# Prediction of electromagnetic wave attenuation due to water in atmosphere. 1. Attenuation due to rain

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**Abstract.** The prediction of the electromagnetic wave (EW) power losses is a very important step in the design of radio systems. It is epecially important for high operating frequencies. Accurate prediction of losses can ensure a reliability of the radio system, decrease in equipment cost, and maybe the system can become less injurious to health of people. Rainfall is one of the factors causing the attenuation of the electromagnetic waves while they are propagating through the atmosphere. In this paper, difficulties in prediction of electromagnetic waves attenuation due to rain are analyzed. According to the climatic peculiarities of Lithuania, appropriate model for calculation of electromagnetic waves attenuation due to rain (rain attenuation) was chosen. Applying this model a large quantity of precipitation data was computed and the specific rain attenuation considering the peculiarities of localities of Lithuania was determined.

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## Introduction

In a design of the radio links the most desirable operating electromagnetic wave (EW) frequencies are below 10 GHz. The reasons causing such demand are listed in the Ref. [1]: "Galactic noise and man – made noise are minimum; atmospheric absorption and rainfall loss may generally be neglected; finally, there is a mature technology with competitive pricing of equipment".

However, the frequency–band below 10 GHz is congested in most of the countries. In addition, the use of high frequency provides larger bandwidth, narrower beam width, good resolution and smaller component size [2]. Therefore, the operating frequencies of 10 GHz and above are often used in the design of the radio systems. However, in the cases of higher frequencies, the losses of energy of the electromagnetic waves (EW) propagating through the atmosphere are more noticeable.

One of the reasons is attenuation due to *hydrometeors* [1]. Hydrometeors are any particles of water or ice that have formed in the atmosphere or at the Earth's surface as a result of condensation or sublimation. With increasing the EW frequency, the influence of the attenuation due to hydrometeors increases. Water or ice particles blown from the ground into the atmosphere are also classified as some sort of hydrometeors. Some well-known hydrometeors are clouds, fog, rain, snow, hail, dew, rime, glaze, blowing snow, and blowing spray [3].

In the Ref. [4], it is noted that hydrometeors may be classified in a number of different ways, the following one is an example of one of them:

1) liquid or solid water particles formed and remaining suspended in the air (damp (high relative humidity) haze, cloud, fog, ice fog, and mist);
2) liquid precipitation (drizzle and rain);
3) freezing precipitation (freezing drizzle and freezing rain);
4) solid (frozen) precipitation (snow, hail, ice pellets, snow pellets (soft hail, graupel), snow grains, and ice crystals);
5) falling particles that evaporate before reaching the ground (*virga*);
6) liquid or solid water particles lifted by the wind from the earth's surface (drifting snow, blowing snow, and blowing spray) [4].

The principal interactions between electromagnetic radiation and hydrometeors are scattering and absorption by the individual particles. Rainfall is one of the hydrometeors affecting electromagnetic waves path loss.

This work is devoted: i) to analyze the Lithuanian climate conditions; and ii) to determine the distribution of specific rain attenuation.

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## 1. EW attenuation due to water

Water is in the atmosphere even during bright days. If we would pour on the Earth surface all the atmospheric water vapors, drops, and ice crystals, the layer as thick as 10 m would be formed around the all Earth [5].

Water of all three states can be found naturally in the atmosphere: the liquid (rain, fog, and clouds), the solid (snowflakes, ice crystals), and gas (water vapor). Attenuation due to water in the atmosphere varies with the density of the rainfall cell or cloud and the size of the rainfall drops or water particles such as fog or mist [1]. Hence, the atmosphere is not homogeneous. The raindrop is an obstacle in the link of the electromagnetic wave (EW). Water is a lossy dielectric medium. The dielectric properties of a raindrop differ from ones of the surrounding medium.

A part of an electromagnetic wave energy is absorbed and a part is scattered when the electromagnetic wave passes over the raindrops. The absorbed energy heats the absorbing raindrop. The molecules of water are polarized, because the centers of charges in the molecules of water are not in one line. 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, the molecules are rotating, hammering one on another and heating. The water molecule also rotates when a negative charge is brought near to it. Electromagnetic waves consist of electric force fields. As time goes on they vary and force water molecules to rotate subsequently [6]. The energy, which is scattered, is quasi–isotropic and relates to the wavelength of the incident wave [1].

The attenuation due to absorption is larger than attenuation due to scatter for wavelengths that are small compared with the drop size; for wavelengths that are long compared to drop size, the attenuation due to scatter is larger than attenuation due to absorption [7]. Scattering is most significant when the wavelength of the electromagnetic radiation is comparable to the dimension of the scattering particles (the diameters of the raindrops typically varied in the range $0.2 \div 6$ mm) [8]. The absorption and scattering by raindrops depends on the size, shape and complex dielectric constant of the drops, and also on polarization and wavelength of the electromagnetic wave. Rain is highly non-uniform and this fact complicates the determination of rain attenuation of electromagnetic waves. It exhibits considerable variation in number density, size and shape. For any given rainfall rate, there is no unique distribution of drop sizes, and it varies in time and space.

The density of the water depends on its temperature. Water is the densest at temperatures up to +4°C. The water relative dielectric constant is high in the contrast to the one of the surrounding air. The dielectric constant and the refractive index of the water depend on the temperature and on the operating frequency of the radio system. The specific heat of the water is high. Therefore, the water absorbs a large amount of warmth, while warms itself.

The dielectric constant of water also depends on the temperature. Therefore, the liquid water and ice are attenuating the electromagnetic waves in different degree. For example, one can ignore the microwave attenuation due to the dry snow, but the attenuation due to the rainfall or due to wet snow is more noticeable and must be predicted in the radio system design. The attenuation due to the wet snow is near the attenuation due to the big raindrops in case of shower rain with the thunderstorm.

The surface tension of water is large. This is the reason why the molecules of water hold together. One of the problems in predicting power losses in electromagnetic waves is the description of the shape of the raindrops. The shape of a raindrop depends on drop‘s size. It is known, that only very small drops are like spheres. Such droplets form in clouds when water vapours condense on the nuclei of condensation. Further, these droplets grow by coalescence and shape of the raindrops is no more spherical. Larger raindrops are not tear-shaped, as it is commonly presented in pictures. The shape of the larger falling raindrops is like a hamburger (see Fig.1) [9].

Both the shape of the drops' size distribution and its parameters are related from the first principles to the dynamics of a single drop deforming as it falls in the air, ultimately breaking into a dispersion of smaller fragments containing the whole spectrum of sizes observed in the rain [10].

The large surface tension of water holds out the airflows pressure on the top of the drop and this is why the drop's shape is still spherical at the top of it. But the airflows are stronger at the bottom of the raindrop and for this reason the bottom of it is flattened [9].

Phillip Lenard (Nobel Prize Laureate 1905) concluded that a velocity of the falling drop depends on its size and grows with it [11]. But he also noticed that the velocity of a falling drop could not exceed 8 $\mathrm{m} \cdot \mathrm{s}^{-1}$. A change in the shape of the drop is a reason for the change in the velocity of the drop. The velocity of the falling drop decreases when the bigger drop takes the shape of a hamburger. The surface area and air resistance increase. However, the increases of raindrop size are limited by the value of the surface tension, which still can compensate the airflows pressure. The hollow in the bottom of the drop increases so greatly that the drops' surface tension can not hold any more pressure of the air and the drop divides nearly into two parts when its size increases to $4 \div 4.5$ mm. Briefly those parts are still together connected by water bail. But eventually the drop divides into two smaller droplets (diameter about 1 mm).

However, in Ref. [12], raindrops diameters of even $0.5 \div 10$ mm were presented. In Ref. [13], was concluded that in thunderstorms raindrops vary in sizes from about 0.5 mm to as much as 8 mm.

Wilson A. Bentley [14] presented data of size distribution of the raindrops. The data shows, that quantities of very small drops (in diameters $\leq 0.85$ mm) and very large drops (in diameters $3.6 \div 5.1$ mm) are nearly equal (17% and 16% correspondingly). The parts of small drops with a diameter $0.84 \div 1.4$ mm and moderate ones with diameters $1.4 \div 3.2$ mm are the largest of all (34% and 29% correspondingly). The part of very large drops with diameters >5.1 mm is very small (only 4%) [14].

Many researchers have been studying the *drop sizes distribution* (DSD). The DSD derived by Laws and Parson [15] is the DSD most commonly used in the prediction of rain attenuation of the electromagnetic waves (EW).

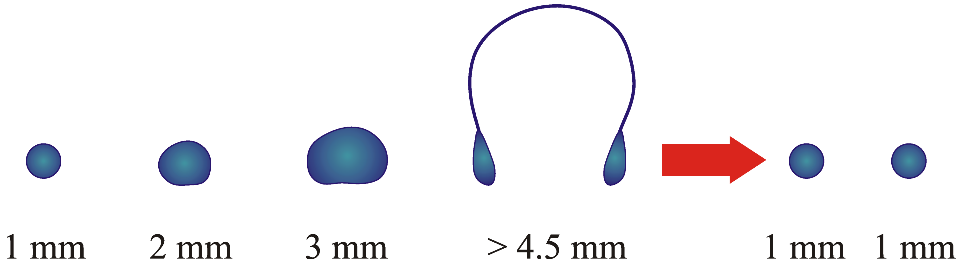

Fig. 1. The variation of the raindrop shape depending on its size (diameter of the drop). Modified according to Ref. [9].

Specific rain attenuation model in prediction methods presented in Ref. [1] and ITU-R's recommendation [16] is based on DSD proposed by Laws and Parson.

The analysis of the rainfall data has assumed traditionally that the raindrop size distribution (DSD) has an exponential form; that is, with $N(D)$ [$\mathrm{m}^{-3}\cdot\mathrm{cm}^{-1}$] equal to the number of raindrops per unit volume per unit size interval having equivolume spherical diameter $D$ [cm], then

$$N(D) = N_0 \cdot \exp[-\Lambda \cdot D], \tag{1}$$

$$0 < D < D_{max}. \tag{2}$$

$N_0$ [$\mathrm{m}^{-3}\cdot\mathrm{cm}^{-1}$] and $\Lambda$ [$\mathrm{cm}^{-1}$] are parameters of the distribution and $D_{max}$ is the maximum drop diameter [17]. Constant value $N_0$ is equal to 80 000 $\mathrm{m}^{-3}\cdot\mathrm{cm}^{-1}$. This form was originally found by Marshall and Palmer (1948) [18] who also suggested that $\Lambda$ varied with rainfall rate $R$ [mm$\cdot$ $\mathrm{h}^{-1}$]:

$$\Lambda = 41 \cdot R^{-0.21}. \tag{3}$$

A similar analysis of the drop size spectra of Laws and Parsons (1943) [15] reveals that that their data can also be represented closely by an exponential form $\Lambda = f(R)$ and $N_0$ weakly dependent on rainfall rate through expression (5):

$$\Lambda = 38 \cdot R^{-0.20}, \tag{4}$$

$$N_0 = 51000 \cdot R^{-0.03}. \tag{5}$$

The shape of the larger raindrops determines that fact that the horizontally polarized waves suffer greater attenuation than vertically polarized waves. The reason is that large raindrops are generally shaped as oblate spheroids and are aligned with the vertical rotation axis [1].

## 2. Calculation of EW attenuation due to the rain

The rain attenuation prediction methods can be grouped into two classes: i) the physical method which makes an attempt to reproduce the physical behavior involved in the attenuation process, and ii) the empirical method which is based on the analysis of databases of the physical measurements. It is necessary to point out that mentioned measurements were done in the stations placed in different climatic zones within a given region [19-20]. When the physical rain attenuation prediction method is being used, one of the difficulties is the description of the shape of raindrops. In most cases the shape of a drop is described as spherical. For example, presented in Ref. [21], a simple spherical model was used for the calculation of the effect of temperature and multiple scattering on rain attenuation of electromagnetic waves. As mentioned above, this description of a raindrop shape in most cases is wrong. Empirical method for prediction of electromagnetic waves attenuation is used more often and more successfully than the physical one.

Commonly, the electromagnetic wave losses are expressed as a function of the rain rate $R$. In prediction of the radio waves attenuation due to the rainfall (rain attenuation), the well known semi–empirical model according to Ref. [1], [16] is being used. Specific rain attenuation is obtained from the rain rate $R$ using the relationship:

$$\alpha = a \cdot R^b, \tag{6}$$

where $\alpha$ represents a specific rain attenuation - dimension in [$\mathrm{dB}\cdot\mathrm{km}^{-1}$]; $R$ - rain rate [$\mathrm{mm}\cdot\mathrm{h}^{-1}$]; $a$ and $b$ are functions of the rain temperature and operating frequency $f$.

The values of $a$ and $b$ from Ref. [1] (see Table 1) are presented for vertical and horizontal polarization. For frequencies other than presented in Table 1, the values of coefficients $a$ and $b$ can be obtained by interpolation.

The rain rate $R$ can be described as the thickness of the layer of the precipitation which fell 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 draught by the wind. $R$ depends on liquid water content and the fall velocity of the drop. The velocity, in turn, depends on the size of a raindrop [1].

$R$-value must be determined for some percentage of time of the year and it must be in correlation with the reliability of the system. In most cases, the $R$–value for 0.01% of time ($R_{0.01\%}$) is desirable in the design of radio systems. It means that $R_{0.01\%}$–value can be exceeded only about 52.56 min. in a year. In this case the reliability of the radio system would be 99.99%.

Despite that $R_{0.01\%}$–value is expressed in [$\mathrm{mm}\cdot\mathrm{h}^{-1}$], the rainfall amount data for the calculations of the $R$–value must be measured in one–minute intervals.

Table 1. Specific rain attenuation coefficients $a$, $b$ for horizontal (h) and vertical (v) polarized waves, respectivelly. According to Ref. [1].

| $f$, GHz | $a_h$ | $a_v$ | $b_h$ | $b_v$ |
|---|---|---|---|---|
| 1 | 0.0000387 | 0.0000352 | 0.912 | 0.88 |
| 2 | 0.000154 | 0.000138 | 0.963 | 0.923 |
| 4 | 0.00065 | 0.000591 | 1.121 | 1.075 |
| 6 | 0.00175 | 0.00155 | 1.308 | 1.265 |
| 7 | 0.00301 | 0.00265 | 1.332 | 1.312 |
| 8 | 0.00454 | 0.00395 | 1.327 | 1.31 |
| 10 | 0.0101 | 0.00887 | 1.276 | 1.264 |
| 12 | 0.0188 | 0.0168 | 1.217 | 1.2 |
| 15 | 0.0367 | 0.0335 | 1.154 | 1.128 |
| 20 | 0.0751 | 0.0691 | 1.099 | 1.065 |
| 25 | 0.124 | 0.113 | 1.061 | 1.03 |
| 30 | 0.187 | 0.167 | 1.021 | 1 |
| 35 | 0.263 | 0.233 | 0.979 | 0.963 |
| 40 | 0.35 | 0.31 | 0.939 | 0.929 |
| 45 | 0.442 | 0.393 | 0.903 | 0.897 |
| 50 | 0.536 | 0.479 | 0.873 | 0.868 |
| 60 | 0.707 | 0.642 | 0.826 | 0.824 |
| 70 | 0.851 | 0.784 | 0.793 | 0.793 |
| 80 | 0.975 | 0.906 | 0.769 | 0.769 |
| 90 | 1.06 | 0.999 | 0.753 | 0.754 |
| 100 | 1.12 | 1.06 | 0.743 | 0.744 |

The time interval between the measurements of the rainfall amount is called integration time $\tau$. In the mentioned case the integration time $\tau$ =1 min. is required.

One–minute $R_{0.01\%}$–value $R_{1min.}$ is commonly referred as “instantaneous” value and has been recognized as the most practical for calculation of signal loss [22]. One–minute rain rate statistics also have applications in other areas, such as the design and operation of aerospace vehicles and radar systems [22].

Though there can be some difficulties while predicting the $R_{1min.}$ -value. In Lithuania, usually the rainfall amount data is measured with the integration time $\tau$=10 min. or more. Consequently in most cases we can calculate only >1 min. rain rate values $R_{\tau min.}$ . Therefore in cases when one–minute rainfall amount data is unavailable, the models converting $R_{\tau min.}$ values into $R_{1min.}$ values can be used. One-minute rainfall rate models are presented in Ref. [20] and Ref. [23]. One of the models mentioned above is Moupfouma model [24], where $R_{1min.}$ represents one-minute rain rate value and $R_{\tau min.}$ - rain rate value, when integration time is equal to $\tau$ min.

$$R_{1min.} = R^{d}_{\tau min.}, \tag{7}$$

$$d = 0.987 \cdot \tau^{0.061}. \tag{8}$$

## 3. The peculiarities of Lithuanian climate

Lithuania, being in the transition geography zone from the Baltic Sea Region to Atlantic and continental east Europe climate, may be distinguished for its variable climate [25] . In Lithuania, humid weathers predominate all over the year; the annual precipitation in a rainy wet year is almost twice higher than in a dry year [26]. The climate of the continental part of Lithuania is definable as middling cold and climate of the west part of Lithuania is specified as the moderate warm climate.

The climate of the continental part of Lithuania is a typical climate of the middle part of the East Europe. The type of the climate of the west part of Lithuania is dominating in the West Europe. Therefore, the conditions of the electromagnetic waves propagation can be different in the East and in the West of Lithuania.

There are many contrasts in Lithuanian climate conditions. For example, the maximum and minimum of annual rainfall amounts - both were registered in Laukuva (>900 mm and 0.0 mm correspondingly) [27]. Thereby, the average annual rainfall amount can be a very informative and at the same time a very deceptive parameter.

In Ref. [26] it was concluded, that the hypothesis about the only value of $R$ for all the territory of Lithuania must be rejected. In average, there are 51.4 events of rain in Žemaitija and 40.4 rain events in the other part of Lithuanian territory. In Vilnius, the maximum rain intensity of rain event with duration of 20 min. (integration time $\tau$ = 20 min.) is 69 mm$\cdot$h$^{-1}$. The rain rate value determined by using rainfall data measured with one-minute integration time may be higher. Such rain rates are observed once per 5 years [26].

## 4. Thunderstorms in Lithuania

The number of the thunderstorms per year is an important parameter in determining the rain rate. The strong vertical air streams are forming in the thunderstorms clouds. The speed of the air streams is 15÷20 m$\cdot$s$^{-1}$ [28]. The rain rate depends on the convection strangeness and the cloud thickness. The stronger convection and the thicker the cloud the higher the rain rate value. The rain rate depends also on the cloud electrification. Therefore, the stronger showers put down in the thunderstorms.

There are 19÷30 days per year with the thunderstorms in Lithuania. However, the number of days of thunderstorms can be even 40÷45 ( according to Ref. [28]). In the South part of Lithuania, the thunderstorms have been observed frequently, because the rough surface of the earth stops the air streams and stimulates the convective processes. 96% of the events of thunderstorms happen in May÷September period [28]. Thunderstorms have a local character. They do not occure in large territories because the convection is the local phenomenon. However, during the summer, the convection is very intense and thunderstorms can occur in more than half of the territory of Lithuania.

The maximum number of days, $N_{max}$ in the year with thunderstorms was registered in the year 2001 in Vilnius.

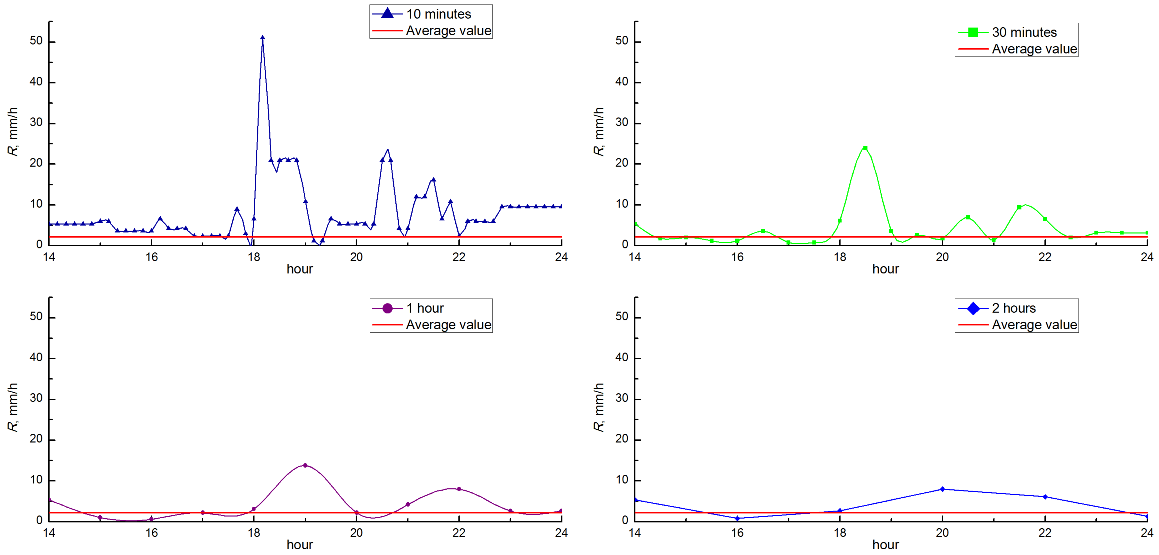

Fig. 2. The variation of rain rate $R$ depending on the integration time $\tau$. Rain event on 17 July 2000.

The duration of all thunderstorms events (in Vilnius, 2001) was $N_{max}$=77 h 18 min. [29]. It is worth to mention, that Vilnius is one of the cloudiest localities in Lithuania. There are about 100 overcast days in the year in this location. The minimum yearly duration (4 hours 30 min) of thunderstorms events was registered in Palanga in the year 1998 [29].

The distribution of the thunderstorm duration in Vilnius Airport is presented in Table 2. The data shows that 55% of the duration of thunderstorm in Vilnius is longer than 1 hour (longer than 0.01% of time of year). In most cases, strong showers are in the correlation with thunderstorms.

Rice-Holmberg model presented in Ref. [30] requires thunderstorm data. It also requires certain parameters like: highest monthly rainfall accumulation observed in a set of 30–year period, the average annual accumulation, and the ratio of thunderstorms precipitation amount with the annual precipitation amount. However, it has been acknowledged that the Rice–Holmberg method overestimates rain rates in the high–availability range (0.01% of time) and underestimates in the range between 0.1% and 1% [23].

Our model (9) was derived in Ref. [25] and [31] on the basis of Rice-Holmberg model [30] in accordance with the peculiarities of Lithuanian climate. They are events of heavy rain and showers happen frequently in the months of May – September; during the warm period, the part of the convection precipitation is 0.48 [32]:

$$R_{1min.} = \frac{1}{0.03} \ln \left( 0.0144 \cdot \frac{M_{V-IX}}{t_p} \right). \qquad (9)$$

$R_{1min.}$ represents 1 minute rain rate value, $M_{V-IX}$ - 30 years average rainfall amount during period from May to September, $t_p$ - the percent of time in a year, when $R_{1min.}$ may be exceeded (when reliability of the radio system should be 99.99%, $t_p$ = 52.56 min. = 0.876 hours).

## 5. Results and discussion

### 5.1. Integration time influence on the $R$ value

We examined the influence of the integration time to the values of the rain rate. One rain event occurs 17 July 2000. We evaluated the rain rate $R$ [mm$\cdot$ h$^{-1}$] values imaging that rain amount data of this rain event was collected with intervals (integration time $\tau$ is equal to 10 min., 30 min., 1 hour, and 2 hours, see Fig. 2). The smallest integration time of 10 minutes was chosen because it is the minimal time interval in Lithuanian rain amount data.

Mentioned interval is 10 times bigger than the recommended one. Despite that, comparison of $R$-values calculated using bigger integration time also reveals how the $R$-values depend on the integration time - see Fig. 2.

The same rain event was shown in four dependences. Each graph represents different integration time: 10 min., 30 min., 1 hour, and 2 hours. Also, in each graph the line representing the average rain rate value is shown. This value is calculated only from two values of rain amount data: the value measured at the start of the rain event and the value measured at the end of the rain event.

Table 2. The distribution of the thunderstorm duration in Vilnius. Data according to Ref. [29].

| Duration, h | Events, % |
|---|---|
| < 1 | 45 |
| 1÷2 | 37 |
| 2÷3 | 12 |
| > 3 | 6 |

Table 3. Distribution of rain rate values $R_{1min.}$ in the localities of Lithuania.

| | $\mathrm{M}_V$ | $\mathrm{M}_{VI}$ | $\mathrm{M}_{VII}$ | $\mathrm{M}_{VIII}$ | $\mathrm{M}_{IX}$ | $\mathrm{M}_{V-IX}$ | $t_p$ | $R_{1min.}$ |
|---|---|---|---|---|---|---|---|---|
| City | mm | mm | mm | mm | mm | mm | h | mm $\cdot$h$^{-1}$ |
| Skuodas | 52 | 54 | 82 | 97 | 88 | 373 | 0.876 | 60.45 |
| Mažeikiai | 47 | 55 | 78 | 78 | 69 | 327 | 0.876 | 56.06 |
| N.Akmenė | 48 | 54 | 77 | 77 | 68 | 324 | 0.876 | 55.75 |
| Joniškis | 50 | 67 | 81 | 70 | 63 | 331 | 0.876 | 56.47 |
| Pasvalys | 58 | 71 | 87 | 86 | 64 | 366 | 0.876 | 59.82 |
| Biržai | 59 | 74 | 90 | 87 | 68 | 378 | 0.876 | 60.89 |
| Rokiškis | 64 | 84 | 98 | 89 | 72 | 407 | 0.876 | 63.36 |
| Kretinga | 49 | 56 | 81 | 96 | 92 | 374 | 0.876 | 60.54 |
| Plungė | 53 | 61 | 90 | 96 | 83 | 383 | 0.876 | 61.33 |
| Telšiai | 58 | 60 | 93 | 96 | 85 | 392 | 0.876 | 62.10 |
| Šiauliai | 50 | 63 | 79 | 78 | 63 | 333 | 0.876 | 56.67 |
| Pakruojis | 44 | 58 | 71 | 73 | 58 | 304 | 0.876 | 53.63 |
| Klaipėda | 46 | 52 | 72 | 88 | 82 | 340 | 0.876 | 57.36 |
| Šilalė | 61 | 73 | 103 | 102 | 89 | 428 | 0.876 | 65.03 |
| Kelmė | 51 | 68 | 90 | 89 | 72 | 370 | 0.876 | 60.18 |
| Radviliškis | 47 | 59 | 74 | 73 | 59 | 312 | 0.876 | 54.50 |
| Panevėžys | 54 | 71 | 76 | 87 | 57 | 345 | 0.876 | 57.85 |
| Kupiškis | 57 | 73 | 86 | 79 | 63 | 358 | 0.876 | 59.08 |
| Anykščiai | 63 | 82 | 95 | 91 | 70 | 401 | 0.876 | 62.86 |
| Utena | 61 | 79 | 89 | 88 | 63 | 380 | 0.876 | 61.07 |
| Zarasai | 64 | 83 | 89 | 88 | 71 | 395 | 0.876 | 62.36 |
| Ignalina | 62 | 82 | 92 | 89 | 69 | 394 | 0.876 | 62.27 |
| Šilutė | 57 | 63 | 86 | 96 | 88 | 390 | 0.876 | 61.93 |
| Tauragė | 57 | 74 | 93 | 93 | 75 | 392 | 0.876 | 62.10 |
| Jurbarkas | 61 | 73 | 94 | 101 | 74 | 403 | 0.876 | 63.03 |
| Raseiniai | 57 | 64 | 88 | 93 | 72 | 374 | 0.876 | 60.54 |
| Kėdainiai | 63 | 72 | 86 | 96 | 61 | 378 | 0.876 | 60.89 |
| Ukmergė | 61 | 75 | 86 | 90 | 61 | 373 | 0.876 | 60.45 |
| Molėtai | 64 | 83 | 97 | 96 | 63 | 403 | 0.876 | 63.03 |
| Švenčionys | 62 | 84 | 87 | 91 | 70 | 394 | 0.876 | 62.27 |
| Šakiai | 54 | 64 | 83 | 86 | 56 | 343 | 0.876 | 57.65 |
| Kaunas | 66 | 80 | 100 | 104 | 64 | 414 | 0.876 | 63.92 |
| Jonava | 61 | 72 | 89 | 98 | 60 | 380 | 0.876 | 61.07 |
| Širvintos | 68 | 76 | 88 | 87 | 58 | 377 | 0.876 | 60.80 |
| Vilkaviškis | 53 | 71 | 90 | 96 | 60 | 370 | 0.876 | 60.18 |
| Marijampolė | 56 | 67 | 89 | 93 | 61 | 366 | 0.876 | 59.82 |
| Prienai | 57 | 74 | 87 | 87 | 57 | 362 | 0.876 | 59.45 |
| Kaišiadorys | 61 | 79 | 92 | 91 | 61 | 384 | 0.876 | 61.42 |
| Trakai | 57 | 77 | 90 | 89 | 60 | 373 | 0.876 | 60.45 |
| Vilnius | 56 | 74 | 87 | 85 | 56 | 358 | 0.876 | 59.08 |
| Lazdijai | 58 | 73 | 91 | 91 | 58 | 371 | 0.876 | 60.27 |
| Alytus | 58 | 75 | 88 | 87 | 58 | 366 | 0.876 | 59.82 |
| Varėna | 63 | 83 | 98 | 82 | 59 | 385 | 0.876 | 61.50 |
| Šalčininkai | 57 | 81 | 91 | 91 | 56 | 376 | 0.876 | 60.72 |
| AVERAGE | | | | | | | | 60.23 |

As can be seen in Fig. 2, the lesser the integration time the higher the values of rain rates. As integration time decreases the pikes of rain rate becomes lower, wider and late. This means that when integration time is more than 10 minutes, the largest rain rate values “hide”.

For example, the rain rate value at 18 hour 15 min. with the integration time of 10 min. is double the value with the integration time of 30 min. That means that data for the calculation of electromagnetic wave (EW) attenuation in Lithuania should be collected with as small as possible integration time (10 min. or less). This assumption is similar to recommendation according tropical environment.

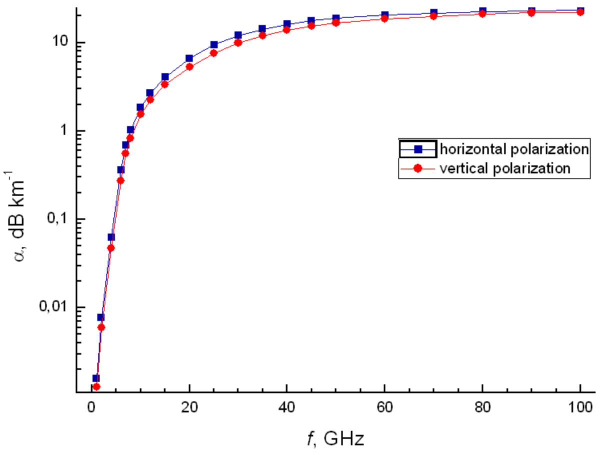

Fig. 3. Dependence of averaged specific rain attenuation for horizontally and vertically polarized EW, $\alpha_h$ and $\alpha_v$, respectively, on frequency $f$.

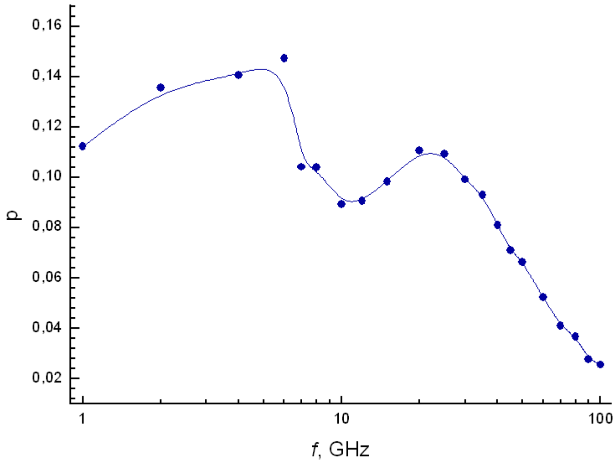

Fig. 4. Dependence of $p$ value on frequency $f$.

## 5.2. $R_{1min.}$ values in the localities of Lithuania

Secondly, we calculated $R_{1min.}$ values for different localities in Lithuania. (8) method has been used. The results are given in Table 3.

The $R_{1min.}$ values in different localities in Lithuania vary from 53.63 mm $\cdot$ h$^{-1}$ in Pakruojis to 65.03 mm$\cdot$ h$^{-1}$ in Šilalė. Average value in Lithuania is equal to $R_{1min.}$ = 60.23 mm$\cdot$ h$^{-1}$. This rain rate value is double the recommended rain rate value for Lithuania (for recommended $R$-value see Ref. [16]).

## 5.3. The specific electromagnetic waves attenuation due to the rainfall

Finally, having $R_{1min.}$ value, we are able to compute the average specific EW attenuation due to the rainfall $\alpha$ [dB $\cdot$ km$^{-1}$]. Eq. (6) was used. We used the averige value in Lithuania $R_{1min.}$=60.23 mm $\cdot$ h$^{-1}$ as $R$. The values of $a$ and $b$ were taken from Table 1. The $\alpha$ values for the operating frequencies 1÷100 GHz were calculated. Values of horizontal and vertical polarization were calculated separately. The results are shown in Fig. 3. There can be seen, that horizontally polarized electromagnetic waves are attenuated more than the vertically polarized ones. Furthermore, the relation between the operating frequency and the electromagnetic waves attenuation starting from about 4 GHz starts to grow and grows exponentially, but this growth slows down at frequency about 60 GHz and almost stops at 100 GHz.

The purpose to distinguish the $\alpha$ values for horizontal polarization and vertical polarization at operating frequencies smaller than 15 GHz the rate $p$ was introduced. The $p$ value is a normalized difference of $\alpha$ for horizontal polarization and vertical polarization, and it is expressed as follows:

$$p = \frac{\alpha_h - \alpha_v}{\alpha_h + \alpha_v}, \tag{10}$$

where $\alpha_h$ and $\alpha_v$ are average specific attenuation for horizontally and vertically polarized EW, respectively.

The dependency of $p$ value to the operating frequency $f$ is shown in Fig. 4. There can be seen that the $p$ value fluctuates at operating frequencies below about 20 GHz, and at operating frequencies above 20 GHz starts to constantly decline from about $p$ = 0.11 at $f$ = 20 GHz to about $p$ = 0.02 at $f$ = 100 GHz. Hence for higher frequencies the $\alpha$ value (both for horizontally and vertically polarized electromagnetic waves) increases, but the normalized difference of the $\alpha$ value for horizontally and vertically polarized electromagnetic waves decreases.

## 6. Conclusions

The values of one-minute rain rate $R$ and average specific electromagnetic waves attenuation due to the rain $\alpha$ were obtained. The average value of the rainfall rate in Lithuania is 60.23 mm $\cdot$ h$^{-1}$. It is double the recommended value. The values of average specific electromagnetic waves attenuation due to the rain differs for different operating frequencies and depends on polarization of the electromagnetic wave. The relation between operating frequency and electromagnetic waves attenuation starting from about 4 GHz starts to grow and grows exponentially, but this growth slows down at frequency about 60 GHz and almost stops at 100 GHz. Horizontally polarized electromagnetic waves are attenuated more than the vertically polarized ones.

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