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Research Article

Comparison of Measured Rain Attenuation in the 12.25 GHz Band with Predictions by the ITU-R Model

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Quantitative analysis and prediction of radio attenuation is necessary in order to improve the reliability of satellite-earth communication links and for economically efficient design. For this reason, many countries have made efforts to develop their own rain attenuation prediction models that are suited to their rain environment. In this paper, we present the results of measurements of rain-induced attenuation in vertically polarized signals propagating at 12.25 GHz during certain rain events, which occurred in the rainy wet season of 2001 and 2007 at Yong-in, Korea. The rain attenuation over the link path was measured experimentally and compared with the attenuation obtained using the ITU-R model.

1. Introduction

Microwave signals propagating through the atmosphere are attenuated by vapor, fog, oxygen, rain, and several other gases. The most severe attenuation is caused by rain; in addition, at frequencies of 22 GHz or 60 GHz, signal degradation due to vapor or oxygen increases. At high frequencies, that is, at 10 GHz or more, the attenuation due to rainfall increases further [1, 2].

Many rain attenuation prediction models have been developed to assist in designing effective satellite-earth communication links, for example, the International Telecommunication Union Radio Communication Sector (ITU-R) model. These models were developed using rain attenuation statistics for rainfall environments native to other countries; thus, owing to their regional peculiarities, these models could not be used to study the effects of rain attenuation in the rainfall environment of Korea. In recent years, some cities in Korea have experienced periods of unusually heavy rainfall, which, according to climatologists, is caused by urban heat island phenomena. Thus, it will be very interesting to see how well the recent rain attenuation data measured in Korea compares with the values obtained using the ITU-R method.

2. A Brief Background on Existing Rain Rate and Rain Attenuation Models

2.1. ITU-R P.837-5 Rain Rate Model. The basic principle of this model [3] involves the use of a database of parameters (P_{r6}, M_t, and β), This database is available from the website of ITU's 3M Group. Each parameter is matched to a (latitude, longitude) pair. MATLAB scripts associated with the implementation of the model are available from the same website. These scripts simplify the calculation of the cumulative distribution function of rain rate. The user is only required to input the probability of exceedance value, and the latitude and longitude of the Earth station under analysis. The method to derive the rain rate exceeded for a given probability of the average year, and a given location is as follows [4].

Step 1. Extract the variables (P_{r6}, M_t, and β) for the four points closest in latitude (Lat) and longitude (Lon) to the geographical coordinates of the desired location. The latitude grid extends from $+90°$N to $-90°$S in steps of $1.125°$ steps; the longitude grid extends from $0°$ to $360°$ in steps of $1.125°$.

Step 2. From the values of P_{r6}, M_t, and β at the four grid points, obtain the values $P_{r6}(\text{Lat, Lon})$, $M_t(\text{Lat, Lon})$, and $\beta(\text{Lat, Lon})$ at the desired location by performing a bi-linear interpolation, as described in Recommendation ITU-R P.1144.

Step 3. Convert M_t and β to M_C and M_S as follows:

$$\begin{aligned} M_C &= \beta M_t, \\ M_S &= (1-\beta) M_t. \end{aligned} \tag{1}$$

Step 4. Derive the percentage probability of rain in an average year, P_0, from

$$\begin{aligned} &P_0(\text{Lat, Lon}) \\ &\quad = P_{r6}(\text{Lat, Lon}) \times \left(1 - e^{-0.0079(M_S(\text{Lat,Lon})/P_{r6}(\text{Lat,Lon}))}\right). \end{aligned} \tag{2}$$

If P_{r6} is equal to zero, the percentage probability of rain in an average year and the rainfall rate exceeded for any percentage of an average year are equal to zero. In this case, the following steps are unnecessary.

Step 5. Derive the rainfall rate, P_p, exceeded for p% of the average year, where $p \le P_0$, from

$$R_p(\text{Lat, Lon}) = \frac{-B + \sqrt{B^2 - 4AC}}{2A} \ [\text{mm/h}], \tag{3}$$

where

$$\begin{aligned} A &= ab, \\ B &= a + c\text{LN}\left(\frac{p}{P_0(\text{Lat, Lon})}\right), \\ C &= \text{LN}\left(\frac{p}{P_0(\text{Lat, Lon})}\right), \\ a &= 1.09, \\ b &= \frac{M_C(\text{Lat, Lon}) + M_S(\text{Lat, Lon})}{21797 P_0}, \\ c &= 26.02b. \end{aligned} \tag{4}$$

2.2. ITU-R P.618-9 Rain Attenuation Model. The ITU-R P.618-9 [5] rain attenuation model uses the rain rate at 0.01% probability level for attenuation estimation. This model has been derived on the basis of the log-normal distribution, and the point rain intensity and attenuation distribution generally conform to the log-normal distribution. Inhomogeneity in rain in the horizontal and vertical directions is accounted for in the prediction. This model is applicable across the 4–55 GHz frequency range and the 0.001–5% percentage probability range. The estimates of the long-term statistics of the slant-path rain attenuation at a given location for frequencies up to 55 GHz are obtained according to the procedure given below. The following parameters are used in this procedure [4]:

$R_{0.01}$: point rainfall rate for the location for 0.01% of an average year [mm/h],

h_S: height above mean sea level of the earth station [km],

θ: elevation angle [°],

φ: latitude of the earth station [°],

f: frequency [GHz],

R_e: effective radius of the Earth [8,500 km].

If the local data for the height above mean sea level of the earth station is not available, an estimate can be obtained from the maps of topographic altitudes given in Recommendation ITU-R P.1511.

Step 1. Determine the rain height, h_R, as given in Recommendation ITU-R P.839.

Step 2. For $\theta > 5°$, compute the slant path length, L_S, below the rain height using

$$L_S = \frac{(h_R - h_S)}{\sin\theta} \ [\text{km}]. \tag{5}$$

Step 3. Calculate the horizontal projection, L_G, of the slant path length using

$$L_G = L_S \cos\theta \ [\text{km}]. \tag{6}$$

Step 4. Obtain the rainfall rate, $R_{0.01}$, exceeded for 0.01% of an average year (with an integration time of 1 min). If this long-term statistic cannot be obtained from local data sources, an estimate can be obtained from the maps of rainfall rate given in Recommendation ITU-R P.837. If $R_{0.01}$ is equal to zero, the predicted rain attenuation is zero for any time percentage, and Step 5 need not be carried out.

Step 5. Obtain the specific attenuation, γ_R, using the frequency-dependent coefficients given in Recommendation ITU-R P.838 and the rainfall rate, $R_{0.01}$, determined from Step 4, using

$$\gamma_R = k(R_{0.01})^{\alpha} \ [\text{dB/km}]. \tag{7}$$

Step 6. Calculate the horizontal reduction factor, $r_{0.01}$, for 0.01% of the time

$$r_{0.01} = \frac{1}{1 + 0.78\sqrt{L_G \gamma_R / f} - 0.38(1 - e^{-2L_G})}. \tag{8}$$

Step 7. Calculate the vertical adjustment factor, $v_{0.01}$, for 0.01% of the time

$$\xi = \tan^{-1}\left(\frac{h_R - h_S}{L_G r_{0.01}}\right). \tag{9}$$

If $\xi > \theta$,

$$L_R = \frac{L_G r_{0.01}}{\cos\theta}\ [\text{km}]. \tag{10}$$

Else,

$$L_R = \left(\frac{h_R - h_S}{\sin\theta}\right)\ [\text{km}]. \tag{11}$$

If $|\varphi| < 36^\circ$,

$$\chi = 36^\circ - |\varphi|. \tag{12}$$

Else,

$$\chi = 0^\circ. \tag{13}$$

Therefore,

$$v_{0.01} = \frac{1}{1 + \sqrt{\sin\theta}\left[31\left(1 - e^{-(\theta/(1+\chi))}\right)\sqrt{L_R\gamma_R}/f^2 - 0.45\right]}. \tag{14}$$

Step 8. The effective path length is

$$L_E = L_R v_{0.01}\ [\text{km}]. \tag{15}$$

Step 9. The predicted attenuation exceeded for 0.01% of an average year is obtained using

$$A_{0.01} = \gamma_R L_E\ [\text{dB}]. \tag{16}$$

Step 10. The estimated attenuation to be exceeded for other percentages of an average year, in the range 0.001–5%, is determined from the attenuation to be exceeded for 0.01% for an average year.

If $p \geq 1\%$ or $|\varphi| \geq 36^\circ$,

$$\beta = 0. \tag{17}$$

If $p \geq 1\%$ or $|\varphi| < 36^\circ$ and $\theta \geq 25^\circ$,

$$\beta = -0.005(|\varphi| - 36^\circ). \tag{18}$$

Otherwise,

$$\beta = -0.005(|\varphi| - 36^\circ) + 1.8 - 4.25\sin\theta,$$

$$A_P = A_{0.01}\left(\frac{p}{0.01}\right)^{-(0.655+0.033\ln(p)-0.045\ln(A_{0.01})-\beta(1-p)\sin\theta)}\ [\text{dB}]. \tag{19}$$

3. Received Beacon Signal Level and Rain Rate

In this study, we selected Koreasat-3, which uses the Ku-band (14GHz/12GHz) frequency and analyzed the beacon signal level data according to the rain rate in 2001 [6] and 2007, respectively.

To measure the rain rate, we used the rain measurement system that was installed when the Yong-in Satellite Control Office was established. The controlling equipment of Koreasat-3 was used to measure the beacon signal level. Block diagrams for the two measurement systems are shown in Figures 1 and 2.

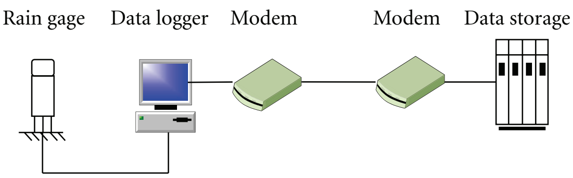

Figure 1: Experimental system used for measuring the rain rate.

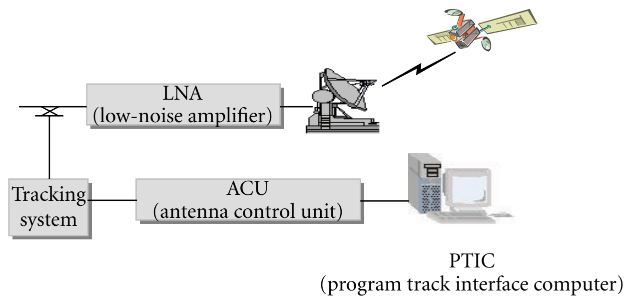

Figure 2: Experimental system used for measuring the beacon signal level.

As shown in Figure 1, the accumulated rain rate data is first collected in a data logger and then saved in a computer. The rain rate data may be saved in either 10-min or 10-s intervals. The rain rate data was collected in intervals of 10-s. The 1-min rain rate, $R_{1-\text{min.}}$ mm/h, can be computed by the following formula using the instantaneous rain rate measured via a rain gauge:

$$R_{1-\text{min.}} = \frac{1}{6}\sum_{S=0}^{5} R(10S)\ [\text{mm/h}], \tag{20}$$

where $R(10S)$ is the instantaneous rain rate measured by a rain gauge and sampled at 10-s intervals for a particular minute.

The experimental system shown in Figure 2 saves the received beacon signal level at 1-min intervals (Table 1).

A cassegrain antenna designed specifically for Koreasat-3 was used to receive the beacon signal. In order to compensate for the changes in the power level caused by perturbation of the transmission from the satellite, which is located in a geostationary orbit, a steptrack tracking system was used.

The amount of attenuation due to rain over the path was determined by measuring the deviation from the clear weather attenuation values at various rain rates recorded using a tipping bucket rain gauge, which usually provides a good approximation to the instantaneous rain rates.

4. Comparison of the Predicted and Measured Rain Attenuation

Figure 3 provides a comparison of the statistical results of the rain rate obtained using the ITU-R model and the measured rain rate; the rain rates obtained using the ITU-R P.837-5 model (predicted value) were lower than the rain

Table 1: Measurement and experimental specifications.

System location	Latitude (Yong-in)	37.43°N
	Longitude (Koreasat-3)	116°E
	Elevation angle	45.20°
	Azimuth angle	198.1°
	Sea level	0.142 [km]
Climate zone	ITU-R model	K zone
Down link	Polarization	Dual liner
	EIRP	34 [dBW]
	Frequency	12.25 [GHz]
Antenna	Type	Cassegrain
	Diameter	7.2 m (2001), 11 m (2007)
Rain gage	Type	Tipping bucket
	Size	Diameter 200 [mm]
	Resolution	0.5 [mm]
	Accuracy	Less than 5% (for rain rate of 10 mm/h)
	Operative temperature	−40°C to +50°C

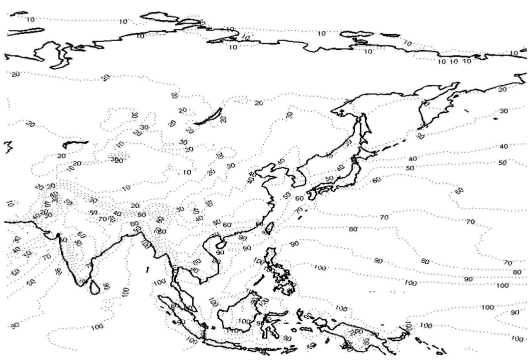

Figure 3: Rain rate (mm/h) exceeded for 0.01% of the average year, obtained using the ITU-R P.837-5.

rates obtained by the Electronic and Telecommunications Research Institute (ETRI) [7, 8] (measured value), except when the time percentage was 0.001%. The rainfall rate at 0.01% of the time, which is an important parameter to predict rain attenuation, is approximately 59 mm/h, as obtained by ETRI, and 50 mm/h, as suggested by the ITU-R P.837-5 model. This difference in the values indicates that the rain rates obtained using the ITU-R P.837-5 model do not fully reflect Korea's local rainfall characteristics. It has been reported that the climate changes from the temperate to the subtropical regions [9]. The Korea Meteorological Administration (KMI) analyzed the mean rainfall for the last 10 years (1998–2008) and the past 30 years (1971–2000) in 15 different regions in Korea and compared the two sets of values. They found a 9.1% increase compared to a normal year [10].

Thus, the ITU-R P.837-5 model gives erroneous rain rate distributions and rain attenuation values on radio links in Korea.

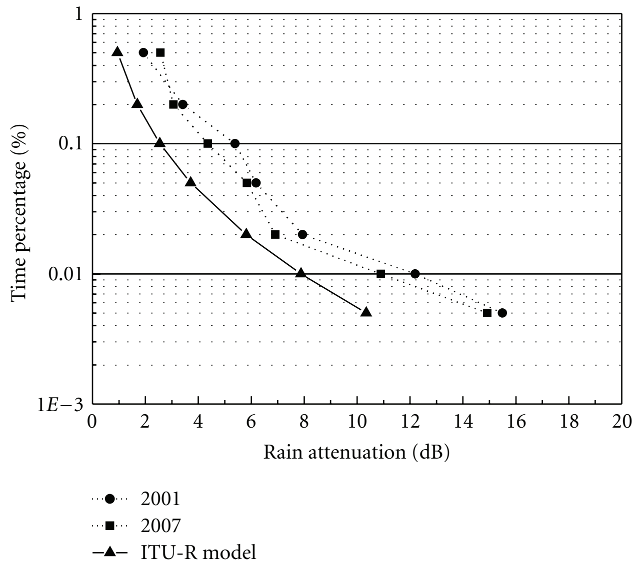

Figure 4: Predicted and measured rain attenuation cumulative distribution.

Figure 4 shows the actual rain attenuation measured for Koreasat-3 in 2001 and 2007 by the Yong-in Satellite Control Office. The rain attenuation in 2001 is similar to that in 2007. The rain attenuation values predicted by the ITU-R model were found to be lower than the actual values. At low rainfall rates, the difference between the predicted and actual values was greater.

The cumulative distribution function obtained from the rain rate and the attenuation dataset was compared with the predicted function obtained from various earth-space path prediction models, both physical and empirical. The ITU-R testing variable was used as the error metric; this variable is defined in Recommendation ITU-R P.311-11 [11] as

$$V_i = \mathrm{LN}\left(\frac{A_p}{A_m}\right) \times \left(\frac{A_m}{10}\right)^2 \quad \text{for } A_m < 10 \text{ [dB]},$$
$$V_i = LN\left(\frac{A_p}{A_m}\right) \quad \text{for other cases,} \tag{21}$$

where A_p is the attenuation predicted using an ITU-R method and A_m is the attenuation estimated from the measured data (both in decibels).

The model under test was ranked according to the RMS of the error. The RMS is estimated by using the formula given below:

$$\mathrm{RMS} = \sqrt{\mathrm{Mean}^2 + \mathrm{St.Dev}^2}. \tag{22}$$

The evolution of error is defined as

$$E = \frac{A_p - A_m}{A_m}. \tag{23}$$

The error variables between the experimental and estimated cumulative distributions are presented in Table 2.

The error between the ITU-R model prediction and the actual value for 2001 obtained from (23) varies considerably,

Table 2: Error, mean, standard deviation, and % RMS for each of the measured with respect to time percentage.

	Percentage error between the measured and the existing model for rain attenuation							Mean	Std.	% RMS
% Time	0.005	0.01	0.02	0.05	0.1	0.2	0.5			
2001	−0.33	−0.35	−0.27	−0.40	−0.53	−0.50	−0.51	−0.41	0.10	43
2007	−0.31	−0.28	−0.16	−0.36	−0.42	−0.45	−0.63	−0.37	0.15	40

the minimum value of 0.27 and the maximum value of 0.53. The error between the ITU-R model prediction and the actual value for 2007 obtained from (23) also varies considerably, the minimum values of 0.16 and the maximum values of 0.63. Furthermore, the ITU-R model prediction shows a large difference from the actual value in RMS percentage with 43% and 40% in 2001 and 2007, respectively.

From Figure 4 and Table 2, we can observe that there is a large difference between the predicted value and the actual value of rain attenuation. This is because the ITU-R Rec. 618-9 model first obtains the rain rate ($R_{0.01}$) for time percentage of 0.01% and then extends it to the whole time percentage. Although it is necessary to obtain the exact rain rate ($R_{0.01}$) for a time percentage of 0.01% to predict rain attenuation, the rain rate obtained using the ITU-R model did not reflect Korea's local rainfall characteristics, as shown in Figure 3.

5. Conclusion

The rain attenuation in the 12.25 GHz band was measured for two years—2001 and 2007. The statistical characteristics of the measured data are presented in this study. The measured rain attenuation in the 12.25 GHz band in Yong-in was compared with the rain rates predicted by the ITU-R model. The main results and conclusions of this study can be summarized as follows.

(1) The rain rates obtained using the ITU-R P.837-4 model were lower than those measured by the Electronic and Telecommunications Research Institute (ETRI) [7, 8], except for a time percentage of 0.001%; moreover, the predicted rain rates did not reflect Korea's local rainfall characteristics.

(2) The rain attenuation values predicted by the ITU-R model were lower than the actual values, and the difference was greater at lower time percentages.

(3) The ITU-R model prediction was considerably different from the actual value in RMS percentage with 49% and 47% in 2001 and 2007, respectively.

The current results will serve as good tools for satellite system designers in improving communication satellite systems in Korea.

Acknowledgment

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