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Research Article

Weighted Mean Annual Rain Height Applied to Rain Attenuation Prediction on Earth-Space Links

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Rain height is crucial for rain attenuation prediction along slant paths, such as Earth-space links. The global digital map of the mean annual rain height is given in Recommendation ITU-R P.839-4. The disadvantage of this model is that heavy rainfall in most regions of the middle and high latitudes of the world is typically concentrated over a few months, such as summer in North China, and the mean rain height during these months and the mean annual rain height are often significantly different. In this study, a new weighted mean annual rain height is proposed by using the ratio of the mean monthly rainfall to the mean annual rainfall as the weight. The analysis shows that the weighted mean annual rain heights have been closer to the statistical rain heights during heavy rainfall in general. On the other hand, the work of this paper helps to improve the accuracy of the rain attenuation prediction model on Earth-space links in China. However, the weighted mean annual rain heights have different characteristics for different rainfall climate zones. This study will contribute to the research of rain attenuation modelling on Earth-space links.

1. Introduction

Rain attenuation is the main impairment in radio communication systems operating at frequencies above 10 GHz, and rain height is vital for rain attenuation prediction along slant paths, such as Earth-space links. Researchers have developed several rain height models [1–7]. The model given in Recommendation ITU-R (Rec.ITU-R) P.839 is the most commonly used, and the newest version of ITU model is P.839-4 [1], which was developed in 2013.

Rain height is usually considered to be the height of the top of the rain column above the mean sea level [4]. In several models [3–6], the rain height may vary with the rainfall rate. For example, Stutzman and Dishman [3] proposed that the rain height increases logarithmically when the rain rate is larger than 10 mm/h. Natarajakumar [4] developed a log-linear combined regression to estimate the rain height based on the rain rate. However, the mean annual 0°C isotherm height is typically regarded as the mean rain height during rain attenuation prediction. In Rec.ITU-R P.839-4, the mean annual rain height above the mean sea level, h_R, may be obtained from the 0 °C isotherm height, h_0, as follows:

$$h_R = h_0 + 0.36\,\text{km}. \tag{1}$$

The digital map of h_0 has also been given by this recommendation. The increase of 0.36 km takes into account the influence of the melting layer.

The disadvantage of this model is that heavy rainfall in most regions of the middle and high latitudes of the world is usually concentrated over a few months, such as summer in North China, and the mean rain height during these months and the mean annual rain height are often significantly different.

In this study, a new weighted mean annual rain height is proposed by using the ratio of the mean monthly rainfall to the mean annual rainfall as the weight. The weighted mean annual rain height is found to be closer to the statistical rain height during heavy rainfall. The analysis shows that the weighted mean annual rain heights have different characteristics for different rainfall climate zones. Moreover, this paper analyzes the influence of the weighted rain height model on the rain attenuation prediction, and the analysis shows that the work of this paper helps to improve the accuracy of the rain attenuation prediction model on Earth-space links in China.

The remainder of this paper is organized as follows. The new weighted rain height model is introduced in Section 2. The analysis of the weighted rain height model at different rainfall climate zones is presented in Section 3. The analysis of the influence of the weighted rain height model on the rain attenuation prediction is presented in Section 4. Finally, the conclusion is provided in Section 5.

2. Weighted Rain Height Model

A new weighted mean annual rain height is proposed herein, using the ratio of the mean monthly rainfall to the mean annual rainfall as the weight. The specific steps are as follows.

Step 1. Based on long-term statistical meteorological data (generally more than 5 years required), the mean monthly rainfall and rain height at a certain site are obtained; the mean monthly rain height is the mean monthly 0°C isotherm height plus 0.36 km, as expressed by (1). When the mean monthly surface temperature of one month is not higher than 0°C, the data for that month are excluded in the statistics because there is usually no rain in this scenario.

Step 2. The mean monthly average rainfall of all rain naturally occurring months (such as January, February, and so on) that meet the conditions given in step 1 is accumulated to obtain the mean annual rainfall.

$$P_Y = \sum_{i=N_0}^{N} P_{\mathrm{Mi}} \,\mathrm{mm}, \tag{2}$$

where P_Y is the mean annual rainfall, P_{Mi} is the mean monthly rainfall of the i-th month, and i is the natural month from $N_0\,(\geq 1)$ to $N\,(\leq 12)$. Then, the weight for each month can be obtained as follows:

$$W_i = \frac{P_{\mathrm{Mi}}}{P_Y}. \tag{3}$$

Step 3. The monthly weight is multiplied by the mean monthly rain height, H_i. The results of each month in the entire year are added to obtain the weighted mean annual rain height. The equation is as follows:

$$H_{\mathrm{WY}} = \sum_{i=N_0}^{N} W_i H_i, \tag{4}$$

where H_i is the mean monthly rain height of the i-th month and H_{WY} is the weighted mean annual rain height; the other parameters are the same as those in step 2.

For comparison, if W_i is set to $1/N$ in every month, then the mean annual rain height, H_Y, can be obtained by using (4).

3. Analysis of the Weighted Rain Height Model at Different Rainfall Climate Zones

3.1. The Analysis with Stations in China. At first, the analysis is performed using data from several stations with different rainfall climates in China. The monthly rainfall data are obtained from the China National Meteorological Science Data Center [8]. The monthly 0°C isotherm height for each month of each station is obtained from the radiosonde data over 2005–2014. Then, the mean monthly rain heights, weighted mean annual rain height, and mean annual rain height can be obtained according to the methods introduced earlier. Meanwhile, the rain height of P.839-4 is also calculated and analyzed herein. Due to their different data sources, the rain height of P.839-4 is for reference only.

We first analyze typical sites with concentrated rainfall in summer, such as Qingdao. The latitude and longitude of Qingdao sounding station are 36.04°N and 120.2°E, respectively. The monthly rainfall data are from 1981 to 2010. The histogram of the mean monthly rainfall in Qingdao is shown in Figure 1. It can be observed that rainfall is mainly concentrated from May to September in Qingdao; therefore, heavy rainfall usually also occurs during this period.

A comparison of the different rain heights is shown in Figure 2, in which the red line represents the weighted mean annual rain height, green dotted line represents the mean annual rain height, black dotted line represents the rain height obtained by P.839-4, and blue curve represents the mean monthly rain heights for each month. As shown in Figures 1 and 2, the weighted mean annual rain height is closer to the statistical rain height from May to September, in which there has been larger monthly rainfall, and the weighted mean annual rain height is more than 1000 m higher than the mean annual rain height. It should be noted that the rain height obtained by P.839-4 is far from the mean annual rain height obtained by statistical meteorological data, but near to the weighted mean annual rain height herein.

Then, we analyze the situation where the rainfall is relatively average, such as Suzhou. The latitude and longitude of Suzhou sounding station are 31.25°N and 120.34°E, respectively. The monthly rainfall data are from 1995 to 2010. The histogram of the mean monthly rainfall in Suzhou is shown in Figure 3. It can be observed that the rainfall is relatively average throughout the months except for June, which has more rainfall. In general, rainfall in summer is slightly higher than that in other seasons.

The comparison of the different rain heights in Suzhou is shown in Figure 4. It can be seen that the weighted mean annual rain height is less than 500 m higher than the mean annual rain height in this case. It should also be noted that the rain height obtained by P.839-4 is far from the mean annual rain height obtained by statistical meteorological

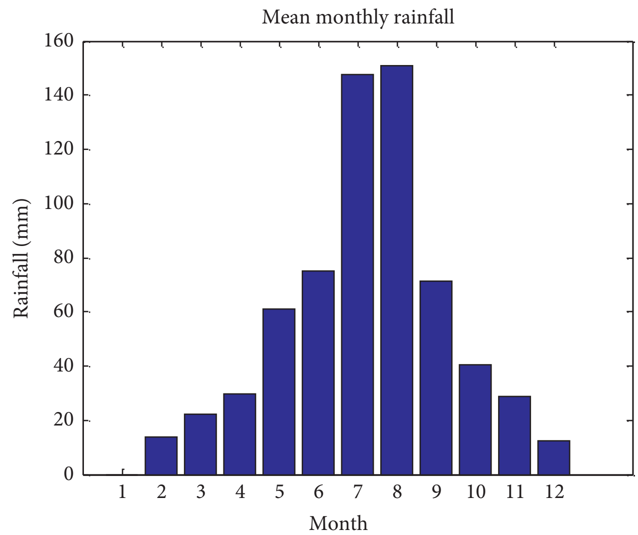

Figure 1: Histogram of the mean monthly rainfall in Qingdao, China.

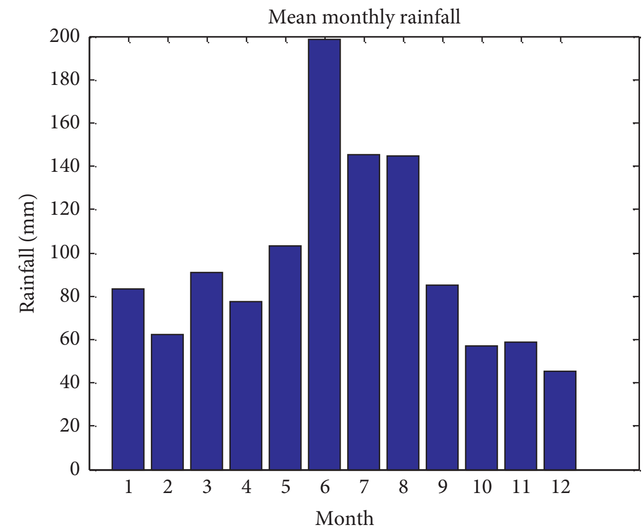

Figure 3: Histogram of the mean monthly rainfall in Suzhou, China.

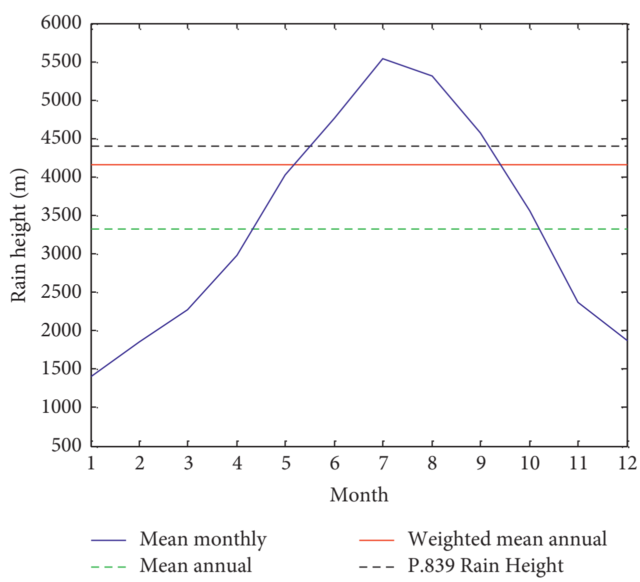

Figure 2: Comparison between different mean rain heights in Qingdao, China.

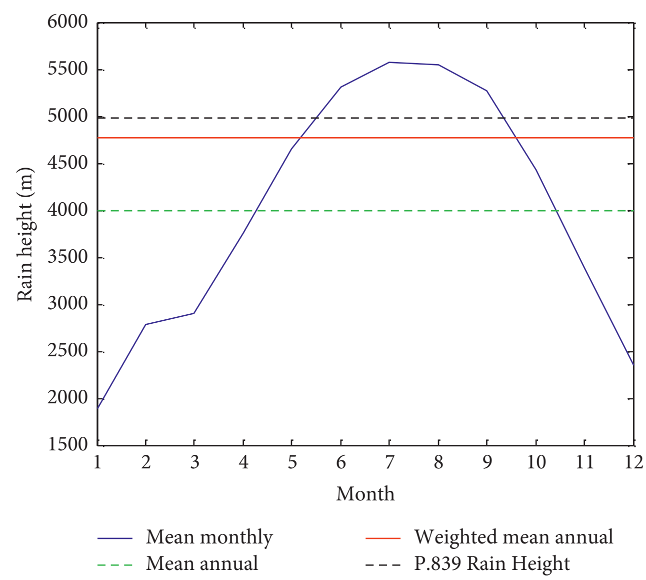

Figure 4: Comparison between different mean rain heights in Suzhou, China.

data, but near to the weighted mean annual rain height herein.

The situation is different in the tropics, such as the station of Haikou. The latitude and longitude of Haikou sounding station are 20°N and 110.15°E, respectively. The monthly rainfall data are from 1981 to 2006. The histogram of the mean monthly rainfall in Haikou is shown in Figure 5. It can be observed that rainfall is mainly concentrated from May to October in Haikou; therefore, heavy rainfall usually also occurs during this period. However, since the average temperature in the tropical regions is not very different from month to month, the mean monthly rain heights are also relatively similar, as shown in Figure 6. It can also be seen from Figure 6 that the weighted mean annual rain height is less than 200 m higher than the mean annual rain height in this case. It should be noted that the rain height obtained by P.839-4 is very near from the mean annual rain height obtained by statistical meteorological data in this case.

3.2. The Analysis with Global Stations. In this part, the analysis is performed using data from several global stations. The monthly rainfall data are obtained from the Global Historical Climatology Network-Monthly v2.0 [9, 10] over 1980–2010. The monthly 0°C isotherm height for each month of each station is obtained from the NCEP (National Centers for Environmental Prediction) FNL (Final Operation Global Analysis) data over 2013–2019 [11]. Then, the

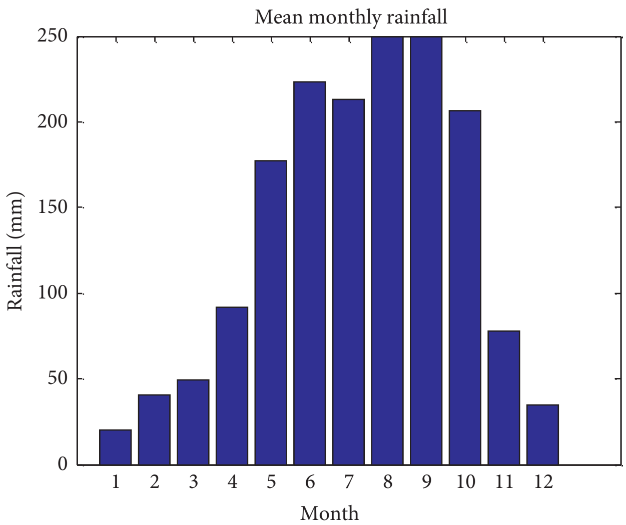

FIGURE 5: Histogram of the mean monthly rainfall in Haikou, China.

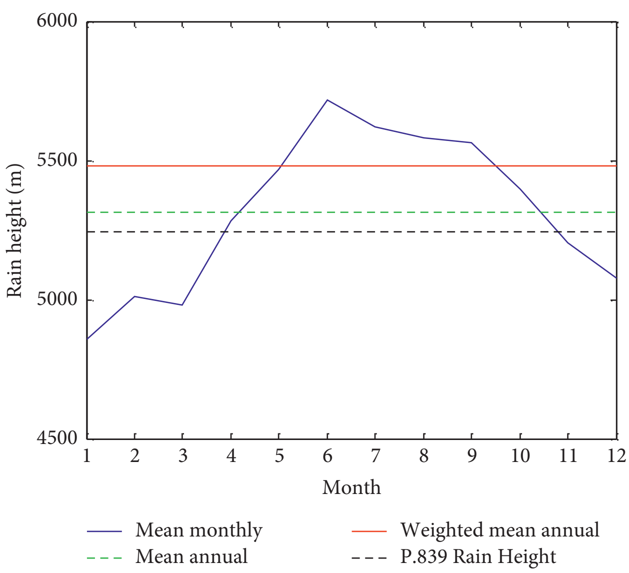

FIGURE 6: Comparison between different mean rain heights in Haikou, China.

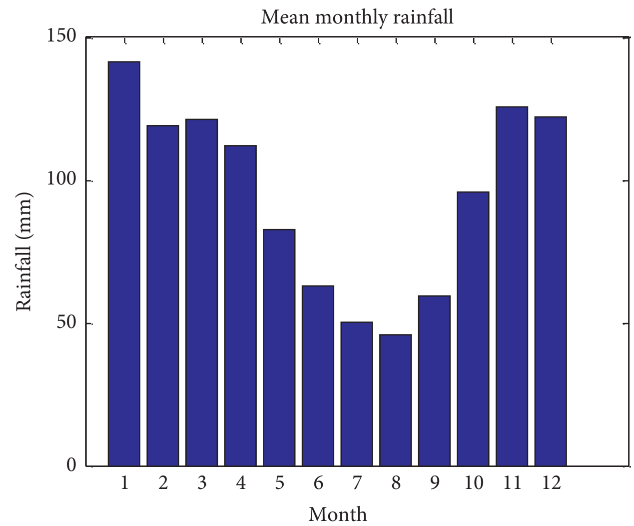

FIGURE 7: Histogram of the mean monthly rainfall in Singapore.

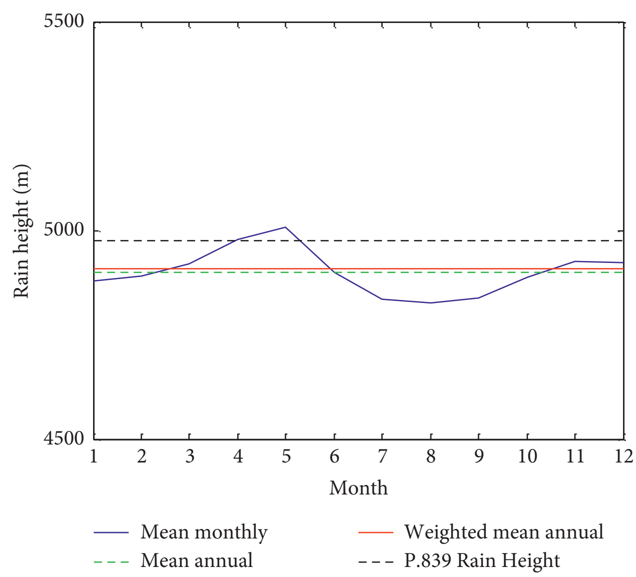

FIGURE 8: Comparison between different mean rain heights in Singapore.

mean monthly rain heights, weighted mean annual rain height, and mean annual rain height can be obtained according to the methods introduced earlier.

In comparison with Haikou in China, Singapore, as a typical site in the tropics, has been analyzed. The latitude and longitude of Singapore station are 1.3°N and 103.9°E, respectively. The histogram of the mean monthly rainfall in Singapore is shown in Figure 7. It can be observed that the cumulative rainfall from June to September is significantly less than other months in Singapore. However, similar to Haikou, China, since the average temperature in the tropical regions is not very different from month to month, the mean monthly rain heights are also relatively similar, as shown in Figure 8. It can also be seen from Figure 8 that the weighted mean annual rain height is almost same as the mean annual rain height in this case. It should be noted that the rain height obtained by P.839-4 is different from the results of the weighted mean annual rain height and the mean annual rain height herein.

The previous examples are all that weighted mean annual rain height is above or close to mean annual rain height. Below is an analysis of the case where the weighted mean annual rain height may be lower than the mean annual rain height. A site with a Mediterranean climate is analyzed here, such as Fucino in Italy. The latitude and longitude of Fucino station are 42°N and 13.6°E, respectively. The histogram of the mean monthly rainfall in Fucino is shown in Figure 9. It can be observed that rainfall is mainly concentrated from October to January in Fucino; therefore, heavy rainfall usually also occurs during this period.

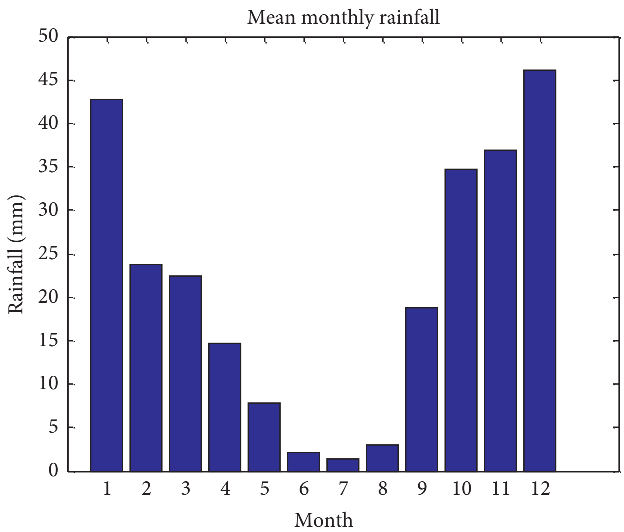

FIGURE 9: Histogram of the mean monthly rainfall in Fucino, Italy.

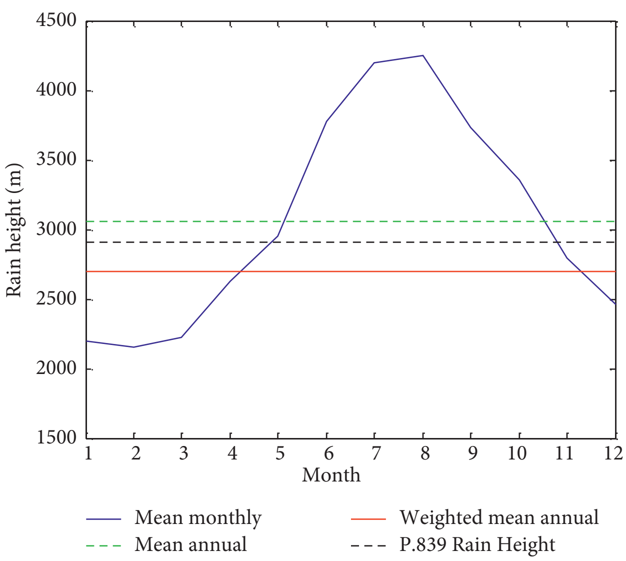

FIGURE 10: Comparison between different mean rain heights in Fucino, Italy.

The comparison of the different rain heights in Fucino is shown in Figure 10. It can be seen that the mean annual rain height is more than 350 m higher than the weighted mean annual rain height in this case. It also can be seen that the rain height obtained by P.839-4 is between the weighted mean annual rain height and the mean annual rain height in this case.

4. The Analysis of the Influence of the Weighted Rain Height Model on the Rain Attenuation Prediction

As mentioned above, rain height is one of key elements for rain attenuation prediction on Earth-space links, which can determine the slant path length through the rainfall area. The influence of rain height on the rain attenuation model on slant path is analyzed here.

The measured rain attenuation data used for comparison are the statistical results of 12 stations in China from 2011 to 2012. The beacon signal comes from the ChinaStar-1 with a center frequency of 12.25 GHz and vertical polarization. The longitude of subsatellite point of the ChinaStar-1 is 87.5°E. The parameters of the radio wave links from the 12 ground stations to the ChinaStar-1 are listed in Table 1.

Firstly, the rain attenuation model in Rec.ITU-R P.618-13 [12] is used for comparison. The mean annual rain heights and the weighted mean annual rain heights of these sites are obtained based on the method of Section 2 with the same meteorological data source. The RMS (root mean square) errors have been used in the assessment of prediction methods as proposed in ITU-R Doc.3 M/FAS/1 [13]. It also can be seen that RMS errors obtained by the rain height of P.839-4 are near to the results obtained by the weighted mean annual rain height, which is because the two kinds of rain heights are very close.

Figure 11 shows the comparison of rain attenuation prediction with different rain heights with the data and model descripted above. It can be seen that the weighted mean annual rain height can improve the accuracy of rain attenuation prediction obviously.

Secondly, the same form is adopted to optimize the rain attenuation modelling for the three rain heights. From the literature review, it can be found [14] that the general structure of the majority of rain attenuation models is

$$A_p = \gamma_R L_S c_f, \tag{5}$$

where γ_R is the specific attenuation (dB/km), L_S is the slant path length (km), and c_f is the path adjustment factor. Here it is considered that the path adjustment factor is related to rain rate at a percentage time R_p and the horizontal path length L_G. Set X as $\lg(R_p L_G + 1.2)$ and Y as $1/c_f$. The analysis shows that Y can be fitted with the second-order function of X (see Figure 12), in which the weighted mean annual rain height is used with the same data described above.

According to the above analysis, the path adjustment factor models are established based on three kinds of rain heights: the weighted mean annual rain height, the mean annual rain height, and the rain height of P.839-4.

The path adjustment factor model with the weighted mean annual rain height is obtained as

$$c_f = \frac{1}{0.518\lg^2\left(R_p L_G + 1.2\right) - 0.6788\lg\left(R_p L_G + 1.2\right) + 0.3733}. \tag{6}$$

The path adjustment factor model with the mean annual rain height is obtained as

$$c_f = \frac{1}{0.4972\lg^2\left(R_p L_G + 1.2\right) - 0.6489\lg\left(R_p L_G + 1.2\right) + 0.3205}. \tag{7}$$

Moreover, the path adjustment factor model with the mean annual rain height of P.839-4 is obtained as

$$c_f = \frac{1}{0.1858\lg^2\left(R_p L_G + 1.2\right) - 0.09096\lg\left(R_p L_G + 1.2\right) + 0.02132}. \tag{8}$$

Table 1: The parameters of the radio wave links of the 12 ground stations.

Site	Longitude (degree)	Latitude (degree)	Altitude (m)	Elevation (degree)	Year of observation
Qingdao	120.18	36.03	77	35.7	2011-2012
Haikou	110.2	20.02	18	55	2011-2012
Beijing	116.46	39.92	55	35	2012
Guangzhou	113.14	23.08	4	50.4	2011-2012
Lhasa	91.08	29.39	3650	54.8	2012
Suzhou	119.58	31.47	11	38.9	2011-2012
Lanzhou	103.51	36.04	1518	44.8	2011-2012
Xinxiang	113.52	35.18	74	40.4	2011-2012
Manzhouli	117.23	49.35	662	26.4	2012
Urumqi	87.36	43.35	398	39.5	2012
Chongqing	106.33	29.35	260	49.7	2011-2012
Changchun	125.19	43.54	238	26.9	2011-2012

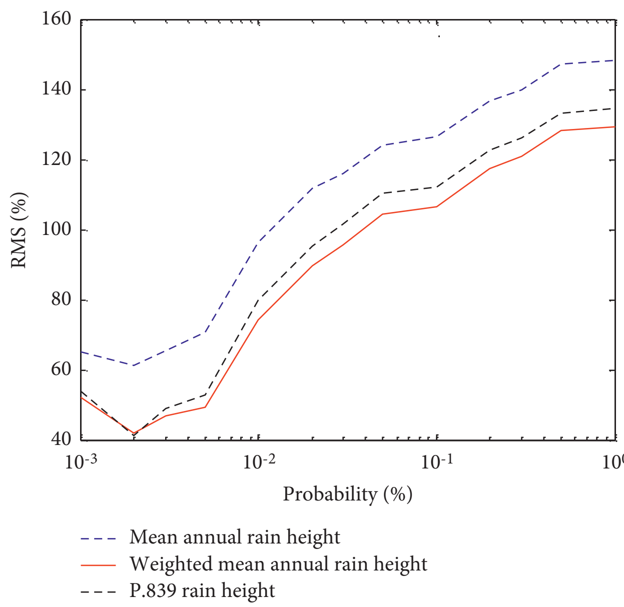

Figure 11: The comparison of rain attenuation prediction with different rain heights.

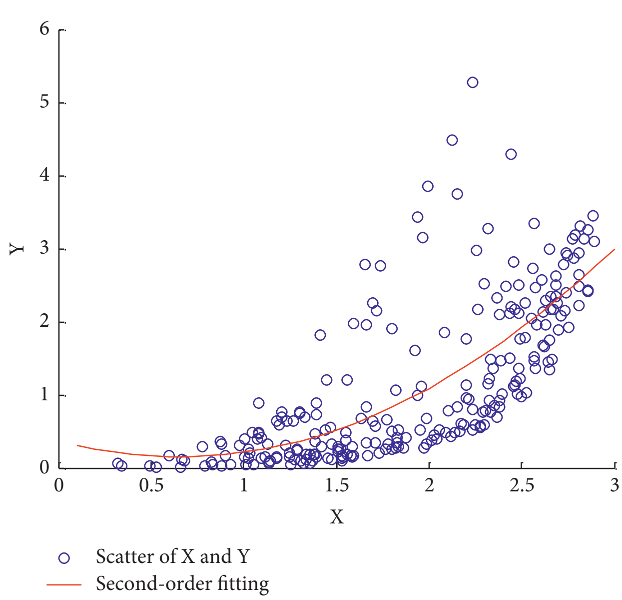

Figure 12: The scatter plot of X and Y and second-order fitting.

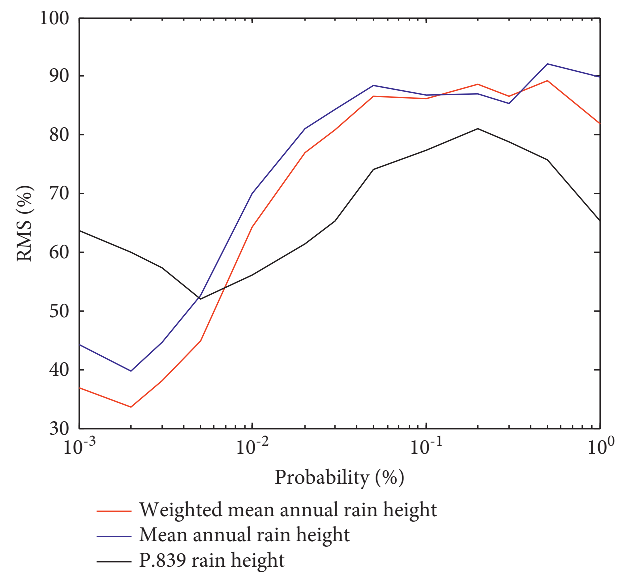

Figure 13: The comparison of rain attenuation prediction with different rain heights and corresponding adjustment factors.

Figure 13 shows the comparison of rain attenuation prediction with different rain heights and corresponding adjustment factors in equations (6)–(8). It can be seen that the weighted mean annual rain height also can improve the accuracy of rain attenuation prediction in this situation. It also can be seen that the rain height of P.839-4 obtains the best results in general but has the worst results at small probabilities. However, as it is said before, due to their different data sources, the results of rain attenuation prediction using the rain height of P.839-4 are for reference only.

5. Conclusion

The mean annual rain height is utilized in Rec.ITU-R P.839-4, whereas a weighted mean annual rain height is proposed in this study. The analysis shows that the weighted mean annual rain heights have different characteristics for different rainfall climate zones. In general, the analysis shows that the weighted mean annual rain height is closer to the statistical rain height during heavy rainfall, and it can improve the accuracy of the rain attenuation prediction model on Earth-space links in China.

A larger mean monthly rainfall usually corresponds to a larger probability of a larger rain rate, which has a significant impact on the radio system design. For example, 9 probability points from 0.001% to 0.1%, which exceed for an average year, are selected to evaluate the rain attenuation models given in ITU-R Doc.3 M/FAS/1 [13]. Therefore, when the rain height used in modelling rain attenuation is closer to the statistical rain height in case of a large rain rate, a more accurate rain attenuation model can be obtained in theory.

However, it also should be noted that the rainfall climates in these China sites are a little bit similar, and the rainfalls are usually concentrated at the warm months in most sites. Therefore, the weighted mean annual rain height is higher than the mean annual rain height. The situation may be different for other rainfall climate zones. For example, in the Mediterranean climate zone, the weighted mean annual rain height may be lower than the mean annual rain height as shown in Figures 9 and 10. In this case, whether the weighted mean annual rain height can improve rain attenuation prediction needs to be further tested.

Moreover, the rain height of P.839-4 is also calculated and analyzed in this paper. However, the result of P.839-4 is for reference only because their data sources are different.

In general, whether the weighted mean annual rain height in this paper is beneficial to the improvement of the rain attenuation model must be investigated further. As mentioned in Section 1, some researchers believe that the rain height is related to the rain rate. In the future, the changes in the rain height with the rain rate should be considered to improve the rain height model.

Data Availability

The monthly rainfall data in China were obtained from the China National Meteorological Science Data Center: http://data.cma.cn. The global monthly rainfall data were obtained from the Global Historical Climatology Network-Monthly v2.0 over 1980–2010: ftp.ncdc.noaa.gov. The monthly 0°C isotherm height for each month of each station was obtained from the NCEP (National Centers for Environmental Prediction) FNL (Final Operation Global Analysis) data over 2013–2019: https://rda.ucar.edu/datasets/ds083.2/.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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