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CALCULATION OF ELECTROMAGNETIC WAVE ATTENUATION DUE TO RAIN USING RAINFALL DATA OF LONG AND SHORT DURATION *

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Almost all methods predicting electromagnetic wave attenuation due to rain require one-minute rain rate data. Due to limited availability of one-minute rainfall rate data in many cases, conversion of rainfall rate distribution over a long integration time (for example, ten-minute, one-hour, or daily data) into the distribution for one minute is needed. Only ten-minute, one-hour, and daily rainfall data are available at Lithuanian Weather Stations in many cases. Several rainfall rate conversion methods are reviewed and their suitability under Lithuanian climatic conditions is revised. The data of rainfall are presented for the extreme cases to demonstrate the high degree of variability that can occur in locations of Lithuania. A simple conversion method of long-term rain rate data to one-minute rain rate distribution has been used. A new method for determination of one-minute rain rate has been proposed. The method can be expected to be applicable to regions of the Baltic Sea areas where the one-minute rain rate data have not yet been available.

Keywords: electromagnetic radiation, rain attenuation, rain rate

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1. Introduction

It is very important to establish a reliable prediction method of electromagnetic wave attenuation due to rain (rain attenuation). In analysis of rain attenuation, the prediction of rain rate is the main step. Although the rain rate is presented in millimetres per hour, an important parameter is the integration time, i. e. the time between readings of the rainfall [1]. Most of rain attenuation prediction methods require one-minute rain rate data as meteorological data of the locality. One-minute rain rate (mm/h) is the rainfall for one minute (mm/min) multiplied by 60 [2]. The example provided in [1] demonstrates the importance of the integration time. The data of rain rates measured with various integration times in Latvia is presented (see Table 1). It is clearly seen that the integration time is the parameter changing the value of rain rate. However, there are very few areas where the one-minute rain rate data is available (for example, in [3, 4]). In [5], an integration time of 5 minutes was used. An integration time of ten minutes was used in [6].

Table 1. The values of rain rates measured with different integration time [1].

Integration time (min)	Rain rate (mm/h)
1	30 90 60 30 30 30 60
5	48 18
10	33
60	5.5

Due to limited availability of one-minute rainfall data in many cases, the methods of conversion of rainfall rate distribution over a long integration time into the distribution for one-minute rate have been developed. After examining the measured one-minute rain rate data and one-hour rain rate data obtained by Automated Meteorological Data Acquisition System in Japan, a conversion method of one-minute rain rate distribution was

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proposed in [2]. Karasawa relationship between one-minute rain rate and one-hour rain rate for 0.01% of time (this corresponds to approximately 53 minutes in the year) in [2] is expressed as

$$\frac{R_{\mathrm{m}\,0.01\%}}{R_{\mathrm{h}\,0.01\%}} = 1.79\,, \tag{1}$$

where $R_{\mathrm{m}\,0.01\%}$ is one-minute rain rate for 0.01% of time, and $R_{\mathrm{h}\,0.01\%}$ is one-hour rain rate for 0.01% of time.

The one-minute rain rate contour maps for microwave applications in Malaysia Peninsula have been developed in [3]. The model presented in [3] defines the rain rate conversion factor, CF_{60}, as the ratio of rain rates $R_1(P)$ and $R_{60}(P)$ for a given percentage of time P with an integration time of 1 min and 60 min, respectively, and is given by

$$CF_{60} = \frac{R_1(P)}{R_{60}(P)} \tag{2}$$

$$= 0.7222P^{-0.041} + 1.141\exp(-2.570\,P)\,.$$

The relationship (2) is valid when $0.001\% \le P \le 1\%$.

The Rice–Holmberg method of predicting one-minute rain rate in terms of annual rainfall and a ratio of rainfall due to thunderstorms to total rainfall was presented in [4]:

$$\beta = \frac{M_1}{M}\,, \tag{3}$$

$$R = \frac{\ln\left(\dfrac{0.03\beta M}{T}\right)}{0.03}\,, \tag{4}$$

where M_1 is the thunderstorm rainfall (mm), M is the average annual rainfall (mm), and T is the number of hours in the year during which rain rates exceed R (mm/h).

In Moupfouma method [7], the relationship between one-minute rain rate for 0.01% of time and τ-minute rain rate for 0.01% of time $R(\tau\,\mathrm{min})_{0.01\%}$ is expressed as

$$R_{\mathrm{m}\,0.01\%} = [R(\tau\,\mathrm{min})_{0.01\%}]^d\,, \tag{5}$$

with $d = 0.987\ (\tau\,\mathrm{min})^{0.061}$, where $R(\tau\,\mathrm{min})_{0.01\%}$ exceeded during 0.01 percent of time for τ minutes integration time.

In [8], a model for estimating one-minute rainfall rates using stepwise multiple regression analysis has been developed. The model requires the data of monthly mean temperature, monthly mean precipitation, and number of days in the month with precipitation, and latitude. Several rainfall rate conversion methods applicable in Southeast Asia countries are proposed in [9]. The application of these methods does not however always give good results in areas where the climatic conditions differ from ones in the localities which meteorological data was used when the methods have been developed.

In [6], a new model for the electromagnetic wave attenuation due to rain medium in atmosphere has been presented. An integration time of ten minutes has been used in this model. The meteorological data measured in the Lithuanian Weather Stations has been used. It was concluded in [6], that there is a need to specify the values of rain attenuation by using one-minute rain rate-values. The main goals of this paper were to review several rainfall rate conversion methods obtained in various countries and to revise their suitability under Lithuanian climatic conditions.

2. An occurrence of very intense rain

The emphasis on rare events with very high rain rates importance was put in [7]. The events in New Jersey when a very large quantity of water fell on the propagation path in a short time were mentioned. An average rain rate of 165 mm/h for a period of about seven minutes was observed. At 18.5 GHz frequency, 6.4 km path attenuation 30 dB would be exceeded by this single storm (5 minutes per year or about 0.001 percent).

The events of heavy rainfall sometimes have happened in the period of years 1970–1996 in Lithuania, too (see Table 2). For example, in Vilnius, the events with the rain rate values of 120 and 150 mm/h were observed. The durations of these events were 11 and 12 minutes respectively [10]. The percentage of the time of the year was about 0.002% in these cases.

The rainfall events with rain rates of 150 and 93 mm/h were observed in Pasvalys. The durations of these showers were 37 minutes and one hour respectively. The percentages of the time were 0.007% and 0.011% respectively in these cases. The shower with rain rate of 104.8 mm/h was observed in Jurbarkas. It continued for 13 minutes (the percentage of the time was about 0.0025%). It is worth to mention that the values of $R_{0.01\%}$ are much higher in the cases when the percentage of the time is less than 0.01%.

The events of high intensity rain happened in the period of years 1999–2004 in Vilnius. The values of rain rates R, the values of integration time, and the values of the percentage of time are presented in Table 3.

Table 2. The values of very intense rain rates R (mm/h) measured at Lithuanian Weather Stations in the period of years 1970–1996 [10].

Locality	R (mm/h)	Integration time (min)	Percentage of time (%)
Vilnius	120.0	11	0.0021
	150.0	12	0.0023
	72.4	30	0.0057
	72.5	25	0.0048
	35.0	120	0.0228
Kaunas	69.0	20	0.0038
	46.0	30	0.0057
	61.5	40	0.0076
Birštonas	69.0	20	0.0038
	46.0	30	0.0057
	36.0	60	0.0110
Klaipėda	32.25	80	0.0150
	80.2	35	0.0067
Pasvalys	150.0	37	0.0070
	93.0	60	0.0110
Jurbarkas	104.8	13	0.0025

Table 3. The values of very intense rain rates R (mm/h) measured at Lithuanian Weather Station in Vilnius in the period of years 1999–2004.

R (mm/h)	Integration time (min)	Percentage of time (%)
35.0	10	0.0019
48.0	10	0.0019
44.0	5	0.0010
54.0	2	0.0004
33.6	10	0.0019
127.8	3	0.0006
51.0	10	0.0019
51.0	10	0.0019
58.2	10	0.0019
43.8	6	0.0011
90.0	2	0.0004
33.0	10	0.0019
33.1	10	0.0019
42.0	10	0.0019
55.2	10	0.0019
32.4	10	0.0019

It was mentioned in [11], that the abundant precipitation was most frequently recorded under dominance of zonal macro-synoptic situation, when the altitudinal frontal zone trended from the British Isles across southern Scandinavia and Baltic Region toward Eastern Europe Lithuania would then be included in the southern periphery. The meridional macro-synoptic situation was responsible for 38.9% of heavy precipitation (≥20 mm per day). The mixed macro-synoptic situation was favourable in 22.2% of cases when the daily amount of precipitation was ≥20 mm [11]. The values of annual rainfall (mm) measured in the localities of Lithuania in the period of years 1999–2004 are presented in Table 4. It is clearly seen the difference in the amount of rainfall from year to year in that period.

Table 4. The values of annual rainfall (mm) measured in the localities of Lithuania in the period of years 1999–2004.

Locality	1999	2000	2001	2002	2003	2004
Vilnius	520	694	653	616	646	720
Klaipėda	770	587	851	645	727	649
Panevėžys	493	640	739	508	522	639
Biržai	711	594	766	625	613	758
Kaunas	487	572	671	653	572	639

Table 5. The values of 10-minute rain rates R (mm/h) for 0.01% of time obtained by using the data of Lithuanian Weather Stations in the period of years 1999–2004.

Locality	1999	2000	2001	2002	2003	2004
Vilnius	45.5	46.7	35.7	26.8	23.1	33.2
Klaipėda	36.8	16.4	28.9	17.8	43.1	–
Panevėžys	37.3	37.6	44.0	–	22.5	20.5
Biržai	71.9	38.6	59.8	38.9	23.9	40.1
Kaunas	31.4	27.9	45.1	30.8	38.6	35.9

Table 6. The values of coefficient a for different localities of Lithuania.

Locality	a
Vilnius [6]	3.23
Klaipėda	3.40
Panevėžys	2.73
Biržai [6]	4.00
Kaunas [6]	3.32

The values of rain rates $R_{0.01\%}$ measured at the Lithuanian Weather Stations in the period starting from 1999 year up to 2004 year are presented in Table 5. The 10 minutes integration time was used. According to the rainfall data measured at Lithuanian Weather Stations, a new revised model for the rain rate estimation was derived in [6]. The review of results measured at Lithuanian Weather Stations (see Table 5) shows that the relation between $R_{0.01\%}$ and the annual precipitation can be written as [6]

$$R_{0.01\%} = a(\gamma M)^{0.4}\,, \tag{6}$$

where M is the annual precipitation, $\gamma = 0.6$ is the warm period coefficient, and a is a coefficient.

The values of the coefficient a obtained by analysing the meteorological data measured at the Lithuanian Weather Stations are presented in Table 6. The aver-

Table 7. The values of 10-minute rain rates $R_{0.01\%}$ (mm/h) measured at Lithuanian Weather Stations in the period of years 1999–2004 and converted to one-minute rain rate values using Moupfoum method [7].

Locality	1999	2000	2001	2002	2003	2004	Average value
Vilnius	71.3	78.7	58.0	41.9	35.4	53.4	56.4
Klaipėda	60.1	24.0	45.6	26.3	71.9	–	45.6
Panevėžys	70.0	61.5	73.6	–	34.3	30.9	54.1
Biržai	128.5	63.4	104.2	64.0	36.8	66.2	77.2
Kaunas	85.4	43.8	75.7	49.1	63.4	58.4	62.6

age value of the coefficient a obtained by averaging the values of a in Biržai, Vilnius, Kaunas, Klaipėda, and Panevėžys is $a = 3.34$. It is worth to mention that the values of the coefficient a were obtained by using measured 10-minute rainfall data.

3. Conversion of rainfall rate distribution over a long integration time into the distribution for one-minute integration time

The knowledge of one-minute rainfall rate data is necessary for the prediction of rain attenuation at any location. The rainfall rate distribution over a long integration time in the localities of Lithuania was presented in [12]. There, we have used one of the rainfall rate conversion methods based on the measurement of rain rate in Chilbolton (United Kingdom) [7]. The rain rate $R(1\,\mathrm{min})_{0.01\%}$ exceeded during 0.01 percent of time for one minute integration time was expressed as a function of τ-minute rain rate for 0.01% of time $R(\tau\,\mathrm{min})_{0.01\%}$ (see Eq. (5)). The values of 10-minute rain rates $R_{0.01\%}$ (mm/h) measured at Lithuanian Weather Stations in the period of years 1999–2004 and converted to one-minute rain rate values by using (5) are presented in Table 7.

In [13], the Rice–Holmberg method [4] was used in calculations of rain rate values for several localities of Lithuania. The average annual rainfall data and the thunderstorm precipitation data were used in calculations. Analysis of rainfall data of the localities in Lithuania shows that the events of heavy rainfall and showers happen frequently in the months of May-September. During the warm period, the part of convectional precipitation is 0.48 in the general precipitation amount [14]. In light of that, the relationship (4) under Lithuanian climatic conditions may be written as

$$R(1\,\mathrm{min}) = \frac{\ln\left(\dfrac{0.03 \cdot 0.48 \cdot M_\mathrm{w}}{t}\right)}{0.03}\,, \qquad (7)$$

where M_w is amount of rainfall in the months of May–September, and t is the number of hours in a year when the value of rain rate exceeds the value R.

Table 8. The values of $R(1\,\mathrm{min})$ (mm/h) obtained by using relation (7) and Moupfoum method [7], and the values of specific attenuation due to rain α (dB/km) in Vilnius.

Integration time (min)	–	10	20
Relation	(7)	(5)	(5)
R (mm/h)	58.9	56.4	63.0
α (dB/km)	16.1	15.5	17.1

The value of $R(1\,\mathrm{min})$ in Vilnius obtained by using model (7) is presented in Table 8. We compared this value with ones obtained by using Moupfoum method (see Table 8). The value of $R_{0.01\%}$ measured with 10 minutes integration time [6] and the value of $R_{0.01\%}$ measured with 20 minutes integration time [15] were used in our calculations. The $R(20\,\mathrm{min})$ value is maximum value of the rain rate on the event of 20 minutes duration when such event occurs once a year. The results presented in Table 8 show that the value of $R(1\,\mathrm{min}) = 58.9$ mm/h is 38% higher than the value of $R(10\,\mathrm{min}) = 35.2$ mm/h. The values of the specific rain attenuation α are presented in Table 8 as well. In calculating the specific attenuation due to rain α (dB/km), we have been using one of the most accepted methods – an empirical procedure based on the approximate relation between α and rain rate R [16]:

$$\alpha = c\,R^b\,, \qquad (8)$$

where b and c are functions of frequency f and rain temperature T.

In [16], the values of b and c for horizontal polarizations are based on a rain temperature of 20 °C and on the Laws–Parson drop-size distribution. The values of specific rain attenuation A (dB/km) (see Table 8) for horizontal polarization at a rain temperature of 20 °C have been calculated using Eq. (8). The frequency $f =$ 40 GHz in our calculations. The values of b and c were taken from [16]. The value $\alpha = 16.1$ dB/km obtained by using one-minute value of $R_{0.01\%} = 58.9$ mm/h is

38.5% higher than the value $\alpha = 9.9$ dB/km obtained by using ten-minute value of $R_{0.01\%} = 35.2$ mm/h. This is the reason to use one-minute rain rate value in the prediction of rain attenuation.

4. Conclusions

The Moupfouma method is the method suitable for use in the calculations of one-minute rain rate under Lithuanian climatic conditions. The contrasts in the decadal average rainfall and rain rate values are much less than the variations in the values of rainfall and rain rate in the adjacent days, seasons or years in Lithuania. Marked differences in the values of rainfall and rain rates sort of hide when averaging these values over long intervals of time. This is the reason why the models obtained by using the decadal average rainfall data are not suitable under Lithuanian climatic conditions. Under our climatic conditions, the one-minute rain rate for signal reserve calculations must be computed by using a new model (7) presented here, on the months starting from May up to September. In October–August the signal reserve can be less than in May–September.

The relation (7) may be revised when the measured rainfall data with one minute integration time is collected at the Lithuanian Weather Stations.

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ELEKTROMAGNETINIŲ BANGŲ SILPNINIMO ĮVERTINIMAS PAGAL ĮVAIRIOS TRUKMĖS KRITULIŲ KIEKIO DUOMENIS

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Santrauka

Įvertinant elektromagnetinių bangų silpninimą, būtina žinoti lietaus intensyvumo vertes. Nors jos išreiškiamos milimetrais per valandą, lietaus intensyvumas dažniausiai matuojamas daug trumpesniais laiko tarpais: kas minutę, kas penkios ar dešimt minučių, kartais – kas valandą. Gautos lietaus intensyvumo vertės priklauso nuo to, kiek laiko prabėgo nuo vieno matavimo iki kito. Jei matuojame ilgesnės trukmės laiko tarpais, tai didelio intensyvumo pirmųjų liūties minučių vertės tarsi pasislepia, kai jas suvidurkiname (pvz., visai valandai). Daugelyje elektromagnetinių bangų silpninimo skaičiavimo metodų yra naudojamos lietaus intensyvumo vertės, gautos matuojant kritulių kiekį kas minutę. Tačiau dažnai turima tik lietaus kritulių kiekio duomenų, gautų juos matuojant kas dešimt minučių, kas valandą ar kas parą. Tokiu atveju „vienos minutės" lietaus intensyvumo vertės apskaičiuojamos iš ilgesnės trukmės matavimų duomenų. Ankstesniame darbe [6] radijo signalo savitojo silpninimo vertės įvairiose Lietuvos vietovėse buvo nustatytos pasinaudojus kritulių kiekio matavimų kas dešimt minučių duomenimis ir pažymėta, kad jas reikia patikslinti pasinaudojus „vienos minutės" lietaus intensyvumo duomenimis. Šiame darbe apžvelgtos „vienos minutės" lietaus intensyvumo skaičiavimo metodikos iš ilgesnės trukmės matavimų. Taip pat, atsižvelgus į Lietuvos klimato ypatumus, remiantis Rice–Holmberg metodu, sukurtas naujas modelis „vienos minutės" lietaus intensyvumo vertėms nustatyti. Jį taikant, pasinaudojus šiltojo laikotarpio kritulių kiekio matavimais, apskaičiuotos „vienos minutės" lietaus intensyvumo vertės. Esant galimybei Lietuvos hidrometeorologijos stotyse sukaupti pakankamai kas minutę išmatuoto kritulių kiekio duomenų, modelis gali būti patikslintas.