

# **FFI RAPPORT**

## **VEGETATION ATTENUATION OF MICROWAVES**

**Measurements and model evaluation**

MOSESEN Kjetil

**FFI/RAPPORT-2002/04143**



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Torleiv Maseng  
Director of Research

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| THESAURUS REFERENCE:  |   |                                      |            |              |                      |                       |                      |                      |                       |                   |                        |                    |                  |                    |
| 8) ABSTRACT<br><p>The aim of this report is to analyse measurements of vegetation attenuation at 18GHz and 38GHz. The transmitter and the receiver are both located in the forest in such a way that the main part of the radio wave propagate through the grove. Experiments are performed with groves of pine, spruce and trees in-leaf and off-leaf. In-leaf groves give the highest median attenuation while groves of pine give the lowest median attenuation.</p> <p>Evaluation of how five current models predict the measured attenuation of the different vegetation types is performed. The result is a set of preferable models for each of the vegetation types.</p> <p>Analysis of the received signal-level in time shows that the estimated distribution approaches a Rayleigh distribution when the standard deviation of the time-series is above 5 dB.</p> <p>Exploration of the received signal-level in space exposes that the estimated distribution resembles a Rayleigh distribution when the standard deviation of the space-series is greater than 6 dB.</p> |   |                                      |            |              |                      |                       |                      |                      |                       |                   |                        |                    |                  |                    |
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## VEGETATION ATTENUATION OF MICROWAVES

### Measurements and model evaluation

## 1 INTRODUCTION

In the project 742 SIGVAT different concepts of wireless communication system are evaluated. Both the transmitter and the receiver are located in a forest where the distance between them varies from a few meters up to one kilometer. To comply with the requirements of a high data-rate the frequencies in the SHF-band and the EHF-band are of current interest.

### 1.1 Background

The evaluation of the different concepts requires predictions of the vegetation attenuation at the actual frequencies and distances. A study of five current empirical models<sup>1</sup> exposes a large difference in the predicted vegetation attenuation. The variation is such that the result of the evaluation is dependent on the model chosen. Also the types of vegetation at the measurement-sites, which the parameters in the models are based on, are very different from the vegetation types of interest. Thus, experiments are required to find the attenuation of current interest.

A measurement-system which at the same time can test one of the concepts was constructed(4). Measurements of the vegetation attenuation were performed at several locations and vegetation types. The aim of this report is to analyse the captured data sets.

### 1.2 Organization of the report

We briefly introduce the themes of this report.

In section 2 we will describe the experimental setup and how the data-sets are captured.

In section 3 we first analyse the variables which influence the median vegetation attenuation. Thereafter we study the performance of the current models.

In section 4 we will analyse the data sets in order to find the distribution of the received signal-level in the time- and space-domain.

Finally, in section 5 we will conclude.

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<sup>1</sup>Details of the models are displayed in 3.2

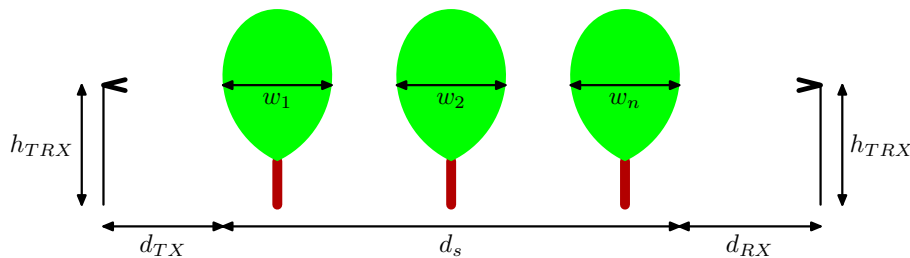


Figure 2.1 A sketch of the experimental setup. Both the transmitter and the receiver have an antenna height less than the height of the trees.

## 2 EXPERIMENTAL WORK

In this section we will give a brief description of the measurement-system and how the data sets were captured.

### 2.1 System setup

The measurement-system is constituted by two commercial radio-links with frequencies of 18GHz and 38GHz. The antennas are mounted on vehicles where all instruments for positioning and data recording are located. In the experiments the transmitter and the receiver are both located in the forest as sketched in Figure 2.1. The height of the antennas,  $h_{TRX}$ , are 5m, which is about one third of the tree height. The distance between the transmitter and the start of the grove,  $d_{TX}$ , and the distance between the receiver and the end of the grove,  $d_{RX}$ , is less than 20m. Thus, the main part of the radio wave propagates through the foliage and not over the top of the trees (5,p. 41).

All the different groves consist of wild vegetation. Pine, spruce and deciduous trees are the main types of wood. The deciduous groves consist mostly of birch and some alder. Both in-leaf and off-leaf measurements are performed. For details of the system and the different locations see (4).

### 2.2 Data

To capture data at each location the antennas are first pointed towards each other according to GPS coordinates, inclination and compass direction. Thereafter, the direction of the antenna at both the transmitter and the receiver are adjusted to maximize the received signal-level. Thus, the obtained data is a measure of the minimum attenuation at each location.

To find the maximum signal-level at the receiver, the direction of the antenna is automatically changed over a space-angle while sampling the signal. Thereafter a refined scan is performed around the maximum point of the first search as displayed in Figure 2.2.

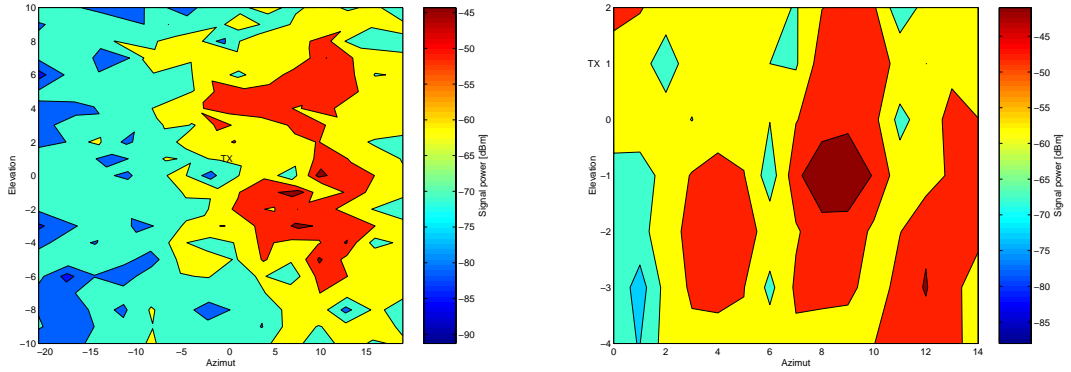


Figure 2.2 Contour-plot of the space-angle scan at the receiver. The left is the wide search and the right is the refined scan. For both plots origo is the line-of-sight between the transmitter and the receiver.

Finally, with the obtained direction of the antennas, 500 samples of the received signal-level is captured with a sample-time of 500ms. In addition to the sampled data the weather conditions and the humidity of ground and foliage are observed. Together with the distances, frequency and descriptions of the grove these observations constitute a set of independent variables.

### 3 THE MEDIAN VEGETATION ATTENUATION

In the previous section we briefly presented the experimental setup and the different data sets that were captured. In this section we will first analyse the data-sets to obtain information about which variables that influence the median vegetation attenuation. Second, we present results achieved when varying the polarization and the frequency. Finally, we compare the output of five current vegetation attenuation models with our experimental data.

#### 3.1 Variables influencing the median

In order to analyse the relation between the median vegetation attenuation  $y$  and the independent variables  $\mathbf{X}$  we use the multiple linear regression, i.e.

$$y = \mathbf{X}\beta + \epsilon \quad (3.1)$$

Here  $\beta$  is the vector of parameters and  $\epsilon$  is a vector of random errors. A test for multicollinearity by inspection of the eigenvalues and eigenvectors of  $\mathbf{X}$  exposes a dependency among some of the variables which most probably is an effect of too few measurements. The dependent variables are excluded from  $\mathbf{X}$  and the final set of variables are displayed in Table 3.1.

Regression of all possible combinations of the variables will take too much computational time<sup>2</sup>. Therefore, a forward selection method is preferred. We use the adjusted coefficient

<sup>2</sup>Approximately half a year on a 700MHz Pentium CPU.

Table 3.1 The final content of the matrix  $X$  after removing linear dependent variables.

| Index | Variable   | Range |      | Unit |
|-------|--|-------|------|------|
| 0     | Constant   |       |      |      |
| 1     | Forest depth                                       | 43    | 337  | m    |
| 2     | Frequency  | 18    | 38   | GHz  |
| 3     | Distance between TX and the first tree( $d_{TX}$ ) | 2     | 18   | m    |
| 4     | Distance between RX and the first tree( $d_{RX}$ ) | 0     | 11   | m    |
| 5     | Part of spruce                                     | 0     | 1    |      |
| 6     | Part of pine                                       | 0     | 0.95 |      |
| 7     | Part of trees in-leaf                              | 0     | 0.95 |      |
| 8     | Part of trees off-leaf                             | 0     | 1    |      |
| 9     | Average height of the trees                        | 10    | 20   | m    |
| 10    | Bare-trunk height                                  | 0     | 5    | m    |
| 11    | Air temperature                                    | -17   | 22   | C    |
| 12-13 | Polarization                                       |       |      |      |
| 14-15 | Forest density                                     |       |      |      |
| 16-19 | Foliage humidity                                   |       |      |      |
| 20-21 | Wind force   |       |      |      |
| 22-28 | Precipitation                                      |       |      |      |

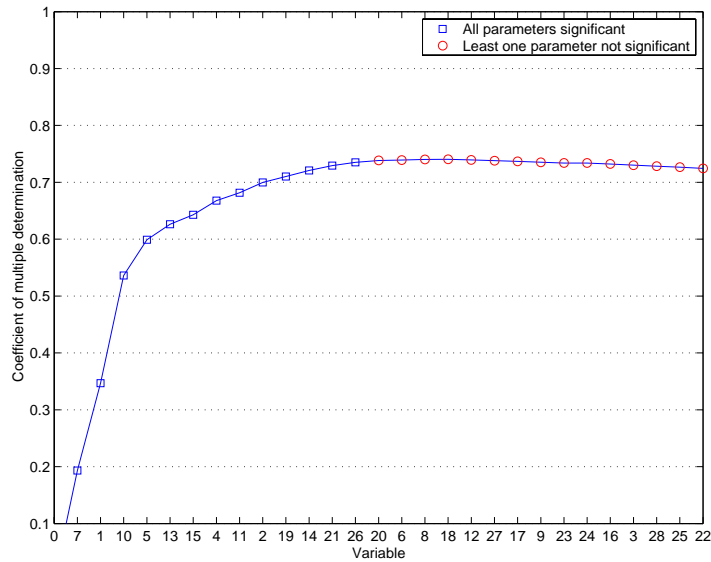


Figure 3.1 The forward selection procedure with a 95% confidence test on the parameters. The coefficient of multiple determination is plotted against the included variables. The numbers along the horizontal axis are the index given in Table 3.1.

of multiple determination to find the next variable in the forward selection(2,p. 160). The adjusted coefficient of multiple determination is a measure of the proportion of the variation explained by the independent variables.

The result of the forward selection regression analysis is displayed in Figure 3.1. The set of variables which consist of trees in-leaf, forest depth, bare-trunk height and spruce explain about 60% of the variation in the median vegetation attenuation. A closer study of the independent variables reveal a dependency between the two variables describing the bare-trunk height and the part of pine . Not unexpected, since a typical pine has a bare-trunk region, while the three other tree types normally have not. In the following analysis we find it convenient to exclude the variable describing the bare-trunk height.

Including new variables after the first five slowly increases the coefficient of multiple determination up to 73%. The test of significance states that the 14 first included variables are significantly influencing the response. The only reasonable explanation for the significance of air temperature is that with 29 variables and a 5% level of significance it is very likely that one of the variables is tested significant when it is not.

We stress that the measurement-sites consist of wild vegetation which most probably give rise to the considerable variations in the measured attenuation. Groves with more homogenous vegetation should be used to further explore the indices pointed out above.

### 3.1.1 Polarization

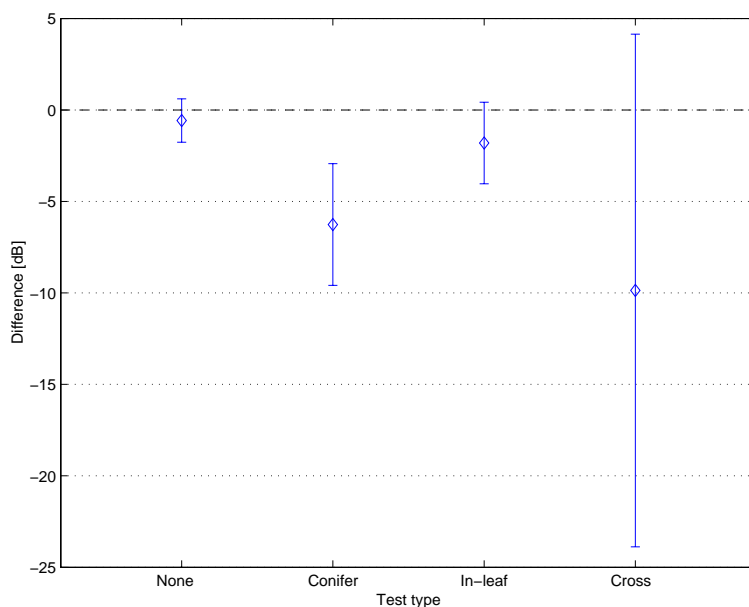
In the experiments pairs of data-sets where the polarization direction of the antennas are changed are obtained at the same location at the same day. Therefore, the stochastic variation due to weather conditions and different measurement-sites should be minimized. Hence, the difference between the mean of these interdependent time-series is a measure of the change in vegetation attenuation due to vary the polarization of the radio wave.

The mean of the differences are displayed in Figure 3.2 with a 95% confidence interval. We observe that in coniferous groves the radio wave with horizontal polarization is more attenuated than the vertical polarized radio wave. There is no significant difference in the attenuation of vertical- and horizontal-polarized radio wave which propagate through an in-leaf grove.

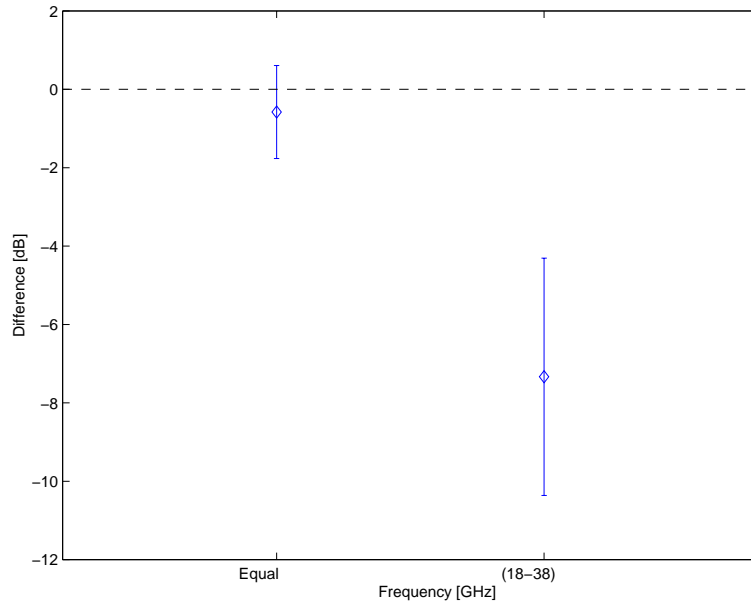
In the case of cross-polarized antennas the received signal seems to be more attenuated than in the case of vertical polarized antennas. Most probably the lack of significance is caused by the low number of data sets.

### 3.1.2 Frequency

Exactly as for the polarization experiments there are pairs of data sets obtained at the same location at the same day where only the frequency is changed between 18GHz and 38GHz. Hence, the difference between the mean of these interdependent time-series is a measure of the change in vegetation attenuation induced by varying the frequency of the radio wave. The mean of the differences are displayed in Figure 3.3. We observe that the vegetation



*Figure 3.2 The mean of the differences in attenuation between measurements were the polarization directions of the antennas are altered. **None** denotes the difference in attenuation when the polarization is unchanged. **Conifer** denotes the difference in attenuation between vertical- and horizontal-polarized radio wave which propagate through a grove of pine or spruce. **In-leaf** denotes the difference in vegetation attenuation between a radio wave with vertical and horizontal polarization in the case of in-leaf trees. **Cross** denotes the difference in vegetation attenuation between a vertical and cross-polarized radio wave. All means are displayed with a 95% confidence interval.*



*Figure 3.3* The mean of the differences in vegetation attenuation when the frequency is changed. **Equal** denotes the difference in attenuation where the frequency is unchanged. **18-38** denotes the difference in attenuation between the 18 GHz radio wave and 38 GHz radio wave.

attenuation of the 18 GHz radio wave is in average 7.5 dB less than the 38 GHz radio wave.

### 3.2 Evaluation of attenuation models

In order to estimate the vegetation attenuation at different distances and frequencies it is convenient to have an equation. We prefer to evaluate existing vegetation attenuation models in the frequency-domain of interest since developing a new model is out of scope of our work.

The details of the International Telecommunications Union model (ITU-R), the modified ITU-R model (MITU-R) the fitted ITU-R model (FITU-R) and the nonzero gradient model (NZG) can be found in (3). The development of the modified exponential decay model (MED) is described in (5). All models except the NZG model are expressed by the equation

$$L_v = \beta_1 f^{\beta_2} d_v^{\beta_3} \quad (3.2)$$

and the NZG model yields the following expression

$$L_v = \beta_3 d_v + \beta_1 - \exp\{-(\beta_2 - \beta_3)d_v/\beta_1\} \quad (3.3)$$

where, for both equations,  $f$  is the frequency in [MHz] and  $d_v$  is the vegetation depth in [m]. The parameters  $\beta_1$ ,  $\beta_2$  and  $\beta_3$  are estimated by means of measurements. Values of the parameters are displayed in Table A.1.

### 3.2.1 Forest depth

Before the performance test of the models we will stress that they use *vegetation depth* as the space variable and not the actual path length. Vegetation depth  $d_v$  is defined as

$$d_v = \sum_{i=1}^n w_i \quad (3.4)$$

where  $w_i$  is the path length in foliage at each tree and  $n$  is the number of trees in the path as sketched in Figure 2.1. The vegetation depth is often obtained by multiplying the number of trees in the path by the average span of the trees at the antenna height.

In our experiments the width of the trees  $w_i$  in the path varies and the number of trees in the path is unknown. Hence, it is more convenient to have the *forest depth* as the path length variable. The forest depth  $d_s$  is the actual path length through the grove as shown in Figure 2.1. To obtain a relation between the forest depth and the vegetation depth we define the *forest-density*  $\rho$  as

$$\rho = \frac{d_v}{d_s} \quad 0 \leq \rho \leq 1 \quad (3.5)$$

In order to test the models against the experimental data we need an estimate of the forest density. To this end we apply equation 3.5 to substitute the vegetation depth with the forest depth in the five models. Then we estimate values of the forest density by means of the models and captured data to find a consistent value of the forest density for the groves at our measurement-sites.

The result is displayed in Figure 3.4 with a 95% confidence interval. Conifers are coded as both in-leaf and off-leaf deciduous trees. We observe that conifers coded as off-leaf give the largest number of forest densities above one, which is invalid according to the definition in equation 3.5. There is no consistent value of the forest density, but the estimation indicate that it should be greater than 0.7. For convenience we continue our study with  $\rho = 1$ .

### 3.2.2 Performance of the models

With the relation between forest depth and forest density developed in the previous section, we are now ready to analyse the performance of the common attenuation models in respect to our experimental data.

We visualize the measured attenuation and the expected values of new observations with prediction intervals. The selection of linear model which generates the prediction interval is based on the analysis of variables influencing the median attenuation performed in section 3.1. For compatibility with the models we include only the variables which describes forest depth, frequency and the four types of vegetation.

Figure 3.5 to Figure 3.8 display the prediction intervals together with the output of the models. We have encoded the pine data as off-leaf because of the low attenuation observed for this type of trees. There is a considerable variation in the median attenuation at a given



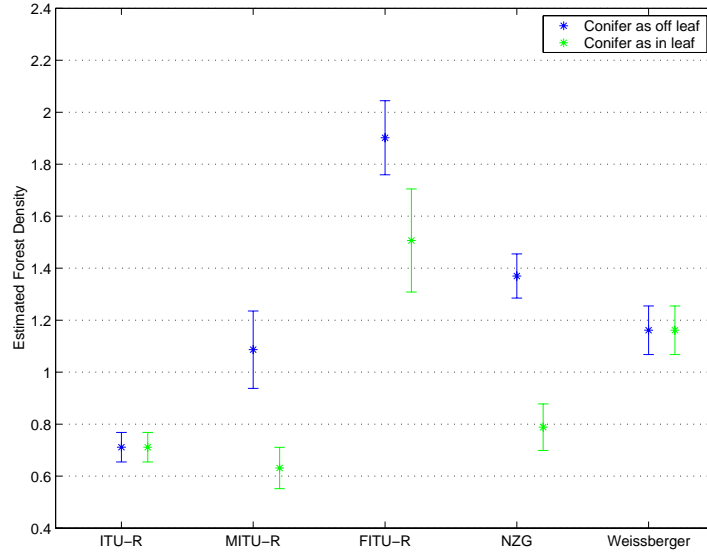


Figure 3.4 Estimation of values of the forest density by means of the experimental data and the models. The densities are displayed with 95% confidence intervals. Coniferous trees are coded as both in-leaf and off-leaf deciduous trees.

forest depth, which is expected since the measurement-sites consist of wild vegetation. Thus, to represent the vegetation attenuation we recommend to use a prediction interval and not a single value. None of the evaluated models are given with a prediction interval in the literature we have. Therefore, from the figures we extract 40dB as a rule of thumb for a 95% prediction interval.

To measure how well the models fit the experimental data we introduce the mean relative error, MRE, defined as follows

$$\text{MRE} = \frac{1}{N} \sum_{i=1}^N \frac{|y_i - \hat{y}_i|}{y_i} \quad (3.6)$$

Here  $N$  is the total number of observations,  $y_i$  is the measured attenuation and  $\hat{y}_i$  is the corresponding value of the actual model.

To choose models for the different types of vegetation we now use both the plot of the prediction intervals together with the models and the measure of fit displayed in Figure 3.9. For the in-leaf data the MITU-R model and NZG model are the best candidates. The mean relative error is lowest for the MITU-R in the off-leaf case, but Figure 3.6 indicates that the MED model has the best prediction of new observations. To model the attenuation induced by a grove of pine we recommend the FITU-R model. The spruce data do not flare the performance of the models much, but Figure 3.7 favours the MED model and the MITU-R model.

We will emphasize that the conclusions in this section assume that the forest density is equal to one in all models. All other values of forest density will decrease the value of the models output and give rise to other performance results.

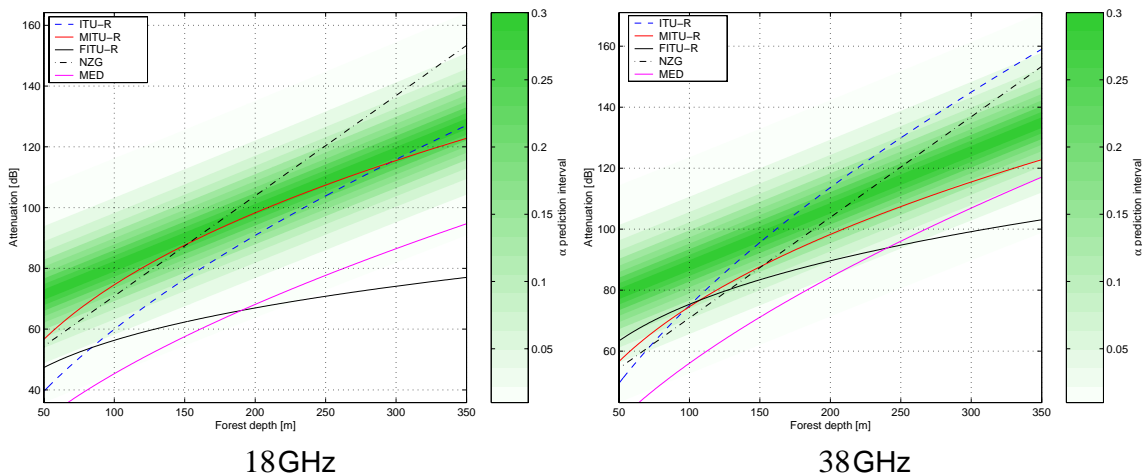


Figure 3.5 In-leaf vegetation attenuation models and the prediction intervals generated from the experimental data.

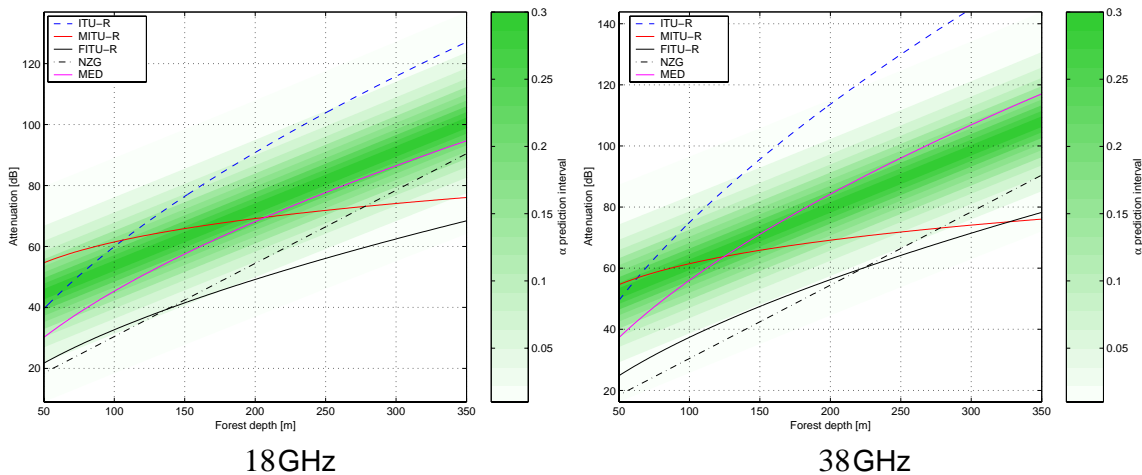


Figure 3.6 Off-leaf vegetation attenuation models and the prediction intervals generated from the experimental data.

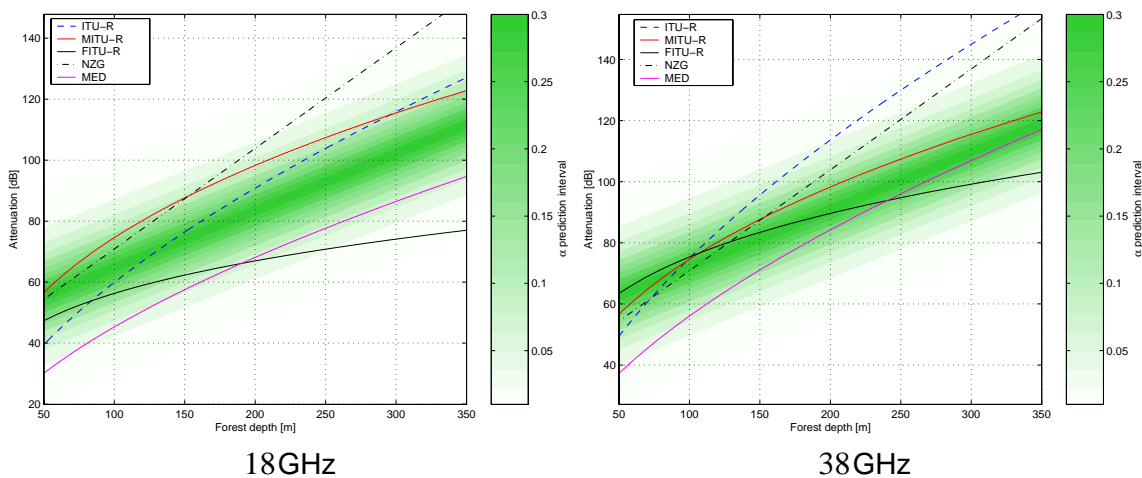


Figure 3.7 The prediction intervals derived from the spruce data and the in-leaf attenuation models.

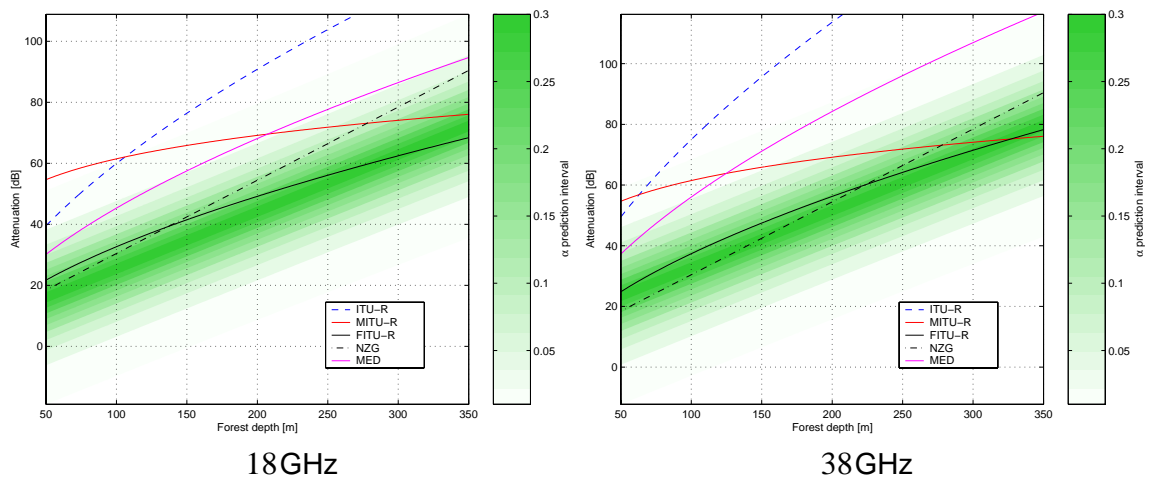


Figure 3.8 Off-leaf vegetation attenuation models and the prediction intervals derived from the pine data.

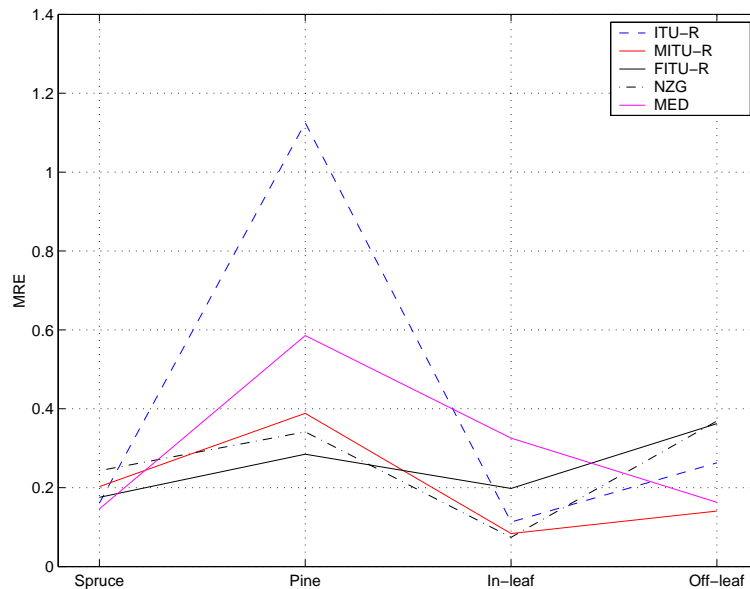


Figure 3.9 The measure of fit for the different models plotted for the different types of vegetation. The mean relative error MRE is defined in equation 3.6

## 4 VARIATIONS OF THE RECEIVED SIGNAL

A radio wave which propagates through a grove is influenced by the presence of scatterers, which are the branches and the foliage. In the case of these scatterers or when the antennas move, it will affect the signal in both the space-, time- and frequency-domain. For many applications the variation of the received signal is essential in the design of the system. Therefore, we will in this section analyse the data sets to obtain information about the signal distribution in the space- and time-domain.

### 4.1 Space-domain

A summary of studies (5,p. 112) of the variation in the space-domain shows that the received signal closely resembles a Rayleigh distribution for dense forests when the frequency is above 100MHz.

To explore the distribution of the signal in the space-domain the separation of the measurement points<sup>3</sup> must be such that the signal-level at one point is uncorrelated with the signal-level at another point. Other examinations indicate that the points at the receiver should be separated by a distance greater than half the wavelength for points located along the same great circle path to the receiver and greater than the wavelength for points on a line transverse to the great circle path (5,p. 109). The antennas are mounted in such a way that a scan will separate the points about 2cm in the horizontal direction and 3cm in the vertical direction. The wavelengths in our experiments are 1.67cm and 0.789cm. Thus, we can use the space-angle data to analyse the distribution of the signal in the space-domain.

The estimated distribution of the space-series are tested against a Normal- and a Rayleigh distribution. The test is performed for each tree type, but the picture is the same for all. Thus, we plot the test result without separating the tree types, as shown in Figure 4.1. The analysis indicates that the distribution of the signal-level in the space-domain resembles a Rayleigh distribution when the standard deviation of the series is above 6dB.

### 4.2 Time-domain

In our measurement setup both the transmitter and the receiver stand still, but in the case of wind the branches and the foliage move. Thus, we can expect variation in the signal level as for a mobile communication unit. From mobile communication theory we know that the short term fading of a multi-path radio wave where there is no main beam follows a Rayleigh distribution (1). Therefore, we test the estimated distribution from the time-series against a Rayleigh and a Normal distribution.

In Figure 4.2 we have displayed the measure of fit without separating the types of vegetation. We observe that for standard deviations greater than 5dB the distribution of the signal-level approaches a Rayleigh distribution. At lower standard deviations the Normal distribution seems to fit better although the picture is more diffuse.

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<sup>3</sup>Here a measurement point refers to the position and direction of the receiving antenna.

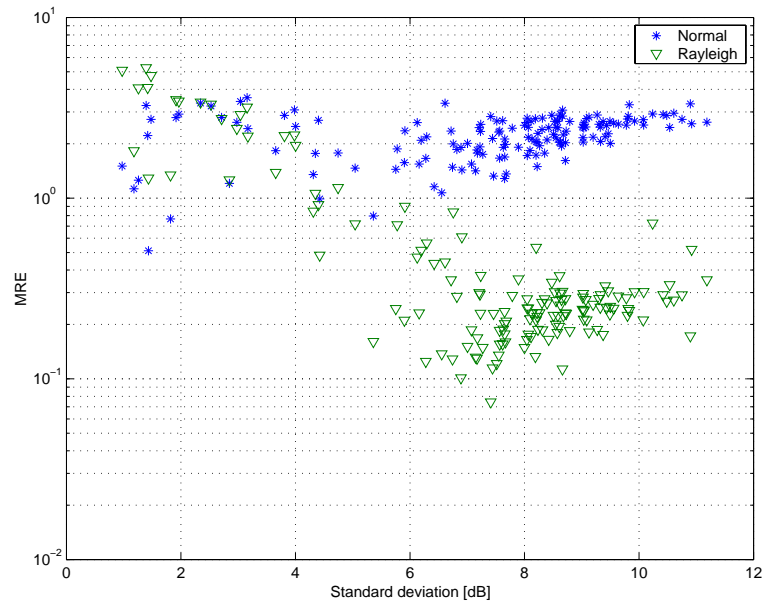


Figure 4.1 Comparison of the estimated cumulative distribution of the space-angle-series against a Normal and a Rayleigh distribution. The mean relative error MRE defined in equation 3.6 is the measure of fit. The MRE is plotted against the standard deviation of the series.

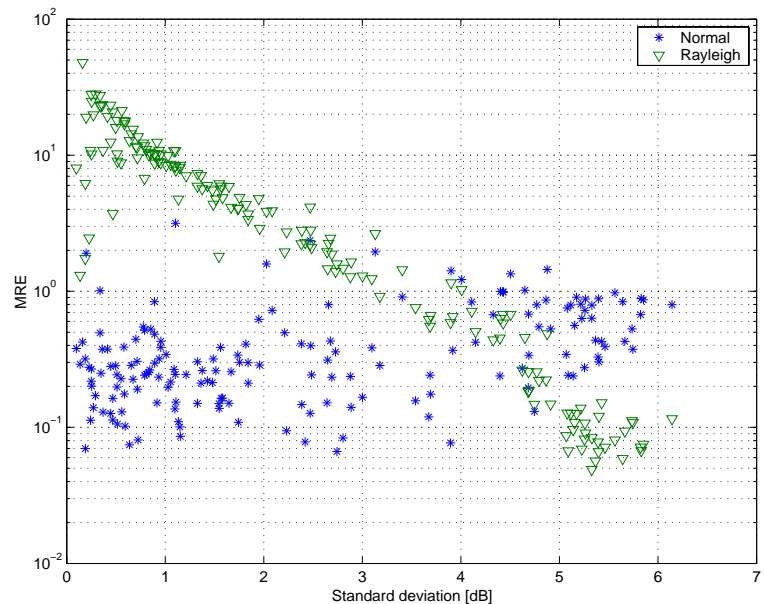


Figure 4.2 Comparison of the estimated cumulative distribution of the time-series against a Normal and a Rayleigh distribution. The mean relative error MRE defined in equation 3.6 is the measure of fit. The MRE is plotted against the standard deviation of the time-series.

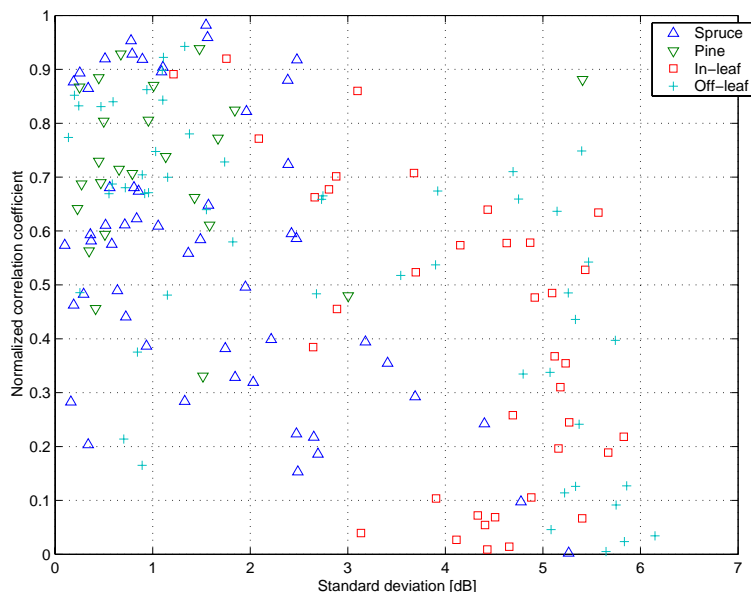


Figure 4.3 Lag one autocorrelation test of the time-series as a function of the standard deviation. The correlation coefficient is normalized such that lag zero is equal to one.

#### 4.2.1 Rate

For many applications the time-rate of the received signal-level is of interest. We will extract some information about the time-rate even though this is out of scope due to the low sample-rate of our measurements. To this end we apply an autocorrelation analysis to the time-series.

In Figure 4.3 the normalized lag one autocorrelation coefficient is plotted as a function of the standard deviation. We observe that increasing the standard deviation seems to decrease the correlation, i.e. the rate increases. The analysis reveals that the changes of the signal-level in time can be faster than 500ms even if the standard deviation is low. Further examination of the time-rates of the received signal requires new experiments where the sample-time is considerable lower than 500ms.

## 5 CONCLUDING REMARKS

Measurements of vegetation attenuation at 18GHz and 38GHz are performed in groves of pine, spruce, trees in-leaf and trees off-leaf. Multiple linear regression analysis revealed that the forest depth and the type of vegetation are the main variables explaining the variation in the median vegetation attenuation. Trees in-leaf give the highest attenuation while groves of pine induce the lowest attenuation. The correlation between the variables representing pine and the bare-trunk height indicates that the least attenuated part of the radio-wave travels through the bare-trunk region.

The usage of the captured data to estimate new observations of the vegetation attenuation motivated us to evaluate five models of interest. For trees in-leaf we recommend the MITU-R model or the NZG model. To predict the attenuation in off-leaf groves the MED model is the best candidate. The FITU-R model is preferable for groves of pine, while we recommend the MED model or the MITU-R model for the groves of spruce.

Our experiments exposed a considerable variation in the median attenuation at a given forest depth, type of vegetation and frequency. That a wild grove is a heterogenous medium probably gives rise to this variation. We recommend to represent the attenuation with an interval and not a single value when predicting new observations. In the studied literature none of the evaluated models are given with a prediction interval. Thus, we introduce 40dB as a rule of thumb for a 95% prediction interval.

Exploration of the received signal-level in the space-domain showed that the estimated distribution approaches a Rayleigh distribution when the standard deviation is greater than 6dB.

The distribution of the signal-level in the time-domain resembles a Rayleigh distribution when the standard deviation is above 5dB. Experiments with a sampling-period less than 500ms must be carried out to investigate the time-rate.

## References

- (1) (1982): *Mobile communications engineering*. McGraw-Hill, Inc.
- (2) (1992): *Introduction to Linear Regression Analysis*. John Wiley & Sons, Inc.
- (3) Al-Nuaimi, M.O. and Stephens, R.B.L. (1998): Measurements and prediction model optimisation for signal attenuation in vegetation media at centimetre wave frequencies. *IEE PROCEEDINGS-MICROWAVES ANTENNAS AND PROPAGATION*.
- (4) Grønnerud, Ove K, Hallingstad, Geir, Sander, Jostein and Skeie, Bjørn (2002): Vegetasjonsdemping av radiobølger - instrumentering og gjennomføring. Technical report, Forsvarets Forskningsinstitutt.
- (5) M. A. Weissberger (1982): An initial critical summary of models for predicting the attenuation of radio waves by trees. Technical report, Department Of Defense, Electromagnetic Compatibility Analysis Center.

## APPENDIX

### A ATTENUATION MODELS

The International Telecommunications Union model (ITU-R) is stated to be applicable in the frequency range from 200MHz up to 95GHz and a maximum vegetation depth of 400m. The modified ITU-R (MITU-R) model is optimized at 11.2GHz and a vegetation depth up to about 120m. The nonzero gradient (NZG) model has the same restriction as the MITU-R model, but the NZG model is also optimized at 20GHz. Nor the MITU-R or the NZG model have the frequency as an input variable. The fitted ITU-R (FITU-R) model is optimized by means of measurement data at 11.2GHz and 20GHz and a maximum vegetation depth of 120m.

Table A.1 *The estimated values of the parameters displayed for each of the vegetation attenuation models.*

| Model  | Vegetation | $\beta_1$ | $\beta_2$ | $\beta_3$ | Range          |
|--------|------------|-----------|-----------|-----------|----------------|
| ITU-R  |            | 0.2       | 0.3       | 0.6       |                |
| MITU-R | in-leaf    | 11.93     | 0         | 0.398     |                |
|        | off-leaf   | 1.75      | 0         | 1         | $d_v \leq 31m$ |
|        | off-leaf   | 28.1      | 0         | 0.17      | $d_v \geq 31m$ |
| MED    |            | 0.0633    | 0.284     | 1         | $d_v \leq 14m$ |
|        |            | 0.187     | 0.284     | 0.588     | $d_v \geq 14m$ |
| FITU-R | in-leaf    | 0.39      | 0.39      | 0.25      |                |
|        | off-leaf   | 0.37      | 0.18      | 0.59      |                |
| NZG    | in-leaf    | 37.87     | 19.82     | 0.33      |                |
|        | off-leaf   | 6.45      | 6.25      | 0.24      |                |



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