrates that the model is able to approximate our data quite well, as expected. The resulting standard deviations were 2.3 dB and 1.7 dB with average errors of 1.8 dB and 1.3 dB for summer and winter measurements, respectively.

Table 4.1

	A	B	C
summer	1.43	0.721	0.356
winter	0.84	0.884	0.043



a) b)

Fig. 4.3: Modeling of experimental data at multiple frequencies when trees were (a) full in leaf and (b) defoliated

The proportion of top and side diffractions L_{top}, L_{sidea} and L_{sideb} calculated from (4.3) changes according to elevation angle and a major contributing factor is given by the top diffraction for higher elevation. Calculations in all scenarios showed that contributions of the diffraction components for the resulting L_{total} in (4.3) are insignificant when compared to the direct path component L_{dir}. In fact, as mentioned above, only the top diffraction contribution is worth considering for the small range of high elevation angles. This is why we simplified the model (4.3) by $L_{total} = L_{dir}$ and performed the data fitting described in the previous section on the data without considering the diffraction, i.e. the total excess loss is then given by (4.4).

It can therefore be concluded that the simple expression (4.4), without considering the diffracted components, can be used at the given frequencies to estimate excess loss caused by single trees of heights ranging between 11 and 18 meters and widths between 11 to 20 meters, where vegetation depths reach up to 20 meters. In general, it is noted that as the distance of the terminal from the tree increases, side and top diffractions become more significant. The same is true for the tree canopy as it decreases in size. Under these conditions, the influence of diffraction components in (4.3) increases and should be taken into account.

Since the empirical modeling of the vegetation attenuation as a function of the vegetation depth is widely available in the literature, albeit mainly for terrestrial systems, a very good match was found at 2.0 GHz with direct signal attenuation as calculated using the RET method with selected parameters [Rec.833-6]. That suggests that the generic RET algorithm can be used instead of (4.4) to calculate L_{dir} for different species of trees than those represented in our study.

5 CONCLUSION

This thesis deals with propagation modeling of shadowing by vegetation for mobile satellite services. It has been shown in the current state of research that over the past decades a number of experimental investigations and modeling of the effect of vegetation have been performed. The majority of work was focused on terrestrial services covering multiple effects, while only a small number of work was focused on scenarios for high elevation angle links, and then only for limited scenarios. Usually the models obtained for terrestrial scenarios are (were) applied to high elevation links as well since no experimental results are available for high elevation angles considering a wide range of elevation angles, multiple frequencies and different seasons.

In order to investigate shadowing by vegetation for high elevation angles, a new extensive measurement trial utilizing a remote-controlled airship as a carrying platform, a receiver on the ground and frequency bands ranging from 2.0 to 6.5 GHz, i.e. covering L, S and C bands, selected with respect to land mobile and navigation satellite services, was proposed. The experimental investigation was performed on a scenario where the ground terminal was completely shadowed inside woodlands and for a scenario where the radio path is obstructed by a single vegetative obstruction with both terminals located outside the vegetative medium, both during seasons where vegetation is full in leaf and defoliated.

The investigation inside woodlands resulted in a new empirical model estimating additional attenuation and derived for both summer and winter at a broad frequency range which considered elevation angles between 25 to 90 degrees. No elevation angle dependence was observed in this scenario. The models can be used to estimate the average, minimum and maximum values of the additional vegetation attenuation in typical moderate climate woodlands for mobile satellite services.

A new model establishing excess loss as a function of vegetation depth and frequency during two seasons while the trees were modeled as ellipsoids to establish vegetation depth was derived from an investigation of a single tree. It was shown that at given scenarios and geometry diffraction plays only a minor role so that it is sufficient to consider only the direct ray through the tree canopy for modeling. The model can be used in ray-tracing tools to address excess loss caused by single tree shadowing.

LIST OF LITERATURE USED IN THE THESIS STATEMENT

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SUMMARY

This doctoral thesis deals with propagation modeling of shadowing caused by vegetation for satellite services. In spite of fact a huge number of experimental investigations focused on researching the influence of vegetation attenuation for wireless systems have been performed, only a small number of these works were focused on high elevation angle links, and only for a limited scenario. Due to aforementioned reasons, new measurement trials were proposed to investigate the influence of vegetation for high elevation angles links, covering different measurement scenarios, wide frequency range and various seasons.

The new measurement trials considered a remote-controlled airship as a carrying platform, frequencies ranging from 2.0 GHz to 6.5 GHz (i.e. covering L, S, and C bands), two various seasons when trees were full in leaf and defoliated, and two selected measurement scenarios (not measured yet). The first scenario introduces ground terminal completely shadowed inside woodlands while the second defines the radio path obstructed by a single vegetative obstruction with both terminals located outside the vegetative medium.

The experimental investigation resulted in new empirical models. The first, derived from measurement inside woodland, estimates additional attenuation for both summer and winter at a broad frequency range considering elevation angles between 25 to 90 degrees. This model can be used to estimate the average, minimum and maximum values of the additional vegetation attenuation in typical moderate climate woodlands. The second, dealing with single tree measurement, establishes additional attenuation as a function of vegetation depth and frequency during two seasons while the trees were modeled as ellipsoids to establish vegetation depth. It was shown that at given scenarios and geometry diffraction plays only a minor role so that it is sufficient to consider only the direct ray through the tree canopy for modeling. The model can be used in ray-tracing tools to address excess loss caused by single tree shadowing.

RESUMÉ

Tato práce se zabývá problematikou vlivu vegetace na bezdrátové spoje, především družicové systémy. Je zde podrobně ukázáno to, že i navzdory velkému počtu provedených experimentálních měření, pouze nepatrná část těchto experimentů byla zaměřena na spoje s vysokou elevací, a když, tak pouze pro omezené měřící scénáře. Na základě této skutečnosti byla navržena měřící kampaň za účelem zkoumání vlivu vegetace na spoje s vysokou elevací pro různé měřící scénáře v širokém rozsahu frekvencí a pro různá roční období.

Nově navržená měřící kampaň využila dálkově ovládanou vzducholoď plněnou inertním plynem jako prostředek nesoucí vysílač. Samotné měření bylo provedeno v kmitočtovém pásmu od 2.0 do 6.5 GHz (tj. pásma L, S a C) během dvou rozdílných ročních období, kdy jsou stromy plné listí a kdy jsou bez listí. Byly využity dva základní měřící scénáře, které nebyly doposud měřeny.

Pro získání experimentálních dat dle prvního měřícího scénáře byl pozemní přijímač umístěn uvnitř lesíku tak, že pro všechny elevační úhly byl spoj zcela zastíněn. Druhý měřící scénář představoval přijímač umístěný v určité vzdálenosti od osamoceného stromu tak, aby spoj byl zastíněn právě tímto stromem.

Výsledkem rozsáhlé experimentální činnosti bylo získání unikátních dat pro dva měřené scénáře, na jejichž základě byly vyvinuty příslušné nové empirické modely šíření vln, které dosud nebyly v literatuře k dispozici. První model, zaměřený na scénář, kdy pozemní terminál byl umístěn uvnitř vegetace, určuje útlum procházejícího signálu vegetací pro dvě různá roční období v širokém frekvenčním rozsahu a to pro elevační úhly mezi 25 a 90 stupni. Tento model určuje průměrnou, minimální a maximální hodnotu útlumu způsobenou vegetací typickou pro naše vegetační pásmo. Druhý model, odvozený z měření, kdy spoj byl zastíněn osamoceným stromem, určuje útlum vegetací jako funkci hloubky vegetace a frekvence pro dvě různá roční období. Za účelem určení hloubky vegetace byl osamocený strom modelován jak elipsoid. Bylo ukázáno, že pro daný scénář a geometrii hraje difrakce pouze minimální roli a může být proto zanedbána. Tento model je určen primárně pro ray-traicingové výpočetní programy pro počítání útlumu osamoceného stromu.