THE THUNDERSTORM RATIO AS A REGIONAL CLIMATIC PARAMETER: Its effects on different-integration-time rain rate conversion, rain attenuation, site-diversity and rain depolarization

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ABSTRACT

The most serious transmission impairment is caused by rain on radio links using frequencies above about 10 GHz. Therefore, it is required to predict radio propagation characteristics in rain at locations of radio links. In this paper, using the databanks made at Kitami Institute of Technology, we developed the worldwide propagation prediction methods, in which regional climatic parameter was taken into account. As the results, the thunderstorm ratio was found to give large effect on worldwide propagation prediction methods during rainy conditions, and to be the most promising regional climatic parameter at present.

INTRODUCTION

In several countries, radio communication companies have developed radio propagation prediction methods for their countries. But, in the worldwide viewpoint, these studies were not widely made except by ITU-R (International Telecommunications Union, Radiocommunication Sector) Study Group 3. Because propagation impairments caused by rain depend largely on regional climate, ITU-R Questions (Q.ITU-R 14/5 etc.) were modified at 1993 Radiocommunication Assembly to include the regional climatic parameters in addition to rain rate to prediction methods.

In this paper, using newly constructed KIT (Kitami Institute of Technology) databanks, we developed the following worldwide propagation prediction methods by multiple regression analysis. Those methods included “thunderstorm ratio” proposed by Rice and Holmberg as a regional climatic parameter.

- The prediction method for one-minute rain rate distribution [1]
- The conversion method for one-minute rain rate from different integration time rain rate [2][3]
- The prediction method for rain attenuation on terrestrial links [4]
- The prediction method for site diversity improvement on satellite links [5]
- The prediction method for rain depolarization on terrestrial links [6]

As results of these analyses, it was found that effects of the thunderstorm ratio are large for all of above methods. It was also found that these prediction methods, proposed in this paper by using the thunderstorm ratio, have more accuracy than existing methods. Therefore, these results show that the thunderstorm ratio is a promising regional climatic parameter to establish a worldwide propagation prediction method during rain conditions.

KIT WORLDWIDE DATABANKS

For analysis in this paper, we constructed KIT databanks as shown in the following. All databanks include measured one-minute rain rate distribution, the average annual total rainfall, the average annual number of thunderstorm days, and the thunderstorm ratio etc., as regional climatic data.

- Databank of rain attenuation on satellite links [1]. This contains 290 data sets from 84 locations in 30 countries.
- Databank of different integration time rain rates. This contains data sets from 49 locations in 21 countries [2]. Now, this databank is extended to data sets from 54 locations in 23 countries [3].
- Databank of rain attenuation on terrestrial links [4]. This contains 82 data sets in 22 countries.
- Databank of site diversity on satellite links [5]. This contains 108 data sets in 12 countries.
- Databank of rain depolarization on terrestrial links [6]. This contains 43 data sets from 26 locations in 10 countries .

THE THUNDERSTORM RATIO AS REGIONAL CLIMATIC PARAMETER

The average annual total rainfall M (mm) is represented as $M=M_1+M_2$, where M_1 (mm) is the rain arising from thunderstorm and M_2 (mm) is from all other rain. Then the thunderstorm ratio β is defined as $\beta = M_1 / M$ [7]. The value of this parameter β is proposed to be given by two ways. One is given by the world map of Rice's paper [7] and the other is proposed by Dutton et al. [8]. The latter value was calculated by (1) from the average annual total rainfall M (mm), the average annual number of thunderstorm days D_{th} (day), the highest monthly precipitation observed over 30 consecutive years M_m (mm). In this paper, we used the Dutton's thunderstorm ratio, because this value was found to affect more seriously rain rate spatial and auto correlation characteristics than the Rice's value.

$$\beta = \left[0.03 + 0.97\exp\{-5\exp(-0.004M_m)\}\right] \times \left[0.25 + 2\exp\{-0.35(1+0.125M)/D_{th}\}\right] \quad (1)$$

DEVELOPMENT OF WORLDWIDE PROPAGATION PREDICTION METHODS

We analyzed the KIT databanks and developed the following worldwide propagation prediction methods during rain conditions.

Prediction Method for One-minute Rain Rate Distribution [1]

For the prediction of rain attenuation distributions, it is necessary to know one-minute rain rate distributions. However these data are rare, because measurements of rain rate are made usually with longer integration time. In addition, there are many locations where even a long integration time data was not observed. Therefore, it is required to establish a prediction method of one-minute rain rate distributions for such locations. Three techniques usually used are as follows; Rice and Holmberg model that uses the annual total rainfall and the thunderstorm ratio [7], improved Rice and Holmberg model proposed by Dutton, Dougherty and Martin [8], and Morita model that uses only the annual total rainfall [9]. In this paper, the correlation between regional climatic parameters and one-minute rain rate was analyzed by using KIT data bank on satellite links [1]. As the result of this analysis, one-minute rain rate for arbitrary percentage of time P (%), R_p (mm/h), can be estimated by using only the average annual total rainfall and the thunderstorm ratio. This model is given by (2)-(5) using coefficients a_p, b_p, c_p with $x=log(P)$ that were determined by multiple regression analysis. Table 1 lists the partial correlation coefficients between measured rain rate R_p and M or β, $r_{Rp\text{-}M}$ or $r_{Rp\text{-}\beta}$, and the number of data samples n. This model was found to give the best prediction accuracy among existing models, especially for small percentage of time, which is important for radio system design. From this result, it was found that the thunderstorm ratio was an important parameter.

Table 1. Partial correlation coefficients

P (%)	$r_{Rp\text{-}M}$	$r_{Rp\text{-}\beta}$	n
0.001	0.34	0.60	196
0.01	0.44	0.62	286
0.1	0.67	0.44	244
1	0.52	0.01	168

$$R_p = a_p M^{b_p} \beta^{c_p} \quad (2)$$

$$\log(a_p) = 0.1574155x^4 + 1.348171x^3 + 3.528175x^2 + 1.479566x - 2.302276 \quad (3)$$

$$b_p = -4.583266\times10^{-2} x^4 - 0.4098161x^3 - 1.162387x^2 - 0.8261178x + 0.911857 \quad (4)$$

$$c_p = 2.574688\times10^{-2} x^4 + 0.1549031x^3 + 0.1747827x^2 - 0.2846313x + 1.255081\times10^{-2} \quad (5)$$

Conversion Method of One-minute Rain Rate from Different Integration Time Rain Rate (Method 1) [2]

As is described above, it is necessary to convert rain rate distributions with longer integration time into that with one-minute. Several methods have been proposed. Because these are empirical methods obtained from relationships between rain rate with different integration time at specified percentage of time, it must be cautious to apply these methods to other locations and integration times that were not used to derived these methods. Therefore, using KIT different integration time rain rates databank [2], we analyzed effects of the thunderstorm ratio for one-minute rain rate conversion method using simplified Moupfouma distribution [2] and autocorrelation characteristics of rain rate. It is known that simplified Moupfouma distribution can approximate very well the rain rate distribution. The probability distribution function $F(R)$ is given by (6). Parameter p, u are positive values. R^* is the solution of (7) from the condition that $F(R^*)=1$, and an approximation equation for R^* was obtained. It is known that the autocorrelation function between two one-minute rain rates separated by t-minute $\rho(t)$ can be approximated by (8). As a result of this analysis, it was found that the autocorrelation characteristics of rain rate had large regional dependence. Moreover, it was found that this autocorrelation characteristics could be estimated by (9) using regional climatic parameters such as the thunderstorm ratio and so on, and it was shown that a good conversion accuracy of different integration time rain rate could be obtained. ϕ (°) is latitude. λ (°) is longitude. $R_{0.01}$ and $R_{0.001}$ (mm/h) are one-minute rain rate for 0.01% and 0.001% of a year, respectively. Table 2 lists the partial correlation coefficients *r* between the autocorrelation parameter α_t and regional climatic parameters. It was found that the effect of the thunderstorm ratio on this conversion method is large. This conversion method can be easily expanded to arbitrary integration times.

Table 2. Partial correlation coefficients
(The number of data samples is 49.)

Parameter	*r*
$R_{0.001}$ (mm/h)	0.73
$R_{0.01}$ (mm/h)	-0.65
β	-0.57

$$F(R) = \frac{p}{R}\exp(-uR) \quad (R^* \le R < \infty) \tag{6}$$

$$p = R^* \exp(uR^*) \tag{7}$$

$$\rho(t) = \exp(-\alpha_t t^{1/2}) \tag{8}$$

$$\begin{aligned}\alpha_t &= -0.0006613\phi - 0.0003005\lambda - 0.0074150R_{0.01} \\ &+ 0.0043216R_{0.001} + 0.0001083M + 0.0030336D_{th} \\ &- 0.5476583\beta + 0.1593369\end{aligned} \tag{9}$$

Conversion Method of One-minute Rain Rate from Different Integration Time Rain Rate (Method 2) [3]

Lavergnat-Gole model as different integration time rain rates conversion method is recently proposed and can be used for arbitrary integration times [10]. This model was developed as an application of stochastic process for the time intervals between raindrops, and has reliable theoretical background. This model was given by (10) and (11). P_1 is the cumulated probability obtained with a rain gauge of integration t_1, and R_1 is rain rate for P_1. P_2 is the cumulated probability obtained with a rain gauge of integration t_2, and R_2 is rain rate for P_2. Therefore, using KIT different integration time rain rates databank [3], we analyzed effects of the thunderstorm ratio on this model to extend this model in the world. As the result, an improved model was obtained by using regional climatic parameters such as the thunderstorm ratio and so on, and parameter *a* was given by (12) determined by multiple regression analysis. Table 3 lists the partial correlation coefficients *r* between parameter *a* and regional climatic parameters. This model had a better conversion accuracy than the above model using simplified Moupfouma distribution, and can also be easily expanded to arbitrary integration times and regions.

Table 3. Partial correlation coefficients
(The number of data samples is 43.)

Parameter	*r*
$R_{0.001}$ (mm/h)	0.34
D_{th} (day)	0.32
β	-0.29

$$P_2(R_2) = k^a P_1(R_1) \tag{10}$$

$$R_2 = R_1 / k^a, \quad k \equiv t_2 / t_1 \tag{11}$$

$$\begin{aligned}a &= 0.00219126|\phi| - 0.000205094|\lambda| - 0.001165957R_{0.01} \\ &+ 0.000869955R_{0.001} + 0.0000492772M + 0.001336088D_{th} \\ &- 0.173738515\beta + 0.035580308\end{aligned} \tag{12}$$

Prediction Method for Rain Attenuation on Terrestrial Links [4]

For the terrestrial links, rain attenuation prediction method that uses Gamma distribution and rain rate spatial correlation is widely used in Japan [11]. The probability density function of Gamma distribution *f(R)* is given by (13). ν and τ are distribution parameters. $\rho(d)$ is the spatial correlation function between two locations separated by *d* (km), and it was known that $\rho(d)$ could be approximated by (14) in Japan. By using KIT databank on terrestrial links [4], it was found that this method was applicable worldwide by using the thunderstorm ratio as a parameter. Table 4 lists the partial correlation coefficients *r* between the spatial correlation parameter α_s and regional climatic parameters. The α_s can be represented by (15) which is determined by multiple regression analysis. The *f* is frequency (GHz). It was shown that significant improvements to existing methods were obtained.

Table 4. Partial correlation coefficients
(The number of data samples is 69.)

Parameter	*r*
β	-0.59
M_m (mm)	-0.33
$R_{0.001}$ (mm/h)	0.30

$$f(R) = \frac{\tau^\nu}{\Gamma(\nu)} R^{\nu-1} \exp(-\tau R) \tag{13}$$

$$\rho(d) = \exp(-\alpha_s \sqrt{d}) \tag{14}$$

$$\begin{aligned}\alpha_s &= 0.85488 + 0.19040\ln(\nu) - 0.054866\ln(\tau) \\ &+ 0.0060303f + 0.0022011d - 0.00028404M_m \\ &- 0.0086091R_{0.01} + 0.0054163R_{0.001} - 0.27599\ln(\beta)\end{aligned} \tag{15}$$

Prediction Method for Site Diversity Improvement on Earth-satellite Links [5]

The site diversity system has been proposed as an improving method for the rain attenuation on satellite links using frequencies above about 10 GHz. In this system, signals of two earth stations located apart each other are switched. Although two prediction methods for site diversity improvement are recommended by ITU-R [12][13], these methods do not consider regional climatic parameters that will affect improvement. These will be further improved in prediction accuracy by considering the climatic parameters. An improved version of the existing ITU-R prediction methods were considered in this research, using KIT satellite link site diversity databank [5] and the thunderstorm ratio. It was found that the effect of β on the site diversity improvement factor is large. As the result of quantitative error evaluation, it was found that both of these methods could be improved by using the thunderstorm ratio.

Prediction Method for Rain Depolarization on Terrestrial Links [6]

Rec. ITU-R P.530-8 method [14] is recommended for the prediction of rain depolarization on terrestrial links in the world. In this method, parameter U_0 is explained as follows; the average is about 15 dB and the lower bound is 9 dB. Using KIT terrestrial link XPD databank [6], we developed worldwide depolarization prediction method for U_0. As the result, it was found that U_0 has regional dependence, and effect of the thunderstorm ratio is large. The partial correlation coefficients between U_0 and regional climatic parameters were 0.55 for β, 0.41 for d (km), and -0.20 for the path elevation angle θ (°), where the number of data samples is 23. The parameter U_0 could be represented by (16) determined by multiple regression analysis. This model has not yet enough accuracy, but it is expected that this method can be improved by extending high quality databank and further analysis in future.

$$U_0 = 37.238 - 0.00041304 f + 0.53199 d - 0.028544\theta + 28.901 \log(\beta) \quad (16)$$

CONCLUSION

As results of above analyses, the thunderstorm ratio was found to give large effect on worldwide propagation prediction methods during rain conditions, and to be the most promising regional climatic parameter at present. Because this parameter is obtained from climatic data observed all over the world, it can be expected to establish a worldwide propagation prediction method that has more estimation accuracy by using this parameter.

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