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## Atmospheric Attenuation due to Humidity

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### 1. Introduction

Humidity remains in the atmosphere even on bright days. Water of all three states can be found naturally in the atmosphere: liquid (rain, fog, and clouds), solid (snowflakes, ice crystals), and gas (water vapour). Water in any state is an obstacle in the link of the electromagnetic wave. When the wave passes through the water particles, a part of its energy is absorbed and a part is scattered. Therefore the electromagnetic wave is attenuated. Prediction of the influence of these factors is very important in radio system design. Attenuation due to rain, fog, and clouds can lead to the perturbations of the wireless, mobile, satellite and other communications. Another problem is the refractive index of the atmosphere, which affects the curvature of the electromagnetic wave path and gives some insight into the fading phenomenon. The anomalous electromagnetic wave propagation can cause disturbances to radar work, because variation of the refractive index of the atmosphere can induce loss of radar coverage. Accurate prediction of losses due to these factors can ensure a reliability of the radio system, decrease an equipment cost, furthermore, the radio systems can become less injurious to health of people.

When there are no possibilities to gather data for calculations of the specific attenuation due to rain, clouds and fog, and atmospheric refractive index, the values recommended by the International Communication Union's Radiocommunication sector (ITU-R) can be used. But the recommended values are not always exact. In design of the radio links, the most desirable operating frequencies are below 10 GHz, because in such cases atmospheric absorption and rainfall loss may generally be neglected (Freeman, 2007). However, in most countries, the frequency-band below 10 GHz is highly congested. In addition, high frequencies provide larger bandwidth, narrower beam width, good resolution and smaller component size (Bhattacharyya et al., 2000). Therefore, the operating frequencies of 10 GHz and above are often used in design of radio systems. The higher the operating frequency, the greater attenuation due to hydrometeors (rain, cloud, fog, snow, and etc.) is observed (Tamošiūnaitė et al., 2010a).

In (Ishimaru, 1978), it was mentioned that the electromagnetic wave attenuation due to snow is less than attenuation due to rain, and that the attenuation due to dry snow may be neglected

in microwave band. However, the attenuation due to wet snow is higher. Some results of attenuation due to hail are presented in (Ishimaru, 1978). In this chapter, our attention would be concentrated on the attenuation due to rain, clouds, and fog. The variation of the radio refractivity will be the object of our investigation presented there as well.

## 2. Attenuation due to rain

The electromagnetic wave attenuation due to rain (the rain attenuation) is one of the most noticeable components of excess losses, especially at frequencies of 10 GHz and above (Freeman, 2007). The methods of prediction of the rain attenuation can be grouped into two groups: the physical (exact) models and the empirical models. The physical models attempt to reproduce the physical behaviour involved in the attenuation processes while the empirical methodologies are based on measurement databases from stations in different climatic zones within a given region. The empirical methods are used widely and frequently with the best success (Emiliani et al., 2004). Two main causes of attenuation are scattering and absorption. When the wavelength is large compared to the size of raindrop, scattering is predominant. Conversely, when the wavelength is small compared to the raindrop's size, attenuation due to absorption is predominant (Ivanovs & Serdega 2006). Water molecules are dipoles. The raindrop's dipoles have the same time variation as the electromagnetic waves and therefore act as an antenna, which re-radiates the electromagnetic wave energy. Hence, a raindrop becomes an "antenna" with low directivity. Consequently, some energy is reradiated in arbitrary directions giving a net loss of energy in the direction towards the receiver (Ivanovs & Serdega 2006). Water is a loss-making dielectric medium. The relative dielectric constant of water is high, compared to the dielectric constant of the surrounding air. It depends on temperature and the operating frequency of the radio system. The specific heat of the water is high. Therefore, water absorbs a large amount of warmth, while warms itself. The surface tension of water is high. This is the reason why the molecules of water are holding together. One of the problems in prediction of electromagnetic wave power losses is description of shape of the raindrop. It depends on the size of droplet. It is known, that only very small droplets are like spheres. Such droplets form in clouds, as water vapour condenses on the nuclei of condensation. Further, these droplets grow by coalescence. Shape of the raindrops, that are larger than 1 mm in diameter, is no more spherical. They are not tear-shaped, as it commonly presented in pictures. The shape of falling large raindrops is more like a hamburger shape. Therefore, horizontally polarized waves suffer greater attenuation than vertically polarized waves (Freeman, 2007).

As mentioned above, the water molecules are polar ones. Those molecules rotate in such way that positive part of one molecule would be as near as possible to the negative part of another molecule. Therefore, molecules are rotating, hammering one on another and heating (Tamošiūnaitė et al., 2010a). The water molecule also rotates when a negative charge is brought near to it. The fields of electromagnetic wave vary up as time goes and force the water molecules to rotate respectively to the variation of fields.

### 2.1 Specific rain attenuation

One of the most widely used rain attenuation prediction methods is an empirical relationship between the specific rain attenuation  $\alpha$  [dB km<sup>-1</sup>] and the rain rate  $R$  [mm·h<sup>-1</sup>] (Freeman, 2007, Rec. ITU-R P.838-3, 2005):

$$\alpha = aR^b \quad (1)$$

where  $a$  and  $b$  are functions of operating frequency  $f$  and rain temperature  $t$ ; the value of  $R$  [ $\text{mm}\cdot\text{h}^{-1}$ ] is for an exceedance of 0.01% of the time for point rainfall rates with an integration time of one minute. The coefficients  $a$  and  $b$  (coefficients  $a_h$  and  $b_h$  to be used for horizontal polarized waves; coefficients  $a_v$  and  $b_v$  to be used for vertical polarized waves) are presented in (Freeman, 2007; Recommendation ITU-R P. 838-3, 2005).

### 2.1.1 Rain rate

In determination of the rain attenuation, the main parameter is rain rate  $R$ , which is expressed in [ $\text{mm}\cdot\text{h}^{-1}$ ]. Gauges at the surface measure the accumulation of rain-water (flux) in a known time interval and report the result as a rain rate (accumulation per unit time) averaged over some measurement or aggregation interval (Crane, 1996). The rain rate can be described as the thickness of the precipitation layer, which felled down over the time period of one hour in the case when the precipitation is not evaporated, not soaked into the soil, and is not blown away by the wind (Tamošiūnaitė et al., 2010a). The evaluation of  $R$ -value is the first step in the rain attenuation prediction. The rain attenuation depends on the meteorological conditions in the considered localities. This is the reason to analyze the rain attenuation in particular locations (eg. country, city, climatic region).

First attempts to predict the rain attenuation under Baltic region climate conditions are described in (Tamošiūnas et al., 2005, 2006; Ivanovs & Serdega, 2006; Zilinskas et al., 2006, 2008). It was mentioned in (Ivanovs & Serdega, 2006), that rain events produce unavailability of microwave link, which sometimes lead operators to economical losses or even license loosing.

The significant differences in annual, seasonal, monthly, and daily amounts of rainfall are observed in localities of Lithuania. The noticeable local differences of rainfall amounts are characteristic of Lithuania as well. The precipitation amount is probably the most changeable meteorological index on Lithuania's territory. It varies from 901 mm in Šilalė district to 520 mm in Pakruojis district (Bukantis, 2001). No month of a year could be described as "an average month" in Lithuania. This is the reason to revise the suitability of the models that derived under climatic conditions other than Lithuanian ones. The models using only annual amount of rainfall was analyzed in (Tamošiūnas et al., 2005). Considering the peculiarities of Lithuania's climate, the change in (Chebil et al., 1999) model was made. This new model for the electromagnetic wave attenuation due to rain medium in atmosphere for the first time has been presented in (Tamošiūnas et al., 2006). Calculation of radio wave attenuation due to rain using annual precipitation and heavy rainfall data is described in (Zilinskas et al., 2006). The heavy rainfall events and showers with thunderstorms occur during the warm season (from May to September) in Lithuania.

### 2.1.2 Integration time

As was mentioned above, the  $R$ -values are expressed in [ $\text{mm}\cdot\text{h}^{-1}$ ]. However, time intervals between the readings of rainfall amount in many cases must be much shorter. Those intervals are called the integration time  $\tau$ . In (Ivanovs & Serdega, 2006; Tamošiūnas et al., 2007; Tamošiūnaitė et al., 2010a) it was mentioned, that the period of time between the readings of the rainfall amount values is a very important parameter, because it can significantly change the  $R$ -value. High  $R$ -values "hides" when  $\tau$  is long.

Consider an example. There were raining. The duration of the rain was 5 minutes. The total amount of the precipitation was 5 mm. It did not rain during remaining 55 minutes of one hour. Thereby, if we would count the average  $R$ -value for that hour ( $\tau = 60$  min.), it would be equal to  $5 \text{ mm}\cdot\text{h}^{-1}$ . But if we would count the  $R$ -value for every minute of that hour, we would find that  $R$ -values are much higher. Consider that in every of those 5 rainy minutes the amount of the precipitation was 1 mm. Consequently, for each of those 5 minutes the  $R$ -value would be  $60 \text{ mm}\cdot\text{h}^{-1}$ . That is why the average  $R$ -values are unreliable.

In Lithuania, the  $\tau$  values must be as small as possible (Tamošiūnaitė et al., 2010a).

### 2.1.3 “One-minute” rain rate

Almost all rain attenuation methods require “one-minute” rain rate value. The “one-minute” rain rate value  $R_{(1 \text{ min.})}$  is expressed in  $[\text{mm}\cdot\text{h}^{-1}]$ .  $R_{(1 \text{ min.})}$ -value can be defined as the  $R$ -value for 0.01% of time of the year, obtained using the rainfall amount value, which was measured in  $\tau = 1$  min and multiplied by 60 (Karasawa & Matsudo, 1991).

However, in many instances data collection is oriented toward agricultural and hydrological purposes, for which annual, monthly, daily, and less commonly, 3- and 6-hourly totals are collected. Therefore the models for conversion of  $R_{(\tau \text{ min.})}$ -values into  $R_{(1 \text{ min.})}$ -values are used. A review of models for estimation of 1 min rainfall rates for microwave attenuation calculations are presented in (Tattelman & Grantham, 1985).

One of such conversion models was presented in (Moupfouma & Martin, 1995):

$$R_{(1 \text{ min.})} = (R_{(\tau \text{ min.})})^d \quad (2)$$

$$d = 0.987\tau^{0.061} \quad (3)$$

where  $R_{(1 \text{ min.})}$  is the “one-minute” rain rate value,  $R_{(\tau \text{ min.})}$  is the rain rate value measured in  $\tau$  minutes ( $\tau \geq 1$  min.).

In (Zilinskas et al, 2008) another model (4) for calculation of the  $R_{(1 \text{ min.})}$ -value was presented. That model was derived on the basis of model presented in (Rice & Holmberg, 1973) in accordance with the peculiarities of Lithuanian climate.

$$R_{(1 \text{ min.})} = \frac{\ln\left(0.0144 \frac{M_{V-IX}}{t}\right)}{0.03} \quad (4)$$

where  $M_{V-IX}$  is amount of rainfall which precipitated in May-September,  $t$  is the number of hours in a year when the value of rain rate could be equal or exceed the  $R_{(1 \text{ min.})}$ -value.

According to data that was collected in Lithuanian weather stations and (4) formula, the average  $R_{(1 \text{ min.})}$ -value for Lithuanian territory was calculated. That value is  $60.23 \text{ mm}\cdot\text{h}^{-1}$ .

This value is double the value, which is suggested by ITU-R (Tamošiūnaitė et al., 2010a).

According to (1) formula, the values of coefficients  $a$  and  $b$  (presented in Freeman, 2007), and the value of  $R_{(1 \text{ min.})} = 60.23 \text{ mm}\cdot\text{h}^{-1}$ , the dependency of the average specific electromagnetic wave attenuation due to rain,  $\alpha$ , on the operating frequency  $f$  was estimated. The results are shown in Fig. 1.

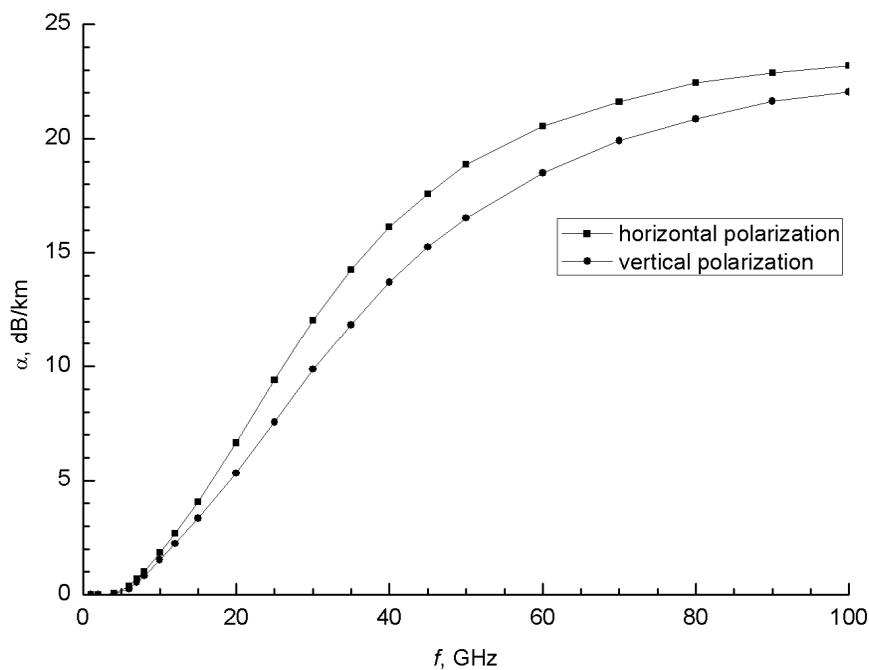


Fig. 1. The dependency of the average specific electromagnetic wave attenuation due to rain  $\alpha$  on the operating frequency  $f$ , in Lithuania.

#### 2.1.4 Worst month statistics

The “Worst-month” model was proposed by ITU-R in (Rec. ITU-R P.481-4, 2005). This model is a supplement of the “One-minute” models, which were explained above. In “One-minute” models a lot of precipitation data must be collected and calculated. Furthermore, majority of those models are appropriate only in cases when the reliability of the radio wave system must be equal 99.99%. The main advantage of the “Worst-month” model is that only the worst-month statistics must be collected. Furthermore, the “Worst-month” model is appropriate in cases when the required reliability of the radio system is other than 99.99%.

The worst-month is the month (or 30 days period) from a year (or twelve consecutive calendar months), during which the threshold is exceeded for the longest time. This month is not necessarily the same month in different year. The fraction of time when the threshold value of rain rate (so, and rain attenuation value) was exceeded is identical to probability that the threshold value of rain rate would be exceeded (Crane, 1996).

The average annual worst-month time percentage of excess,  $p_m$ , is proportional to the average annual time percentage of excess,  $p$ , in such relation:

$$p_m = Qp \quad (5)$$

where  $Q$  is the conversion factor;  $p_m$  [%] and  $p$  [%] must refer to the same threshold levels (the same rain rate value).

The conversion factor  $Q$  is a two-parameters ( $Q_1, \beta$ ) function of  $p$ . In most cases a high reliability of the radio system is required ( $p \leq 3\%$ ). Then  $Q$  can be expressed as (Rec. ITU-R P.481-4, 2005):

$$Q = Q_1 p^{-\beta} \quad (6)$$

For global planning purposes the following values of the parameters  $Q_1$  and  $\beta$  may be used:  $Q_1 = 2.85$  and  $\beta = 0.13$  (Rec. ITU-R P.481-4, 2005).

For global rain rate applications, the following values for the parameters  $Q_1$  and  $\beta$  should be used:  $Q_1 = 2.82$  and  $\beta = 0.15$ , for tropical, subtropical and temperate climate regions with frequent rain;  $Q_1 = 4.48$  and  $\beta = 0.11$ , for dry temperate, polar and desert regions. Yet ITU-R recommends that more precise values of  $Q_1$  and  $\beta$  should be used where possible.

Since

$$p = \frac{p_m}{Q} \quad (7)$$

and (6), consequently:

$$p = \frac{1}{Q_1} p_m^{\frac{1}{1-\beta}} \quad (8)$$

Mark  $\frac{1}{Q_1} = q$  and  $\frac{1}{1-\beta} = \xi$ , then:

$$p = qp_m^\xi \quad (9)$$

According to (2), (3) and annual data, the relation between  $p$  and  $R_{(1 \text{ min.})}$  can be found. This relation could be compared to the relation calculated according to (8) and ITU-R suggested  $Q_1$  and  $\beta$  values. According to Lithuanian climate, the values  $Q_1 = 2.82$  and  $\beta = 0.15$  should be appropriate.

For example, we evaluated the "Worst-month" model in Vilnius, the capital of Lithuania. The results are shown in Fig. 2. As can be seen, the values  $Q_1 = 2.82$  and  $\beta = 0.15$  are

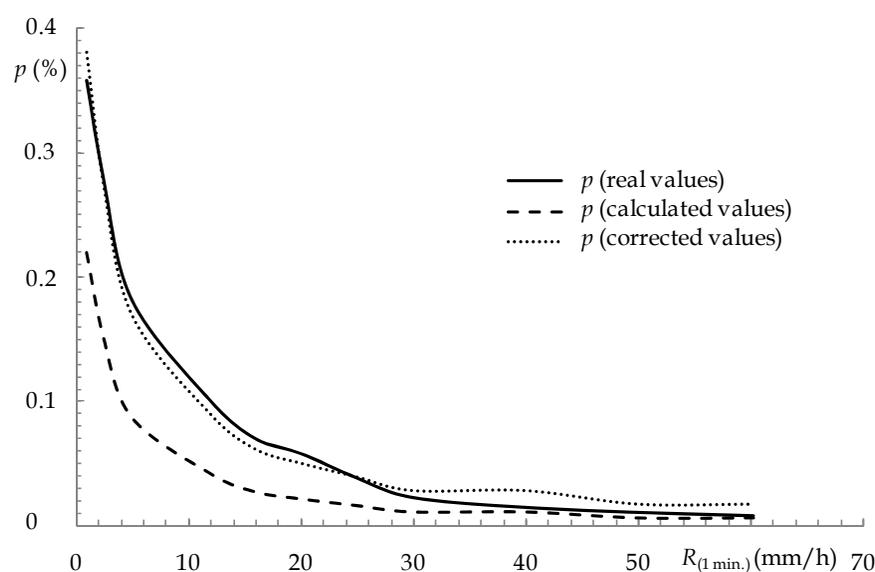


Fig. 2. The correlation between the real, calculated and corrected values of  $p$  (in Vilnius).

appropriate only in cases when  $R_{(1 \text{ min.})} > 38 \text{ mm}\cdot\text{h}^{-1}$ . When  $R_{(1 \text{ min.})} \leq 38 \text{ mm}\cdot\text{h}^{-1}$ , the calculated values are apparently distant from the real values. Therefore, the values of  $Q_1$  and  $\beta$  must be corrected. The best correlation is when in (6) there are  $q = 0.5$  and  $\xi = 1.03$ . Consequently, the corrected  $Q_1$  and  $\beta$  values should be  $Q_1 = 2$  and  $\beta = 0.03$ . But still, as can be seen in Fig. 2, the corrected values are only correct when  $R_{(1 \text{ min.})} \leq 30 \text{ mm}\cdot\text{h}^{-1}$ . Furthermore, when  $R_{(1 \text{ min.})} > 34 \text{ mm}\cdot\text{h}^{-1}$ , the values  $Q_1 = 2.82$  and  $\beta = 0.15$  are more proper than  $Q_1 = 2$  and  $\beta = 0.03$ . As a result, in cases when  $R_{(1 \text{ min.})} \leq 34$ , the values  $Q_1 = 2$  and  $\beta = 0.03$  should be used, and in cases when  $R_{(1 \text{ min.})} > 34 \text{ mm}\cdot\text{h}^{-1}$ , the ITU-R suggested values  $Q_1 = 2.82$  and  $\beta = 0.15$  may be used.

### 3. Attenuation due to clouds

The effect of rain attenuation is greater than that of clouds in many cases, but clouds occur more often than rain. In clouds, water droplets are generally less than 0.01 cm in diameter (Freeman, 2007). In (Altshuler & Mart, 1989), it was mentioned that cloud attenuation was primarily due to absorption by the cloud droplets, and scattering losses were secondary. With increase in operating frequency the attenuation due to clouds also increases, but as the temperature of the clouds decreases the attenuation value increases (Sarkar et. al., 2005).

On average, the clouds cover more than 50% of the territory of Lithuania. According to the data of its weather stations, November and December are the cloudiest months. The clearest sky is in May and June. There are about 100 overcast days in the year.

#### 3.1 Liquid water content

The liquid water content  $M$  is one of the most important parameters of the clouds.  $M$  describes the mass of water drops in the volume units of the cloud. It has been mentioned in (Freeman, 2007) that the specific cloud attenuation  $\alpha_C$  [dB/km] is a function of the liquid water content  $M$  [g/m<sup>3</sup>], the frequency  $f$ , and the temperature within the cloud  $T$ . The measurements of  $M$  at a point in space or averaged over a radio wave path are very complicated. Direct methods for measuring  $M$  consists of extracting a known volume through a cotton pad or of rotating cups in an impeller apparatus, both to be weighed; also, resistance changes can be measured with a hot wire probe attached to an aircraft flying through clouds (Liebe et al., 1989). The liquid water content in the cloud varies in a wide range. In most of the cloud attenuation models, it is required to know the value of  $M$ .

The climate conditions (humidity, temperature, etc.) and cloud morphology are different over various localities of several regions; accordingly, the liquid water contents differ within the clouds as well. This factor must be considered when analyzing rain attenuation and cloud attenuation. Our first attempt to determine the specific cloud attenuation under the Lithuanian climatic conditions is presented in (Tamošiūnaitė et al., 2008; Zilinskas et al., 2008). The humid weather predominates over the year in Lithuania.

#### 3.2 Calculation of the specific cloud attenuation

The specific cloud attenuation is a function of clouds' liquid water content and a coefficient, which is a function of frequency and temperature. In this case, the main problem is the value of clouds' water content, because the direct measurements at a point in space are

problematic. In cases when such data is unavailable, models that require only the meteorological parameters, measured at ground level, can be used. These models are based on the fact that the condensation is possible when the water vapour concentration exceeds the saturation density at the temperature, which is prevailing at that height. The water vapour density can be estimated from the humidity measurements carried out at ground level. The cloud's water content value can be estimated as the difference between water vapour concentration and saturation density at cloud temperature. The specific cloud attenuation is, unlike the case of rain, independent of drop-size distribution (Freeman, 2007). Several cloud attenuation models were developed. In (Freeman, 2007), the specific cloud attenuation was expressed as the function of liquid water content  $M$ :

$$\alpha_C = K_C M \quad (10)$$

where  $K_C$  is the attenuation constant.

The attenuation constant  $K_C$  is the function of frequency  $f$  and temperature  $T$ . The values of  $K_C$  for pure water droplets are presented in (Freeman, 2007). The values of  $K_C$  for salt-water droplets (over the sea and ocean surfaces) are higher. The necessity to know  $M$  value is limiting the direct use of relationship (10).

Often there are no possibility to measure the liquid water content and temperature within the clouds. In such cases the methods that require only meteorological parameters measured at the ground level may be used. The basic idea of such models (Dintelmann & Ortgies, 1989) is that the water vapour in the atmosphere would lead to the formation of clouds whenever there would be a possibility for condensation at some height  $h$  above ground level. There is also mentioned that the condensation is possible when the water vapour density  $\rho$  exceeds the saturation density  $\rho_s$  at temperature  $T$  prevailing at that height. It is assumed that the water vapour density  $\rho$  can be estimated from humidity measurements carried out at ground level.

The height at which cloud exists is very important for accurate determination of results of attenuation due to clouds (Sarkar et al., 2005). It was assumed in (Ito, 1989, as cited in Dintelmann & Ortgies, 1989) that clouds are created starting in the vicinity of the height  $h$ , and  $h$  [km] follows ground temperature  $T_0$  [K] as:

$$h = 0.89 + 0.165(T_0 - 273) \quad (11)$$

Relation (11) is based on analysis of temperature profiles in rain and on the Aerological Data of Japan and we have specified the applicability of this relation in the territory of Lithuania. The condensed water content  $M$  is estimated as the difference between  $\rho$  and saturation density  $\rho_s$  at cloud temperature (Dintelmann & Ortgies, 1989):

$$M = \rho - \rho_s \quad (12)$$

where  $\rho_s$  [g/m<sup>3</sup>] is the saturated vapour density.

It is assumed that clouds are formed when  $M > 0$ . As mentioned above, the determination of the water content value  $M$  is complicated. Its values differ in each group of the clouds (the clouds are grouped according to their shape, height, and structure). In our calculations, the main problem was determination of  $M$ . According to (Dintelmann & Ortgies, 1989), the values of water vapour density  $\rho$  at the height  $h$  can be estimated from the equation of state, assuming an adiabatic process:

$$\rho = \frac{\rho_0 T_0}{T} \left( 1 - \frac{\kappa - 1}{\kappa} \cdot \frac{\mu g h}{R T_0} \right)^{\frac{\kappa}{\kappa - 1}} \quad (13)$$

where  $\rho_0$  is the water vapour density at the ground level,  $T_0$  is the ground level temperature,  $T$  is the absolute temperature in the vicinity of  $h$ , denotes the specific heat ratio which is 4/3 for the water vapour molecule,  $\mu$  is the water molar mass,  $g$  is the acceleration due to gravity,  $h$  is the height, and  $R$  is the fundamental gas constant. The values of  $\rho_0$  can be determined by using known relations (Freeman, 2007).

We assume that the clouds are created starting in the vicinity of the height  $h$ . We determine the values of  $h$  by using relation (11) or the data of the dew point temperature, temperature at the ground level, and the temperature gradient of 6.5°C/km (Rec. ITU-R P. P.835-3, 2004). The values of  $h$  obtained here we compared to the cloud base height values measured at the weather stations (see Table 1). The analysis of the cloud cover over the localities of Lithuania data shows that the relationship (11) can be used only in the cases when the middle or high clouds are formed over those localities.

$T_0$ [K]	Cloud base height (data of weather stations)	Cloud base height (equation 11)
280.1	0.6-1.0	2.06
280.1	2.0-2.5	2.06
280.4	2.0-2.5	2.11
281.5	2.0-2.5	2.29
281.6	2.0-2.5	2.31
282.6	2.0-2.5	2.47
284.4	2.0-2.5	2.77

Table 1. Temperature at the ground level and the values of the cloud base heights (data of weather station) in Vilnius in April 2007, as well as the height  $h$  determined using equation (8) (Tamošiūnaitė et al., 2008).

#### 4. Attenuation due to fog

The influence of the fog on the attenuation of the electromagnetic waves can lead to the perturbation of the wireless communication. In (Chen et al., 2004), it was mentioned that fog may be one of dominant factors in determination of the reliability of millimeter wave systems, especially in coastal areas, where dense moist fog with high liquid water content happen frequently. Fog results from the condensation of atmospheric water vapour into water droplets that remain suspended in air (Freeman, 2007). Moist fog frequently appears over the localities of Lithuania (Tamosiunas et al., 2009). There are several meteorological mechanisms for determination whether fog will form and of degree of its intensity. The physical mechanism of the formation of the fog can be reduced to three processes: cooling, moistening, and vertical mixing of air parcels with different temperatures and humidity (Duynderke et al., 1991). All three processes can occur, although one meteorological mechanism may dominate. This circumstance leads to the different types of the fog. In (Galati et al., 2006), the fog is classified in four types: strong advection fog, light advection fog, strong radiation fog, and light radiation fog.

The calculation methods for determination of fog attenuation are used in many cases. The propagation properties for microwave and millimeter-wave frequencies at the foggy air conditions were examined in (Liebe et. al, 1989). The values of the specific attenuation were derived from a complex refractivity based on the Rayleigh absorption approximation of Mie's scattering theory. In (Liebe et. al, 1989), the particle mass content and permittivity, which depends on the frequency and the temperature, were key variables. Attenuation due to fog is a complex function of the particle size distribution, density, extent, index of refraction, and wavelength (Altshuler, 1984). Normalized fog attenuation directly, given only the wavelength and fog temperature is presented in (Altshuler, 1984):

$$A = -1.347 + 0.0372\lambda + \frac{18}{\lambda} - 0.022T_0 \quad (14)$$

where  $A$  is attenuation in [(dB/km)/(g/m<sup>3</sup>)],  $\lambda$  is wavelength in [mm],  $t$  is temperature in [°C]; the relation (14) is valid only for  $3 \text{ mm} < \lambda < 3 \text{ cm}$  and  $-8^\circ\text{C} < T < 25^\circ\text{C}$ .

It was mentioned in (Altshuler, 1984), that the total fog attenuation could be obtained by multiplying the normalized attenuation by the fog density in [g/m<sup>3</sup>] and the fog extent in [km]. In (Zhao & Wu, 2000), it was mentioned that fog is often characterized by the visibility and the visibility is defined as the greatest distance at which it is just possible for an observer to see a prominent dark object against the sky at the horizon.

Attenuation due to fog can be expressed in terms of the water content  $M$ , and the microstructure of the fog can be ignored (Galati et al., 2000). In (Altshuler, 1984), the empirical formula for fog visibility as a function of fog density was derived:

$$V = 0.024M^{-0.65} \quad (15)$$

where  $V$  is the visibility in [km] and  $M$  is the liquid water content in [g/m<sup>3</sup>].

It was mentioned in (Altshuler, 1984), that the empirical formula (15) is valid for drop diameter between  $0.3 \text{ }\mu\text{m}$  and  $10 \text{ }\mu\text{m}$ . For the case of dense haze or other special type fogs, it is recommended to replace the coefficient 0.024 with 0.017 (Altshuler, 1984). If the visibility data are available, but the fog density data are not available, the following expression may be used (Altshuler, 1984):

$$M = \left( \frac{0.024}{V} \right)^{1.54} \quad (16)$$

In (Chen et al., 2004; Galati et al., 2006; Recommendation ITU-R PN 840-4, 2009), based on the Rayleigh approximation, the specific attenuation due to the fog  $\alpha_{\text{fog}}$  has been written as:

$$\alpha_{\text{fog}} = KM \text{ [dB/km]}, \quad (17)$$

where  $K$  is specific attenuation coefficient.

$$K = 6.0826 \cdot 10^{-4} f^{-1.8963} \theta^{7.8087 - 0.01565f - 3.0730 \cdot 10^{-4} f^2} \quad (18)$$

where  $\theta = 300/T$ ,  $f$  is frequency, and  $T$  is temperature [K].

V, km	M, g/m <sup>3</sup>
0.1	0.111
0.2	0.038
0.3	0.020
0.5	0.010
1.0	0.003

Table 2. The values of visibility  $V$  measured in the localities of Lithuania and the values of fog water content  $M$  (Tamosiunas et al., 2009).

The values of the visibility measured in the localities of Lithuania and the values of fog water content  $M$  determined using (16) are presented in Table 2. The highest value of the specific fog attenuation determined using  $M$ -data presented in Table 2 was 0.59 dB/km.

In (Naveen Kumar Chaudhary et al., 2011), it was concluded, that the link reliability can be improved by increasing the transmission power or using high gain directional antennas in the cases when the foggy conditions occur and the visibility is less than 500 meters. For the same value of visibility, the fog attenuation decreases when the temperature increases (Naveen Kumar Chaudhary et al., 2011).

## 5. Radio refractive index and its variability

The atmospheric refractive index is the ratio of the velocity of propagating electromagnetic wave in free space and its velocity in a specific medium (Freeman, 2007). The value of the atmosphere's refractive index is very close to the unit. Furthermore, changes of the refractive index value are very small in time and space. In the aim to make those changes more noticeable, the term of refractivity is used. It is a function of temperature, atmospheric pressure and partial vapour pressure. The value of the refractivity is about million times greater than the value of refractive index.

In design of the radio communication networks, it is important to know the atmospheric radio refractive index. The path of a radio ray becomes curved when the radio wave propagates through the Earth's atmosphere due to the variations in the atmospheric refractivity index along its trajectory (Freeman, 2007). Refractivity of the atmosphere affects not only the curvature of the radio ray path but also gives some insight into the fading phenomenon. The anomalous electromagnetic wave propagation can be a problem for radars because the variation of the refractive index can induce loss of radar coverage (Norland, 2006). In practice, the propagation conditions are more complicated in comparison with the conditions predictable in design of radio system in most cases.

The anomalous propagation is due to the variations of the humidity, temperature and pressure at the atmosphere that cause variations in the refractive index (Norland, 2006). The climatic conditions are very changeable and unstable in Lithuania (Pankauskas & Bukantis, 2006). The territory of Lithuania belongs to the area where there is the excess of moisture. The relative humidity is about 70% in spring and summer while in winter it is as high as 85 - 90% (Bagdonas & Karalevičienė, 1987). Lithuanian climate is also characterized by large temperature fluctuations. Difference between the warmest and coldest months is 21.8°C (Pankauskas & Bukantis, 2006). It was noted in (Priestley & Hill, 1985; Kablak, 2007) that even small changes of temperature, humidity and partial water vapour pressure lead to changes in the atmospheric refractive index. In (Zilinskas et al., 2008), the measurements of these meteorological parameters were analyzed in the different time of year and different

time of day. The values of the refractive index have been determined by using measured meteorological data. In (Žilinskas et al., 2010), it was mentioned that seasonal variation of refractivity gradient could cause microwave systems unavailability.

### 5.1 Calculation of radio refractivity

As mentioned above, the value of the radio refractive index,  $n$ , is very close to the unit and changes in this value are very small in the time and in the space. With the aim to make those changes more noticeable, the term of radio refractivity,  $N$ , is used (Freeman, 2007; Rec. ITU-R P. 453-9, 2003):

$$N = (n - 1) \cdot 10^6. \quad (20)$$

According to the recommendation of ITU -R (Rec. ITU-R P. 453-9, 2003):

$$N = \frac{77.6}{T} \left( p + 4810 \frac{e}{T} \right) \quad (21)$$

where  $T$  [K] is a temperature;  $p$  [hPa] is the atmospheric pressure;  $e$  [hPa] is partial water vapour pressure. The refractivity is expressed in  $N$  - units.

It was mentioned in (Freeman, 2007; Rec. ITU-R P. 453-9, 2003), that expression (21) may be used for all radio frequencies; for frequencies up to 100 GHz, the error is less than 0.5%. There are two terms (the "dry term" and the "wet term") in relationship (21).

The values of the refractivity  $N$  in Lithuania were determined by using (21). The data of temperature, humidity, and atmospheric pressure were taken from a meteorological data website (<http://rp5.ru>).

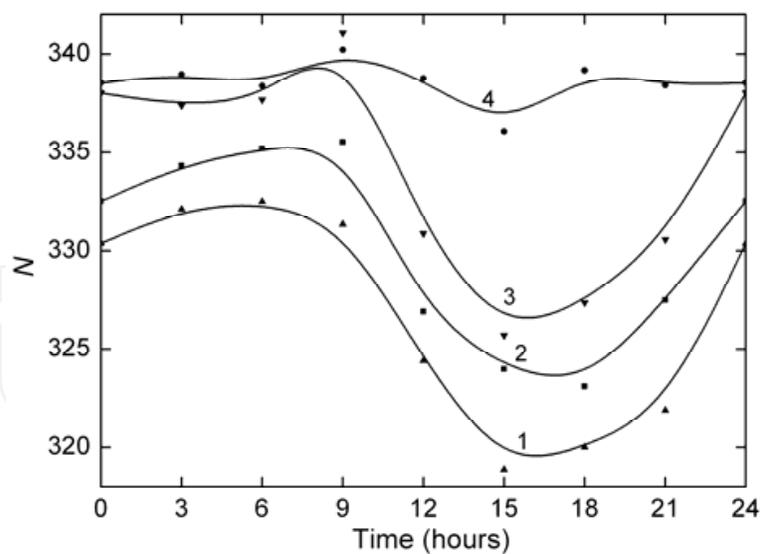


Fig. 3. The dependences of average  $N$ - values on the time of day in cities of Lithuania: Vilnius (curve 1), Mažeikiai (curve 2), Kaunas (curve 3), and Klaipėda (curve 4) in July 2008 (Valma, et al., 2010).

The dependences of average  $N$ -values on the time of day in cities of Lithuania are presented in Fig. 3. As can be seen, the behaviours of those dependences at the diurnal time are similar in all localities that are situated in the Continental part of Lithuania (Vilnius, Kaunas and

Mažeikiai) and slightly different in Seacoast (Klaipėda). The climate of Klaipėda is moderate and warm (Pankauskas & Bukantis, 2006; Zilinskas et al., 2008). The climate of Continental part of Lithuania is typical climate of the middle part of the Eastern Europe. This may explain the difference between the daily variations of  $N$  in Klaipėda and in other localities analyzed here. In Lithuania, the highest  $N$ -values were in July.

## 6. Conclusions

The main models for calculation of electromagnetic wave attenuation due to atmosphere humidity were revised. In Lithuania, when the reliability of the radio system of 99,99% is required, the  $R_{(1 \text{ min.})}$ -value is  $R_{(1 \text{ min.})} = 60.23 \text{ mm/h}$ . It is twice the ITU-R recommended value. The dependency of the average specific electromagnetic wave attenuation due to rain on the operating frequency (0-100 GHz) was determined. The attenuation of horizontally polarized electromagnetic waves is greater than the attenuation of vertically polarized electromagnetic waves. In cases when the required reliability of the radio system is other than 99,99%, the "Worst-month" model can be used. However, for small  $R_{(1 \text{ min.})}$ -values the parameters of that model should be corrected. In Vilnius, the city of Lithuania, when  $R_{(1 \text{ min.})} > 34 \text{ mm/h}$ , ITU-R recommended values  $Q_1 = 2.82$  and  $\beta = 0.15$  could be used. In cases when  $R_{(1 \text{ min.})} \leq 34 \text{ mm/h}$ , the corrected values  $Q_1 = 2$  and  $\beta = 0.03$  are more appropriate.

The main problem of models for calculation of electromagnetic wave attenuation due to clouds and fog is the required value of liquid water content. In Lithuania it is impossible to gather such meteorological information. Therefore, models excluding or calculating the liquid water content were revised. The variations of the atmospheric humidity, temperature and pressure can cause the fluctuations of the atmospheric refractive index. In Lithuania, the atmosphere refractive index fluctuates most in July. The variations of  $N$  in diurnal time are similar in all localities that are situated in the Continental part of Lithuania and slightly different in Seacoast.

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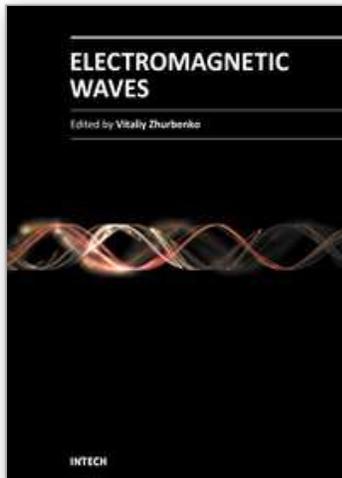
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