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Research Article

Rain Attenuation at 58 GHz: Prediction versus Long-Term Trial Results

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Electromagnetic wave propagation research in frequency band 58 GHz was started at TESTCOM in Praha due to lack of experimentally obtained results needed for a realistic calculation of quality and availability of point-to-point fixed systems. Rain attenuation data obtained from a path at 58 GHz with V polarization located in Praha was processed over a 5-year period. Rainfall intensities have been measured by means of a heated siphon rain gauge. In parallel, rainfall intensity data from rain gauge records was statistically processed over the same year periods as the rain attenuation data. Cumulative distributions of rainfall intensities obtained as well as cumulative distributions of rain attenuation obtained are compared with the calculated ones in accordance with relevant ITU-R recommendations. The results obtained can be used as the primary basis for the possible extension of the ITU-R recommendation for calculating rain attenuation distributions up to 60 GHz. The obtained dependence of percentages of time of the average year on the percentages of time of the average worst month is also compared with the relevant ITU-R recommendation. The results obtained are discussed.

1. INTRODUCTION

Frequency bands above 38 GHz will be extensively utilized by terrestrial digital fixed services in the near future because the lower bands are almost fully occupied. It means that the 60 GHz frequency band will be utilized now although there is a lack of experimentally obtained primary bases which are needed for realistic calculations of both availability and reliability of service. Some experimental activities is focused on specific attenuation due to rain [1] or intervehicle communications [2]. One-year results of propagation experiment at 58 GHz carried out in Sydney and Praha were described in [3]. Results of 2-year measurement of attenuation due to specific hydrometeors (rain, rain with hail, snow, fog) were described in [4]. Relevant ITU-R recommendation [5] which can be used for estimating long-term statistics of rain attenuation is considered to be valid in all parts of the world at least for frequencies up to 40 GHz and path lengths up to 60 km. Minimum usable path length is not mentioned.

The 60 GHz frequency band is suitable for short-range communications technologies. Significant oxygen absorption, water vapour absorption, and attenuation due to hydrometeors (rain, snow, hail, and fog) limit communications systems. The oxygen absorption has a peak near 60 GHz, typically around 16 dB/km [6]. Water vapour further slightly attenuates the signal, about 0.2 dB/km. Therefore the band is the most suitable one for intensive frequency reuse.

This contribution presents rain attenuation characteristics at 58 GHz with V polarization obtained on a path 850 m long, over a 5-year period of observation.

2. EXPERIMENTAL SETUP

Electromagnetic wave propagation research in the frequency band 58 GHz was started at TESTCOM in December 2000. NOKIA MetroHopper equipment working on frequency 57.650 GHz with V polarization has been used. The length of the experimental path which is located in Praha is about 850 m. Recording margin has been about 30 dB due to special offset antennas used. The research is focused on attenuation due to hydrometeors. The calibrated AGC voltages corresponding to the received signal level have been gathered continuously with the sampling of 10 Hz on PC hard disc, and data obtained over a 5-year period from December 2000 to November 2005 was processed statistically.

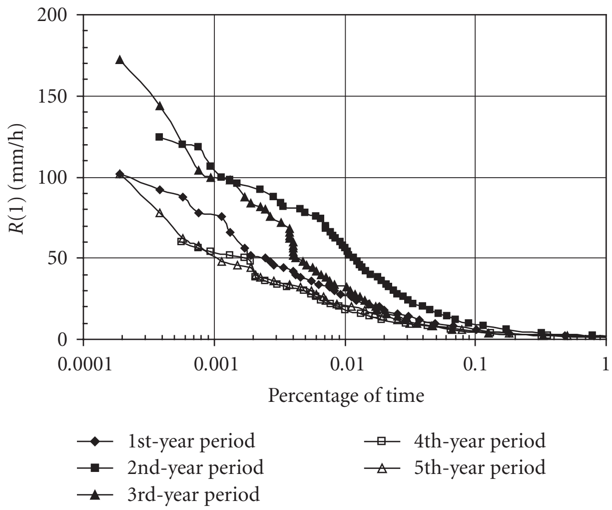

Figure 1: CDs of average 1-minute rain intensities for individual 1-year periods.

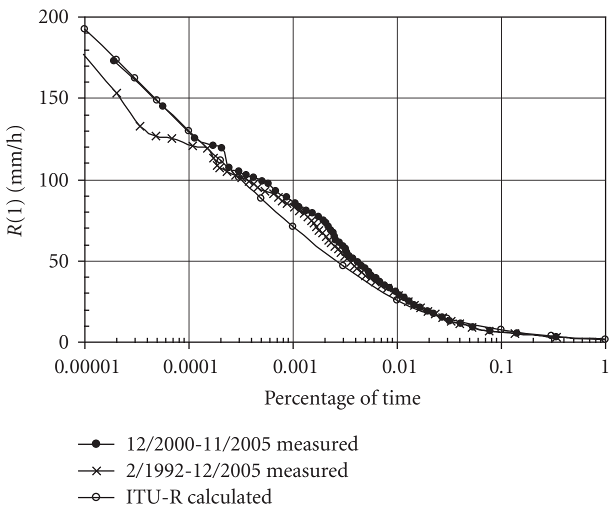

Figure 2: CDs of average 1-minute rain intensities for AY.

It should be noted that only rain attenuation events were processed. Not only attenuation due to rain but also attenuation due to rain with snow, snow, fog, and hail occurred within the 5-year period of observation. Individual attenuation events were compared with concurrent meteorological situations and were carefully classified according to the types of individual hydrometeors occurring.

Meteorological conditions were identified by means of both video BW camera images of the space between transmitter and receiver sites, and data obtained from an automatic meteorological station located near the receiver site. The automatic meteorological station is equipped with VAISALA sensors for measurement of temperature, humidity and pressure of air, velocity and direction of wind, visibility and 2 tipping-bucket rain gauges with differing collecting areas. These rain gauges were used only for indication of rainfalls due to their low time resolution of tips.

Rainfall intensities have been measured since February 1992 by means of a heated siphon rain gauge. Rainfall intensity data from rain gauge records was statistically processed over the same contiguous 1-year periods as was the rain attenuation data.

Both the rain attenuation data and the rainfall intensity data were statistically processed twice: (1) over five individual contiguous 1-year periods, and (2) together over the entire 5-year period.

3. TRIAL RESULTS AND DISCUSSION

3.1. Rainfall intensity distributions

Resulting cumulative distributions (CDs) of average 1-minute rainfall intensities ($R(1)$) for individual 1-year periods of observation are given in Figure 1.

Large year-to-year variations of individual year distributions may be seen clearly in Figure 1. Differences up to +15 mm/h − 37 mm/h for 0.001% of time, +25 mm/h − 11 mm/h for 0.01% of time, and +5 mm/h − 2 mm/h for 0.1% of time occur between measured average 1-minute rainfall intensities and rainfall intensities corresponding to CD of $R(1)$ for the average year (AY).

It should be noted that the values of rain intensities for the lowest percentages of time correspond mostly to a single rain event in a full year, and therefore they are not statistically reliable.

Resulting CD of $R(1)$ for the AY over the 5-year period, resulting CD of $R(1)$ for the AY over the 14-year period 1992–2005, and CD of $R(1)$ for the AY in accordance with ITU-R recommendation [7] are plotted together in Figure 2.

It can be seen that the value of $R(1)$ for 0.01% of time for the entire 5-year period is 30.2 mm/h while the value of $R(1)$ for the same percentage of time obtained through processing rainfall intensity data over the 14-year period is 29.3 mm/h, and the $R(1)$ for 0.01% of time in accordance with ITU-R recommendation [7] is 26.0 mm/h.

Resulting CDs of $R(1)$ for the whole 5-year period of observation together and for the 14-year period are very much alike: they differ from each other by no more than 14 mm/h in the range from 1% to 0.0001%. $R(1)$ obtained over the 5-year period are up to 20 mm/h greater (for the percentage of time of about 0.002%) than the $R(1)$ calculated in accordance with ITU-R recommendation [7].

Perfect agreement emerging between the obtained values $R(1)$ and the calculated ones for percentages of time smaller than 0.0001% is remarkable.

3.2. Rain attenuation distributions

Rain attenuation data obtained on the path at 58 GHz with V polarization was processed over the same 5-year period as was rainfall intensity data. For the first 3-year period, special offset V-polarized antennas were not covered with radomes. Radomes made of special rubberized canvas have been used since November 2003 to protect antennas against snow drifts.

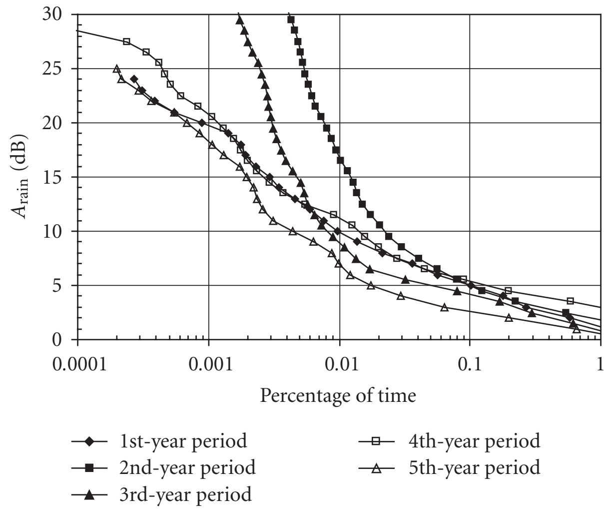

Figure 3: CDs of rain attenuation for individual 1-year periods.

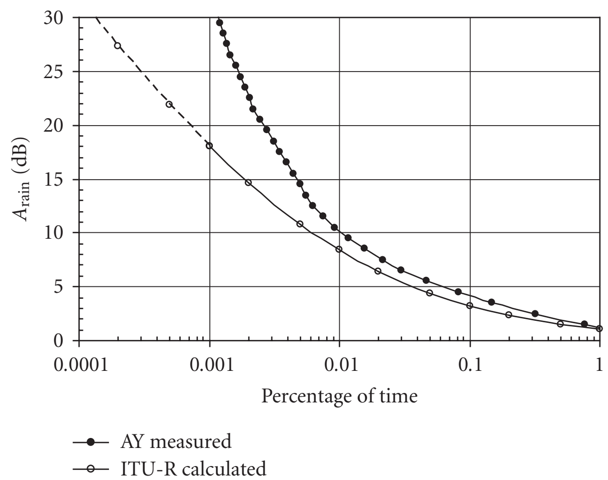

Figure 4: CDs of rain attenuation for AY.

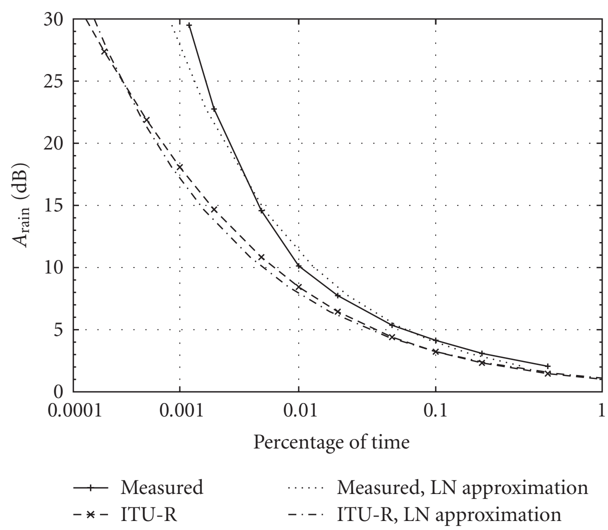

Figure 5: CDs of rain attenuation for AY and its LN approximations.

Moreover, when radomes installed on antennas were wet, additional attenuation about 2 dB was observed. Therefore the obtained CDs of attenuation due to rain were shifted about 2 dB since November 2003 to compensate for this effect. Of course, CDs of attenuation due to rain for the first 3-year period of observation remained without modifications.

Resulting CDs of attenuation due to rain for individual 1-year periods of observation separately are plotted in Figure 3.

Large year-to-year variations of individual year distributions may be seen, similarly as in Figure 1. The notice concerning the low statistic reliability of the values of rain attenuation for the lowest percentages of time is also valid for distributions given in Figures 3 and 6. The comparison of CDs of $R(1)$ and CDs of rain attenuation, as plotted in Figures 1 and 3, is very interesting. Very good correspondence exists between rainfall intensities and rain attenuation for the second year of observation. The values of both rainfall intensities and rain attenuation are the highest ones for time percentages between 0.1% and 0.004%. While the rainfall intensities for the 4th- and the fifth-year periods are very close to each other, associated rain attenuation values significantly differ. Relevant analysis in more detail is given in Section 3.3.

Resulting CD of attenuation due to rain for the average year over the 5-year period of observation and CDs of attenuation due to rain for the AY in accordance with ITU-R recommendation [5] are plotted together in Figure 4. The measured value of $R(1) = 30.2$ mm/h for 0.01% of time over all the 5-years of observation, obtained from Figure 2, was used for the calculation of CD of rain attenuation in accordance with ITU-R recommendation [5].

Due to the fact that the recommendation is valid for percentages of time of AY between 0.001% and 1% only, the part of CD calculated for percentages of time smaller than 0.001% is plotted by dashed line. This convention is also used in Figures 8–12. It must be stressed that all the comparisons made out of the range of validity must be treated with care. Naturally, availability smaller than 0.001% can be assessed only exceptionally. If the calculated value of $R(1) = 26.0$ mm/h for 0.01% of time, obtained from ITU-R recommendation [7], is used for the calculation of CD, the calculated values of attenuation will be even smaller if the measured value of $R(1)$ over the entire 5-year period of observation is used.

Very smooth curve was obtained for the measured CD of attenuation due to rain for the average year over the 5-year period of observation. It can be seen that the smaller the percentage of time is, the greater the difference between measured values of rain attenuation and the calculated ones is. For percentages of time greater than 0.01%, measured values of attenuation due to rain are greater than the calculated ones up to about 1.5 dB. The obtained values of rain attenuation then grow up rapidly for percentages of time smaller than 0.01%. A difference of about 13 dB can be observed between the measured rain attenuation and the calculated one for the chosen percentage of time of about 0.001%.

From the point of view of the percentages of time, it can be noted that for the value of attenuation due to rain of 30 dB, the difference between the measured percentage of time and the calculated one is about one decade. These

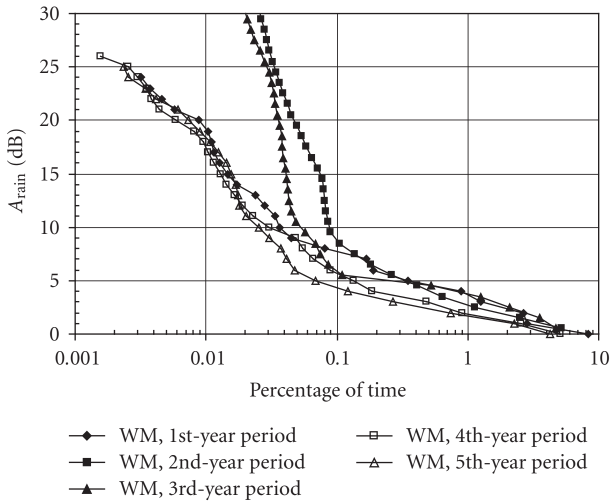

FIGURE 6: CDs of rain attenuation for WM of individual 1-year periods.

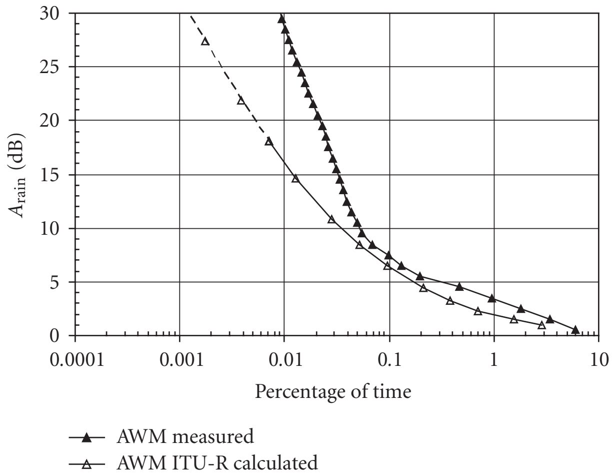

FIGURE 7: CDs of rain attenuation for AWM.

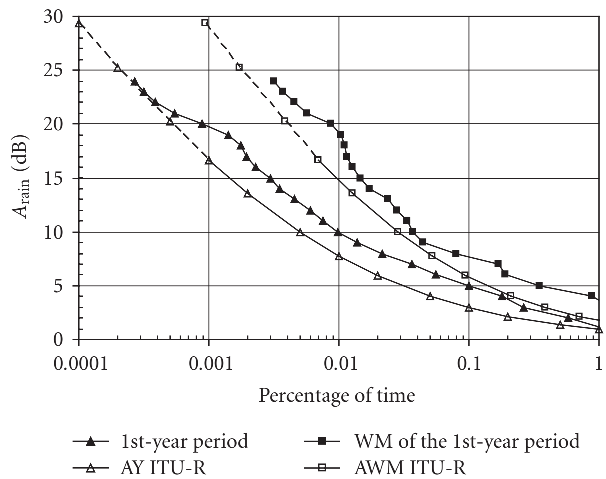

FIGURE 8: CDs of rain attenuation obtained for the first-year period.

differences can be explained (1) by the fact that the ITU-R prediction procedure is considered to be valid for frequencies up to 40 GHz, and (2) by the influence of local climate conditions.

The cumulative distributions of rain attenuation for the average year, as plotted in Figure 4, can be approximated by log-normal (LN) distributions. The measured CD of rain attenuation can be approximated by LN distribution with the parameters $\mu = 0.0239$ dB and $\sigma^2 = 2.7394$, and the calculated CD of rain attenuation in accordance with ITU-R recommendation [7] can be approximated by LN distribution with the parameters $\mu = 0.0402$ dB and $\sigma^2 = 2.0154$. All distributions mentioned here are shown together in Figure 5 in the dB-normal scale to better see the differences between the obtained distributions and their LN approximations than when shown in the log-normal scale. Differences between the calculated CD of rain attenuation in accordance with the ITU-R recommendation and its LN approximation are about ± 1 dB. Slightly greater differences can be seen between the measured CD of rain attenuation and its LN approximation, about +1.5 dB for 0.01% of time and about 3.5 dB for about 0.001% of time of year.

Resulting CDs of attenuation due to rain for the worst months (WMs) of individual 1-year periods of observation separately are plotted in Figure 6.

The CD of rain attenuation obtained for the average worst month (AWM) over the entire 5-year period of observation and CDs of attenuation due to rain for the AWM in accordance with ITU-R recommendation [5] are plotted together in Figure 7. The measured value of $R(1) = 30.2$ mm/h for 0.01% of time over the entire 5-year period of observation (obtained from Figure 2) was used for the calculation of CD of rain attenuation for the average worst month in accordance with ITU-R recommendation [5]. Because the recommendation is valid for percentages of time of AWM between 0.007% and 1% only, the part of CD calculated for percentages of time smaller than 0.007% is plotted by dashed line. This convention is also used in Figures 8–12. The comparisons made out of the validity range must be treated again with care.

For percentages of time greater than 0.05%, measured values of attenuation due to rain are greater than the calculated ones up to about 2 dB. The difference up to about 13 dB can be observed between the measured rain attenuation and the calculated one for the percentage of time of about 0.01%.

From the point of view of the percentages of time, the difference between measured percentage of time and the calculated one is about one decade for the attenuation due to rain of 30 dB. These significant differences can also be explained by the fact that the ITU-R prediction procedure is considered to be valid for frequencies up to 40 GHz only and by influence of local climate conditions.

3.3. Year-to-year variability of rain attenuation distributions

Due to the fact that measured values of attenuation due to rain are greater than those calculated in accordance with

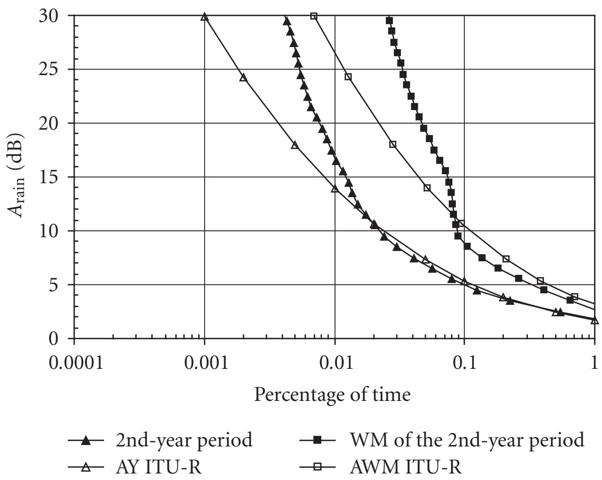

FIGURE 9: CDs of rain attenuation obtained for the second-year period.

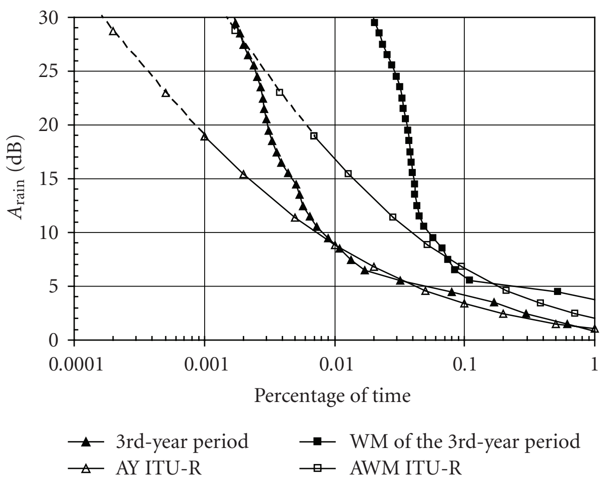

FIGURE 10: CDs of rain attenuation obtained for the third-year period.

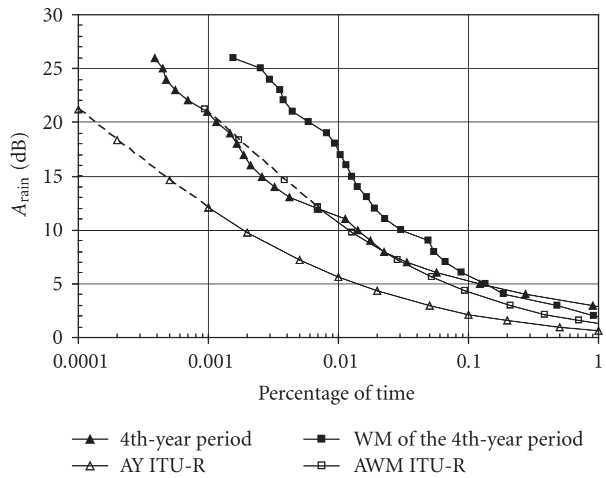

FIGURE 11: CDs of rain attenuation obtained for the fourth-year period.

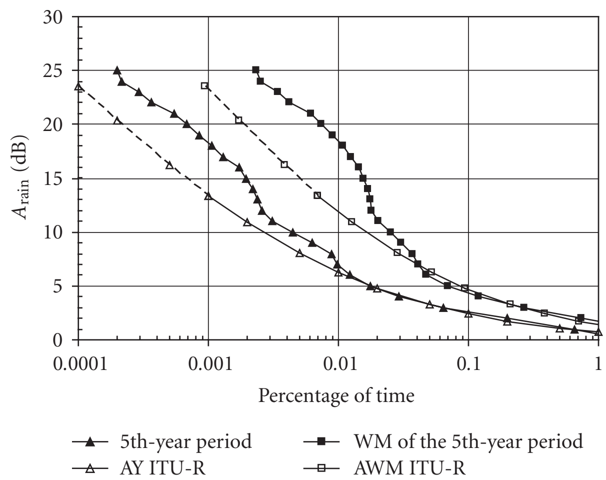

FIGURE 12: CDs of rain attenuation obtained for the fifth-year period.

ITU-R recommendation [5] for both the average year distribution (Figure 4) and the average worst-month distribution (Figure 7), it will be useful to analyze the results obtained on a year-to-year basis. Measured values of $R(1)$ for 0.01% of time in individual-year periods, obtained from Figure 1, were used for the calculation of CDs of rain attenuation for individual-year periods in accordance with ITU-R recommendation [5]. Worst-month distributions were calculated from the year distributions using ITU-R recommendation [8].

Resulting CDs of attenuation due to rain and the calculated ones in accordance with [5] for both the first-year period and the worst month of the first-year period are plotted together in Figure 8.

It can be seen that measured values of attenuation due to rain are greater than the calculated ones by up to about 4.5 dB for both the first-year period and the worst month of the first-year period.

The results obtained for the second-year period are shown in Figure 9.

For the second-year period, the measured values of attenuation due to rain agree very well with the calculated values of attenuation due to rain in accordance with the ITU-R recommendation [5] for the percentages of time greater than 0.02%. For the worst month of the second-year period, measured values of attenuation due to rain are lower than the calculated ones by up to about 1.5 dB for percentages of time greater than 0.09%. Measured values of attenuation are greater than the calculated ones for smaller percentages of time than forenamed.

The results obtained for the third-year period are drawn in Figure 10.

For the third-year period, measured values of attenuation due to rain agree very well with the calculated values of attenuation due to rain in accordance with the ITU-R recommendation [5] for percentages of time greater than 0.01%. For the

Table 1: Comparison of the measured rainfall intensities, the calculated attenuation due to rain, and the measured attenuation due to rain for the individual-year periods and the entire 5-year period for 0.01% of time of year only. *Note that the numbers in parenthesis are the span of relevant quantities from the highest value to the lowest one.*

Period	$R_{0.01}(1)$ (mm/h)	$A_{0.01}$ (dB) ITU-R [1]	$A_{0.01}$ (dB) measured
1st year	27.4 (3)	7.8 (3)	10.0 (3)
2nd year	56.4 (1)	14.0 (1)	16.8 (1)
3rd year	32.0 (2)	8.8 (2)	9.0 (4)
4th year	18.5 (5)	5.6 (5)	11.2 (2)
5th year	21.0 (4)	6.3 (4)	7.0 (5)
5 years	30.2	8.4	10.1

worst month of the third-year period, measured values of attenuation due to rain agree very well with calculated values of attenuation due to rain in accordance with the ITU-R recommendation [5] for percentages of time greater than 0.07%. Measured values of attenuation for both the third-year period and its worst month grow up rapidly for smaller percentages of time than forenamed.

The results obtained for the fourth-year period are plotted in Figure 11.

Both the measured values of attenuation due to rain for the fourth-year period and for its worst month are greater than the calculated ones by up to about 10 dB. Besides this, the measured CD of attenuation due to rain for the fourth-year period agree very well with the calculated CD of attenuation due to rain for its worst month.

The results obtained for last-the fifth-year periods are shown in Figure 12.

For the fifth-year period, measured values of attenuation due to rain agree very well with calculated values of attenuation due to rain in accordance with the ITU-R recommendation [5] for percentages of time greater than 0.01%. For the worst month of the third-year period, measured values of attenuation due to rain agree very well with the calculated ones for percentages of time greater than 0.04%. For percentages of time smaller than the forenamed ones, measured values of attenuation due to rain are greater than the calculated ones by up to about 5 dB for the year period and by up to about 7 dB for its worst month.

For the average year distribution, good agreement between measured values of rain attenuation and those calculated was found for percentages of time greater than 0.01%. For percentages of time smaller than 0.01%, obtained values of rain attenuation then grow up rapidly and a difference of about 13 dB occurs for 0.001 percentage of time.

For the average worst-month distribution, good agreement between measured values of rain attenuation and those calculated was found for percentages of time greater than 0.05%. For percentages of time smaller than 0.05%, obtained values of rain attenuation then grow up rapidly, and a difference of about 13 dB occurs for 0.01% of time.

Comparison of measured rainfall intensities, calculated attenuation due to rain, and measured attenuation due to rain for individual 1-year periods and the entire 5-year period for exclusively 0.01% of time of year are given in Table 1.

Best agreement between the measured value of rain attenuation and the calculated one for exclusively 0.01% of time of year was found for the third year of observation. Very good agreement, that is, a difference smaller than 3 dB between the calculated value of rain attenuation and the measured one, can be observed for the first-, the second-, and the fifth-year periods.

While calculated values of attenuation in accordance with the ITU-R recommendation correspond with measured rainfall intensities in individual-year periods very well (i.e., the higher rain intensity, the higher rain attenuation), measured values of rain attenuation do not correspond exactly with measured rainfall intensities for the second, fourth, and fifth years. Better correspondence can be found for the first and the third years of observation.

While rainfall intensities for the fourth- and the fifth-year periods are very close to each other, rain attenuation values significantly differ by about 4 dB. While rainfall intensities for the first- and the third-year periods are greater than rainfall intensities for the fourth- and fifth-year periods, rain attenuation values are situated between the CDs for the fourth- and the fifth-year periods.

Although the measured rainfall intensity of 32.0 mm/h is the second highest one, the measured rain attenuation of 9.0 dB is on the fourth position. Similarly, the measured rainfall intensity of 18.5 mm/h is the lowest one while the measured rain attenuation of 11.2 dB is on the second position. Finally, the measured rainfall intensity of 21.0 mm/h is on the fourth position while the measured rain attenuation of 7.7 dB is the lowest one.

It is apparent that the span of measured rain attenuation values for individual-year periods should correspond with the span of values of measured rainfall intensities, similarly as the correspondence is in the case of the span of rain attenuation values calculated in accordance with the ITU-R recommendation. It should be further analyzed why it is not so.

3.4. Conversion of annual statistics to worst-month statistics

The obtained dependence of the percentage of time of the average year P_{AY} on the percentage of time of the average worst month P_{AWM} for selected values of rain attenuation is drawn in Figure 13. The dependence can be approximated for 1 dB $\leq A_{rain} \leq$ 30 dB by the formula

$$P_{AWM} = 3.79 P_{AY}^{0.89} \ (\%) \tag{1}$$

with a correlation coefficient $r = 0.9895$.

It can be seen from Figure 13 that calculated percentages of time of AWM in accordance with ITU-R recommendation [8] are slightly lower than percentages of time corresponding to linear approximation of measured values. The reason is that ITU-R recommendation [8] presents slightly different

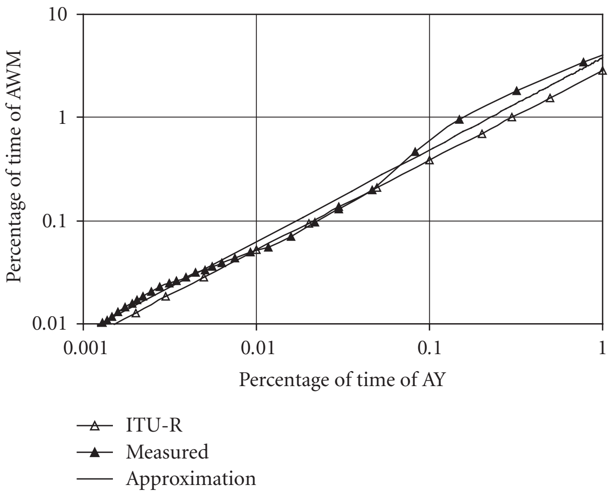

Figure 13: Dependence of percentages of time of AWM on percentages of time of AY.

formulas for the calculation of P_{AWM} from P_{AY}:

$$P_{\mathrm{AWM}} = 2.85 P_{\mathrm{AY}}^{0.87}\ (\%). \tag{2}$$

4. CONCLUSIONS

Rain attenuation data obtained at 58 GHz for V polarizations on an 850 m terrestrial path as well as rainfall intensity data from rain gauge records were statistically processed over five individual contiguous 1-year periods and over the entire 5-year period of observation together. Cumulative distributions of average 1-minute rainfall intensities as well as cumulative distributions of rain attenuation for individual-year periods, individual worst months of 1-year periods, for the average year and the average worst month were obtained.

Large year-to year variations of individual-year distributions were noted. Cumulative distributions of rain attenuation for both the average year and the average worst month obtained were compared with those calculated in accordance with relevant ITU-R recommendation. Results obtained can be used as basis for the extension of ITU-R recommendation [5] for frequencies over 40 GHz.

Cumulative distributions of rain attenuation obtained were analyzed in detail on a year-to-year basis and were compared with distributions corresponding to relevant ITU-R recommendation. It may be seen clearly that the results obtained from 1-year measurement only are not statistically reliable from the long-term point of view. Results of long-term measurements only, that is, at least 3-year measurement, are needed for the realistic assessment of availability of point-to-point fixed systems. The conversion of cumulative distributions of rainfall intensities into cumulative distributions of rain attenuation should be further analyzed. The dependence of average worst-month time percentages on average year time percentages was examined and the result obtained was compared with relevant ITU-R recommendation.

Our long-term experimental research will continue. Further work will be focused on conversion of cumulative distributions of rainfall intensities into cumulative distributions of rain attenuation and on polarization dependence of rain attenuation at 58 GHz.

ACKNOWLEDGMENTS

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