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Investigation of accuracy of rain-rate and rain-attenuation prediction models in satellite communications based on meteorological skills

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सार – वर्षा मुख्य विनाशक घटक हैं जो उपग्रह संचार के प्रसारित संकेतकों की गुणवक्ता एवं विश्वसनीयता को बुरी तरह प्रभावित करती है। इसलिए वर्षा क्षीणन अनुमान उपग्रह रेडियो संपर्क योजना एवं इंजीनियरिंग में व्यापक भूमिका अदा करता है। वर्षा क्षीणन अनुमान मॉडल की सटीकता दो बातों पर निर्भर करती है। (*i*) वर्षा दर सूचना की सटीकता और (*ii*) अध्ययन का क्षेत्र। अत: बिना किसी विशेष अनुमान मॉडल और प्रयोगात्मक नापी गई वर्षा दर एक नए स्थल के लिए उचित वर्षा क्षीणन अनुमान मॉडल चुनना चुनौती भरा होगा। इस संबंध में, यह शोध पत्र इस तरह के क्षेत्रों के लिए सटीक मॉडल का पता लगाने में जलवायु विज्ञान कौशल के लिए लाभप्रद है। ऐसा करने से हमने उर्मिया स्थल (37.55° उ., 45.1° पूर्व) और इसके यूटेलसैट 25A (25.5° पूर्व) के साथ संचार सम्पर्क का अध्ययन करते हैं जहाँ प्रयोगात्मक रूप से मापा हुआ आँकड़ा और उस स्थल के लिए विशेष अनुमान मॉडल उपलब्ध नहीं है। इसलिए मौसम विज्ञान जानकारी पर आधारित दक्षिणी कोरिया में (37.43° उ., 126.93° पूर्व) योंग-इन स्थल चुना गया था जो उर्मिया के समान जैसा क्षेत्र है जिसका वर्षा का और वर्षा क्षीणन का आँकड़ा उपलब्ध है। इसके बाद योंग-इन पर अधिकतम सामान्य प्रयोग किया हुआ विश्व अनुमान मॉडल का अनुप्रयोग किया गया है और परिणामों की वर्तमान मापों से तुलना की गई है। परिणाम स्वरूप अधिक सटीक वर्षा दर और वर्षा क्षीणन अनुमान मॉडलों का निरीक्षण किया गया। तथा उर्मिया के लिए समान माना गया है जो क्रमश: 34% मूल माध्य वर्ग के साथ ITU-RP.837-5 मॉडल और 18% मूल माध्य वर्ग के साथ जू-हवान मॉडल हैं। अंत में जू-हवान मॉडल द्वारा उर्मिया के लिए विभिन्न उपयुक्त आवृत्ति बैंड (10-50 GHz) में वर्षा क्षीणन की राशि का निरीक्षण किया गया है।

ABSTRACT. Rainfall is a major destructive factor which severely reduces the quality and reliability of propagated signals in satellite communications. Hence, rain-attenuation prediction plays a vital role in the satellite radio link planning and engineering. The accuracy of the rain-attenuation prediction models depends on two things; (*i*) the accuracy of rain-rate information and (*ii*) the area of study. Therefore, selecting an appropriate rain-attenuation prediction model for a new site without having any specific prediction model and experimental measured rain-rate would be challenging. In this regard, this letter takes advantage of climatology skills to find an accurate model for such kind of areas. To do so, we study the Urmia-site (37.55° N, 45.1° E) and its communication link with the Eutelsat 25A (25.5° E), where there is no available experimental measured data and specific prediction models for that site. Therefore, based on the meteorological skills, the Yong-in site in South-Korea (37.43° N, 126.93° E) was chosen, as a homogeneous area with Urmia, which has available measured data of rainfall and rain-attenuation. Afterward, the most common used global prediction models are applied to Yong-in and the results are compared with the existing measurements. Consequently, the more accurate rain-rate and rain-attenuation prediction models are investigated and generalized to Urmia, which are the ITU-R P.837-5 model with 34% r.m.s. and the Joo-Hwan model with 18% r.m.s., respectively. Finally, the amount of rain-attenuation in different useful frequency bands (10-50 GHz) is investigated for Urmia by the Joo-Hwan model.

Key words – Rain- rate model, rain-attenuation prediction models.

1. Introduction

In wireless communications, the system performance greatly depends on the characteristics of the channel on which the transmitted signal is propagated. Based on the nature of wireless channels, characteristics are random and, particularly in millimetre-wave communications, vary with destructive factors such as rain, cloud, fog, vapour and oxygen. Among the aforementioned parameters, rain makes the most severe attenuation in frequency bands over 10 GHz, where, for wavelengths smaller than one millimetre, raindrops absorb, scatter and attenuate electromagnetic waves and consequently reduce the system availability and reliability (Crane, 2003). The destructive impact of rainfall increases as the carrier-frequency increases.

Therefore, to design a microwave space-to-earth link utilization of an accurate prediction model, for estimating the amount of rain-attenuation, is vital. To develop a prediction model, information such as precise knowledge of system, experimental data (*i.e.*, for each elevation, location and frequency), climatic statistics (*i.e.*, maximum and minimum average monthly temperature), amount of yearly rain rate and humidity are required. Moreover, some of the climatic characteristics (e.g., raindrop size and shape, orientation and temperature) vary with time and space. Therefore, due to infeasibility of measuring the required data for all locations around the world, developing specific prediction models for all the locations is also impossible. Nevertheless, it has been recently proved in Efstathiou *et al*., 2011 and Varotsos *et al*., 2012 that many climatic parameters exhibit long-range power law correlations in their time evolution, which can lead researchers to develop more accurate prediction models. Hence, some countries, such as United States, Canada and Japan, which are leading the satellite industry, developed their own rain attenuation models. On the other hand, some prediction models are introduced for global usage, such as the Crane Global model (Crane, 1982) and the International Telecommunication Union Radio Communication Sector (ITU-R) model (ITU-R, 2007). However, the global models do not have sufficient accuracy for some locations around the world. Therefore, some authors modified the global models (*i.e.*, ITU-R) to improve the accuracy of prediction for specific regions, such as Mandeep *et al*. (2011) for equatorial climate and Choi (2006) for South-Korea.

Since the amount of rain-attenuation is derived from the available or predicted information of rain-rate, the accuracy of rain-attenuation prediction models depend on the rainfall statistics in the considered geographical area. Therefore, knowledge of rainfall statistics is vital and should be used as a 1-min rain-rate cumulative distribution. In order to measure the 1-min rain-rate, accurate knowledge of rain parameters, such as raindrop size, orientation and temperature, is required. However, when the aforementioned data are not available, a statistical rain-rate prediction model should be utilized (Crane, 2003). Various global rain-rate prediction models are available, as applied in this study, such as Crane (2003), ITU-R (2007), Rice and Holmberg (1973), Moupfouma (1993) and Ito and Hosoya (1999).

Therefore, in the absence of a specific prediction model for an area of study, finding an accurate prediction model is always challenging. Conventionally, to find the most accurate prediction model, researchers investigate the accuracy of predictions models by comparing available models with the measured data (rain-rate and rain-attenuation) of the geographical area of study (Ojo *et al*., 2008; Nalinggam *et al*., 2011; Mandeep *et al*., 2008; Mandeep, 2009). At this stage, there is a question; is there an alternative optimal solution to find an accurate prediction model in the absence of measured data?

To answer the question, in this study, we use the meteorological skills in Lotfi-Neyestanak (2011) to find the most accurate prediction models (rain-rate and rain-attenuation) for our geographic area of study, which is Urmia in northwest Iran (37.55° N and 45.1° E). To investigate the amount of attenuation arisen by rain in space-to-earth link in Urmia, no information is available regarding the 1-min rain-rate and experimental result of rain-attenuation. Therefore, we use climatology skills to find a homogeneous site (H-site) with similar climatic statistics to Urmia, where experimental measurements of rain-rate and rain-attenuation are available. Then, by comparing the prediction models with the existing measured values of the H-site, the most precise prediction model can be recognized and then the results can be generalized to the Urmia-site. However, to find a homogeneous area, long-term climate information of both sites has to be available. Hence, we used the past 50 years of Urmia's climate data and, based on climatology skills, we found Yong-in in South-Korea (37.43° N and 126.93° E) as the most homogeneous area (H-site) which uses the Koreasat-3 satellite (116° E) in Ku-band and all the required measured data are available. After investigating the most accurate prediction method for the Yong-in site, the results are generalized to Urmia and finally the amount of rain-attenuation in different useful frequency bands (10-50 GHz) is investigated for Urmia. Simulation results for Urmia are based on the communication link between the earth-station (37.55° N and 45.1° E) and the Eutelsat-25A satellite (25.5° E) that operates in the Ku-band (12-14 GHz).

The rest of the paper is organized as follows. Section 2 presents an overview of various rain-rate and rain-attenuation prediction models. Section 3 contains an explanation of methods and tools used in this study. After that, the results and observations are discussed in Section 4. Finally, in Section 5, the conclusions are summarized.

TABLE 1

Five considered rain-rate prediction models

Model	Notes
ITU-R P.837-5	Global model based on 15 years of numerical model analysis data by ECMWF
Crane	Based on meteorological observation from weather stations in US and some stations through the world
Rice-Holmberg	Based on the local climatological data
Moupfouma	Analytical method, estimates gamma and log-normal distribution at high and low rain-rate
Chieko	Empirical method, made at KIT, Japan

2. Overview of rain-rate and rain-attenuation prediction models

2.1. *Rain- rate model*

To consider the attenuation caused by rain on the terrestrial and satellite links, accurate knowledge of rainfall statistics for the desired location, as the major input, is required. Therefore, the International Telecommunication Union (ITU) recommends the use of a 1-min integration rain-rate cumulative distribution function (CDF). On one hand, meteorological organizations use long periods of observation of rain intensity and they are not interested in observing rapid changes. Also, for many regions, even high-integration rain-rate data is not available. On the other hand, to compute the 1-min rain-rate, information about rain structure, such as raindrop size, shape, orientation and temperature, is required and this information should be observed for a long time (Crane, 2003). Therefore, it is not feasible to measure 1-min integration time for all locations in the world. This fact leads research towards developing global or regional rain rate prediction models. The existing rain-rate prediction models can be categorized into three groups (Capsoni and Luini, 2008):

(*i*) *Meteorological methods*, which are based on the climatic statistics, such as annual or monthly precipitation, average number of rainy days and peak annual rain rate.

(*ii*) *Analytical methods*, which are based on the prediction of change of CDF parameters in different integration times.

(*iii*) *Empirical methods*, which are based on the long-term local data observation and attempt to provide a regional coefficient for conversion factors between known CDF and the one to be estimated.

The following subsections present five different rain-rate distribution prediction models which were considered in this paper, as listed in Table 1.

2.1.1. *ITU-R model P.837-5*

This recommendation is a new global rain-rate prediction model which provides 1-min integration time from higher integration time and is exceeded for any given percentage of the average year. The proposed model is based on the latest revised maps by the European Centre for Medium-Range Weather Forecasts (ECMWF), ERA-40 project. Accordingly, the regression coefficients used in ITU-R P.837-5 (ITU-R, 2007) are more optimized compared to the previous ITU-R recommendations. The disadvantage of this model is that the model cannot generate monthly statistics because of a lack of available monthly empirical statistics. Therefore, the model only provides an annual prediction (Crane, 2003).

The rainfall rate, R_P, exceeded for $p\%$ of the average year can be derive as follow:

$$R_P = \frac{-B+\sqrt{B^2-4AC}}{2A} \quad \text{mm/h} \tag{1}$$

and

$$\begin{aligned} A &= M_T/(2\times 10^4 \times P_0) \\ B &= 1.09 + [M_T/(838\times P_0)] \times \ln(p/P_0) \\ C &= \ln(p/P_0) \\ P_0 &= P_{r6}(1-e^{-0.0079(M_S/P_{r6})}) \end{aligned} \tag{2}$$

where, $M_S = (1-\beta)M_T$ and P_{r6}, M_T and β are the numerical variables based on the latitude and longitude of the geographical area of study, which can be found in (ITU-R, 2007).

2.1.2. *Crane model*

The Crane model is completely based on the meteorological observations which are gathered from first

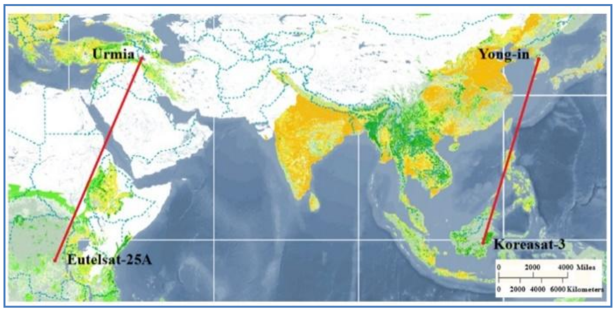

Fig. 1. Position of the satellites relative to the selected earth-stations (WRI, 2010)

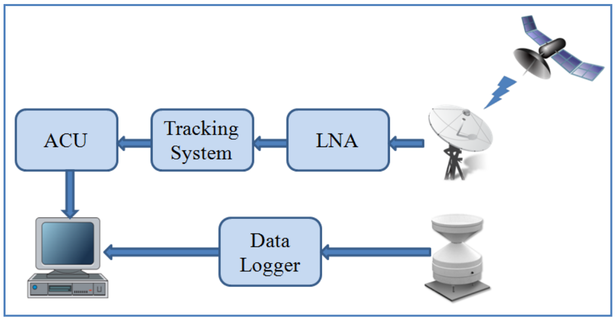

Fig. 2. The experimental block setup used for measuring the rainfall and beacon signal level at Yong-in Satellite Control Office

order weather stations in the United States and some limited stations through the rest of world. It provides median distribution estimates for broad geographical regions. The proposed method classifies the world into eight geographic rain climate regions (A through H) and estimates the instantaneous point rain rate distribution for each region. The presented climate regions are very broad and can cause uncertainty in the prediction value, where meteorological statistics are required in order to improve accuracy. Therefore, the Crane method is further expanded for the United States, Canada and Europe and subdivides the climate regions B and D (Crane, 1980).

The Crane model is approximated by (Crane, 2003):

$$P(r \geq R) \approx P_V(r \geq R) + P_W(r \geq R) \tag{3}$$

where, it is a combination of two rain-rate distributions; (*i*) P_V, that is an exponential distribution to describe the contributions of small or volume cells and (*ii*) P_W, which is a log-normal distribution to describe the rates produced in the rain debris region surrounding the small cell. Therefore,

$$P_V(r \geq R) = 4.585 R_C^{-0.004} E_1\left(\frac{R}{R_C}\right) \approx P_C e^{-\frac{R}{R_C}} \tag{4}$$

$$P_W(r \geq R) = P_D Q\left(\frac{\ln R - \ln R_D}{S_D}\right)$$

where, Q is the upper tail of the normal distribution and P_C, R_C, P_D, R_D and S_D are distribution parameters (can be found in Crane, 2003) and E_1 is the exponential integral of order 1.

2.1.3. *Rice-Holmberg model*

The RH model uses the physical analysis of thunderstorms and monthly and annual rain accumulation to determine the rainfall statistical model. Local climatological data are needed to determine the model input parameters, such as mean annual precipitation and ratio of thunderstorm to total rain rate. However, this model is uncertain in rain rate distribution between 0.001 and 0.1 percentage of the year.

The percentage of an average year during which t-min average rainfall rates exceed R mm/h can be calculated as:

$$T_1(R) = M\{0.03\beta e^{-0.03R} + 0.2(1-\beta)[e^{-0.258R} + 1.86 e^{-1.63R}]\}/87.66 \tag{5}$$

where, M and β are regional coefficients (depends to the latitude and longitude of the geographical area of study) which can be found in the Figs. 2 and 3 of Rice and Holmberg, (1973), respectively.

2.1.4. *Moupfouma model*

The Moupfouma model adopts the prediction model proposed by the International Radio Consultative Committee (CCIR), which estimates a gamma distribution at high rain rates and a log-normal distribution at low rain rates. This model predicts the whole rain cumulative distribution from the available rain rate exceed for 0.01 percentage of time. Determination of the slope of rain cumulative distribution is based on the use of local climatological data and geographical conditions. This model expressed the parameter of the slope of rain rate distribution for tropical and temperate zones. However, this model is uncertain for regions which are not tropical or temperate. The cumulative distribution of rain-rate is presented as Moupfouma (1993):

$$P(R \geq r) = \left(\frac{R_{0.01} + 1}{r + 1}\right)^b \times e^{[u \times (R_{0.01} - r)] - ln(10^4)} \tag{6}$$

$$b = \left(\frac{r - R_{0.01}}{R_{0.01}}\right) \times ln\left(1 + \frac{r}{R_{0.01}}\right) \tag{7}$$

TABLE 2

Six considered rain-attenuation prediction models

Model	Notes
ITU-R	ITU-R Rec. P.618-9 2007
Karasawa	ITU-R model enhanced for lower availabilities
Two-Component	Mathematically intensive. Consider cell & Debris
Joo-Hwan	Modified version of ITU-R for South-Korea
Brazil	Enhanced model of ITU-R for tropical areas
Garcia-Lopez	A simple method optimized for intense rain

TABLE 3

System specifications

Earth-station	Yong-in	Urmia
Latitude	37.43° N	37.55° N
Longitude	126.93° E	45.1° E
Elevation angle	45.20°	41.86°
Azimuth angle	198.1°	210.3°
Altitude	0.142 km	1.330 km
Satellite longitude	116° E	25.5° E
Downlink frequency	12.25 GHz	12.25 GHz

where, $R_{0.01}$ is the rain-rate value exceed for 0.01 percentage of time and parameter u depends on the climatic conditions and geographical features, as Moupfouma (1993);

For temperate zones:

$$u = \frac{\log_e(10)^4}{R_{0.01}} \times \frac{1}{[5.56 \times (\frac{r}{R_{0.01}})^{1.03}]} \tag{8}$$

For tropical zones:

$$u = \frac{\log_e(10^4)}{R_{0.01}} \times e^{-0.228\times(r/R_{0.01})} \tag{9}$$

2.1.5. *Chieko model*

This method uses the regional climatic parameters made by the Kitami Institute of Technology (KIT), Japan to develop the global rain rate prediction method for 1-min rain rate distribution based on the thunderstorm ration proposed by Rice and Holmberg. The thunderstorm ration is an important regional climatic parameter that has a large effect on global rainfall prediction models. Therefore the rain-rate distribution is as follows (Ito and Hosoya, 1999);

$$R_P = a_P M^{b_P} \beta^{c_P} \tag{10}$$

where, $M$and β are fixed for desired location as given in the (Rice and Holmberg, 1973) and coefficients a_P, b_P and c_P are determined by multiple regression analyses, which are available in the (Ito and Hosoya, 1999).

2.2. *Rain attenuation model*

Rain significantly attenuates electromagnetic waves on the frequency-bands above 10 GHz. Therefore, to design a reliable satellite-link, rain-attenuation prediction models have been developed. The existing prediction models can be categorized into two classes: (*i*) The empirical method which is based on the available database of rain-rate and path-attenuation in different sites and (*ii*) The physical method which is based on statistical information of the rain occurrence and rain-scattering to reproduce the physical behaviour related to the attenuation process. However all the needed parameters as input for the physical method are not available, therefore the empirical method is the most used methodology (Crane, 2003). Empirical models can also be categorized into two groups: the first group is like the ITU-R model which calculates the attenuation distribution for all time percentages from 0.01% values and the second group predicts the attenuation based on the full rainfall rate distribution like the Two-component model (Feldhake and Ailes-Sengers, 2002; Choi and Park, 2007). This Subsection, briefly reviews six types of rain-attenuation prediction models which are widely utilized in satellite communication systems, as listed in Table 2.

2.2.1. *ITU-R model*

The objective of the ITU-R model is to provide a worldwide prediction model for a broad range of elevation angels, frequency bands and rain-climates. The ITU-R REC-P.618-9 (ITU-R, 2007) is the latest model that is improved by amending path characteristics and adjusting the computations across a broader range of availabilities. The performance of this model depends highly on the rainfall intensity, rain height and slant-path length. On the other hand, the rain characteristics vary over time and space, therefore the accuracy of prediction for some regions of the world is not sufficient. However, this model is flexible to adjust for regional prediction models.

The ITU-R model uses the following equation to estimate the long-term statistics of the slant-path rain attenuation at different percentage of time,

$$A_P(i) = k \times R(i)^{\alpha} \times L_s \times \eta(i) \quad [\text{dB}] \qquad (11)$$

where, k and α are frequency-dependent coefficients which are available in (ITU-R, 2005) and $R(i)$ is 1-min rain-rate i yearly time percentage and $\eta(i)$ is the slant path length adjustment factor and can be calculated as the following formula;

$$\eta(i) = (\frac{R_{0.01}}{R(i)})^{\alpha} \times \eta_{0.01} \times (\frac{i}{0.01})^{-\lambda} \qquad (12)$$

where,

$$\lambda = 0.655 + 0.033 \times \ln(i) - 0.045 \times \ln(A_{0.01}) - \beta(1-i) \times \sin\theta \qquad (13)$$

$$\beta = -0.005(|\varphi| - 36)$$

where, φ is latitude of the earth-station and $\eta_{0.01}$ is the reduction factor, which can be calculated from ITU-R P.618-9 (ITU-R, 2007). L_s is the actual slant path length as follows;

$$L_s = \frac{hr - h_s}{\sin\theta} \quad [\text{km}] \qquad (14)$$

where, h_s is the high above mean sea level of the earth station, θ is the elevation angle and h_r is the rain-high. To determine the h_r several methods are proposed but some of them are not accurate enough for all regions. Therefore, in this study, rain-height is calculated from the following formula, proposed by Satoh, 1983. This model was developed for Japan based on the local annual average rain height and can be generalized to South-Korea due to similar climatic,

$$h_r = 3.66 + 0.14 \times L - 0.00342 \times L^2 \quad [km] \qquad (15)$$

where, L is the latitude of the earth-station.

2.2.2. *Two-Component model*

The Two-Component model is an extension of the Crane Global model, which was developed by Crane in 1982 to include an empirical approach based on the statistical models and available measured path attenuation data. This model proposes a technique in which the effects of surrounding debris and isolated cells can be computed individually (Crane, 1982). Therefore, the total rain-distribution function is given by:

$$P(r \geq R) = \underset{\underset{\substack{\text{Volume cell}\\\text{(exponential)}}}{\Uparrow}}{P_C e^{-(R/R_C)}} + \underset{\underset{\substack{\text{Debris}\\\text{(log-normal)}}}{\Uparrow}}{P_D N[(\ln R - \ln R_D)/\sigma_D]} \qquad (16)$$

where, $P(r \geq R)$ is the probability that the observed rain-rate exceeds the specified rain-rate R, N is the normal probability distribution function, P_C is the probability of a cell, R_C is the average cell rain-rate, P_D is the probability of debris, R_D is the average rain-rate in the debris and σ_D is the standard deviation of the natural log of the rain rate.

2.2.3. *Joo-Hwan model*

The ITU-R model presents a worldwide method to predict attenuation due to precipitation but does not have sufficient accuracy for some parts of the world. Therefore, to improve the accuracy of prediction for the South-Korea region, Lee *et al.* (2000) modified the ITU-R model by dividing the slant path length adjustment factor into horizontal, F_h and vertical, F_v path components,

$$F_s = F_h cos^2\theta \times F_v sin^2\theta$$

$$F_h = \frac{1}{1 + 0.025857 \times L_g \times e^{0.015R}} \qquad (17)$$

$$F_v = 0.703 + 0.24e^{-0.039R} \qquad \text{(for } \leq 60 \text{ mm/h)}$$

$$F_v = 0.714 + 0.13e^{0.04(R-60)} \qquad \text{(for } > 60 \text{ mm/h)}$$

where, R is the 1-min rain-rate and L_g is the horizontal projection.

2.2.4. *Karasawa model*

The Karasawa or Japan model is a refinement of the ITU-R model which improves the prediction accuracy at lower system availability levels (Feldhake and Ailes-Sengers, 2002). In this method the rain-attenuation, A_s can be calculated as follows:

$$A_s = 10^{m+sq(p)} \qquad 0.01 \leq p \leq 1$$

$$A_s = A_{0.01} - 1.74s10^{m+3.1s}(\log_{10} p + 2) \qquad 0.01 \leq p \leq 0.01 \qquad (18)$$

where;

$$q(x) = 2.33 - 0.847x - 0.144x^2 - 0.0657x^3$$

$$x = 1 + \log_{10} p$$

$$m = 4.031 \log_{10} A_{0.1} - 3.03 \log_{10} A_{0.01} \qquad (19)$$

$$s = 1.30 \log_{10}(A_{0.01}/A_{0.1})$$

where, $A_{0.1}$ and $A_{0.01}$ are the predicted attenuation exceeded for 0.1% and 0.01% of an average year, respectively.

2.2.5. *Brazil model*

This method maintains the concept of the ITU-R model and is enhanced for tropical regions by proposing the new methods to calculate the length L_{R_0} and height H_r at the time percentage, *p*:

$$L_{R_0}(R_p, p) = 200\left[1 + R_p^{(0.425-0.089\log p)^{-1}}\right] \qquad (20)$$

$$H_r(R_p, p) = (3.849 + 0.334\log p)\,[1+\exp(-0.2\,R_p)] \qquad (21)$$

where, R_p is the rain-rate exceeded at p percentage of time.

2.2.6. *Garcia-Lopez model*

This method is an extension of the terrestrial model, which is proposed in (ITU-R, 2007). It is a simple method which is optimized for intense rain and the rain-attenuation A_s can be obtained as follows,

$$A_s = kR_p{}^{\alpha}L_s/\{\text{a} + [L_s(\text{b}R + \text{c}L_s + \text{d})/e]\} \qquad (22)$$

where, a, b, c and d are constant coefficients based on the geographical area, k is frequency-dependent coefficient which can be found in (ITU-R, 2005) and e is scaling factor, which are available in Fiser, 2006.

3. Methodology

The main goal behind the study is to investigate the amount of attenuation caused by rain at the Urmia-site, in northwest Iran. Nevertheless, due to the lack of required data and specific rain-attenuation prediction models for Urmia, this study uses meteorological skills to find a homogeneous area (H-site) with available measured data of rain-rate and rain-attenuation.

Based on meteorological science, world climate can be categorized into two general groups; the first group divides the world into seven subgroups based on the average, minimum and maximum monthly temperature and difference between minimum and maximum monthly temperature and the second group divides the world into four subgroups according to the amount of yearly precipitation and annual temperature. The full description of categorizations can be found in Section II of (Lotfi-Neyestanak *et al*., 2011). Hence, long-term climatic information of the desired site has to be available. In this regard, we used the climatic information of Urmia over past-50-years (IRIMO, 2006) and then, based on the world climate classification in (Lotfi-Neyestanak *et al*., 2011), we searched among the previous published research works to find a site that fulfils two criteria; (*i*) to be homogeneous with Urmia and (*ii*) to have available experimental measurements of rain-rate and rain-attenuation data. As the results of Section 4. A show, the most homogeneous area with Urmia is Yong-in in South Korea.

The general system parameters that are used to investigate the rain-rate and rain-attenuation of selected homogeneous areas are listed in Table 3. Fig. 1 illustrates the location of geostationary satellites which were considered in this study.

In order to analyse the rain-rate and rain-attenuation prediction models, the measured data of Yong-in site is required as a reference. Therefore, this study uses the 1-min rain-rate for different percentages of time which were measured by the Electronic and Telecommunications Research Institute (ETRI) from 1984 to 1993 (ETRI, 1996).

TABLE 4

Monthly amount of mean rain rate and average temperature of Urmia (1964-2014) and Yong-in (1984-1993)

Parameter	Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max. Temp.	Urmia	2.6	4.8	10.4	16.8	22.2	27.5	31.2	31	27.1	20.1	12.2	5.7
	Yong-in	0.4	3.3	9.8	17.9	24.1	27.1	29.3	30.3	26.4	19.9	11.5	3.4
Min. Temp.	Urmia	-6.1	-4.8	-0.1	5.2	9.1	12.9	16.6	15.9	11.5	6.6	1.4	-3.2
	Yong-in	-7.1	-3.8	0.4	7.6	12.8	17.8	22.2	23.2	17	9.8	2.4	-4.2
Avg. Temp.	Urmia	-1.8	0	5.1	11	15.7	20.2	23.9	23.5	19.3	13.4	6.8	1.2
	Yong-in	-3.4	-0.3	5.1	12.7	18.4	22.4	24.8	26.7	21.7	14.8	6.9	-0.4
Pre-cipitation	Urmia	30.2	33.2	52.3	62	45.6	14.2	5.5	2.1	4.4	21.8	40	29.7
	Yong-in	22.5	25	47.5	95	92.5	135	370	295	170	50	52.5	22.5

TABLE 5

Mean error, standard deviation and r.m.s. of different rain-rate prediction models for Yong-in

Model	Mean	St. Dev	r.m.s. (%)
Crane	0.0192	0.3630	36.35
ITU-R	0.0514	0.3362	34.01
R.H	-0.173	0.4807	51.08
Moupfouma	-0.4915	0.0595	49.51
Chieko	-0.2486	0.4056	47.57

On the other hand, Choi (2005) observed the rain-attenuation on the Koreasat-3 at Ku-band (12.25 GHz) at the Yong-in Satellite Control Office, South-Korea, during the rainy wet season from June to August 2001. Fig. 2 shows the block diagram of rainfall and beacon signal level measurement systems which were used in Choi's measurements. As illustrated in Fig. 2, an Optical Rain Gauge (ORG) collected the rain-rate data and saved it into a computer. The data can be saved in 10-second or 10-minute intervals. As the accuracy of 10-minute intervals is not sufficient for the assessment of satellite rain-attenuation, the 10-second interval was used. The collected data of rainfall in 10-second intervals was used as an input to the simulator to transfer to 1-min rain-rate, $\mathrm{R}_{1-\mathrm{min}}$ by the following equation:

$$\mathrm{R}_{1-\mathrm{min}} = \frac{1}{6}\sum_{S=0}^{5}\mathrm{R}(10S) \qquad [\mathrm{mm/h}] \qquad (23)$$

where, $\mathrm{R}(10S)$ is the instantaneously measured rain-rate by ORG at a 10-second interval.

As illustrated in Fig. 2, a cassegrain antenna of 7.2 meter in diameter, a dual linear polarization and a receive gain of 56.2 dBi (at 11.7 GHz) (which was specifically designed for Koreasat-3) were used to receive the beacon signal. A Low Noise Amplifier (LNA) was installed to the front of the antenna which transmits the Intermediate Frequency (IF) signal to a Tracking system. A step-track system was used to compensate the altering of signal levels due to perturbation of the transmitted signal from the geostationary satellite. In the next step, an Antenna Control Unit (ACU) measures the changes in the received signal power and finally the received signal level saved at 1-minute intervals. To obtain the rain-attenuation, author measured and recorded the received beacon signal level in a clear sky condition as a reference level and subtracted this value from the observed beacon signal level during different recorded rainfall events.

The following section applies the aforementioned prediction models (in Section 2) to Yong-in, investigates the accuracy of each method based on the available measured values of Yong-in and then generalizes the results to Urmia.

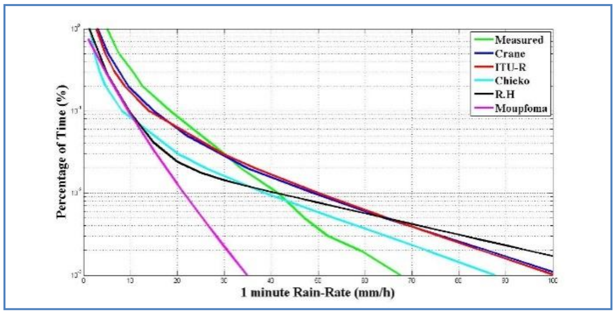

Fig. 3. Empirical 1-min rain-rate in Yong-in and rain-rate prediction models

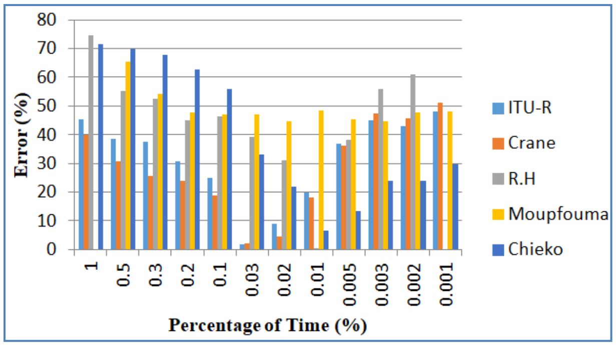

Fig. 4 Percentage of Error in different time percentages

4. Results and discussion

4.1. *Homogeneous meteorological areas*

Table 4 represents the long-term meteorological statistics of Urmia and Yong-in. By considering the information about the temperature and based on the *first climatic classification* in (Lotfi-Neyestanak *et al.*, 2011), both sites are in the category of "warm extreme", where (*i*) the average temperature of one month is at least more than 13.8 °C, (*ii*) the average temperature of one month is at least less than 4.4 °C and (*iii*) the difference between the larger and the lower average temperature is more than 27.8 °C. Moreover, considering the information about precipitations and the *second climatic classification* in (Lotfi-Neyestanak *et al.*, 2011), both sites are in the category of "moderate rainy", where the effectiveness of rain is a parameter of temperature.

4.2. *Comparison of rain-rate prediction models*

This Subsection investigates the accuracy of all aforementioned rain-rate prediction models in Section 2.A. The results of Fig. 3 show the predicted value of rain-rate by the five models, as well as the experimental value of the 1-min rain-rate for different percentages of time for the Yong-in site. The errors between the predicted and the measured value of rain-rate are calculated in terms of root-mean-square (r.m.s.), as,

$$\mathrm{e_{rms}} = \sqrt{\mathrm{Mean}^2 + \mathrm{St.Dev}^2} \tag{24}$$

where, Mean is the mean error and St. Dev is the standard deviation. Moreover, the percentage of errors is calculated as,

$$E = \frac{(A_p - A_m)}{A_m} \times 100 \tag{25}$$

where, A_p and A_m are predicted and measured values, respectively.

Based on the results of Fig. 3 and (Fiser, 2006), the percentage of error in different percentages of time for all five models is presented in Fig. 4.

According to the results, there is a large difference between the Moupfouma model and the experimental result, with the mean error of around 50%. That is because, Moupfouma model is mainly developed based on the slope of rain rate distribution for tropical zones. Moreover, this model is an Analytical model, where predicts the whole rain cumulative distribution from the available rain rate exceed for 0.01 percentage of time. The RH model, which was developed based on meteorological statistics, does not act accurately with South Korea climate conditions. The Chieko model is a modified version of the RH model for Japan for percentage time between 1 and 0.01. It acts like the RH model, but for a percentage time smaller than 0.01 the Chieko model has the best accuracy, specifically for 0.01% time which is the important percentage for ITU-R, Karasawa and Joo-Hwan rain-attenuation prediction models. In this percentage, the model accuracy is 99.4%. Finally, the results of ITU-R and Crane models are very similar to each other and for percentages between 1 and 0.01 these models follow the measured diagram with acceptable error. Both of them were developed based on long-term and comprehensive meteorological information and the ITU-R model is also based on the new maps which optimize the regression coefficients.

Table 5 presents the mean error, standard deviation and r.m.s. between the experimental and the predicted values of rain-rate in the Yong-in site. According to the results, the ITU-R model, as a new worldwide prediction model, provides the best estimation for rain-rate distribution with 34% r.m.s. The Crane model also

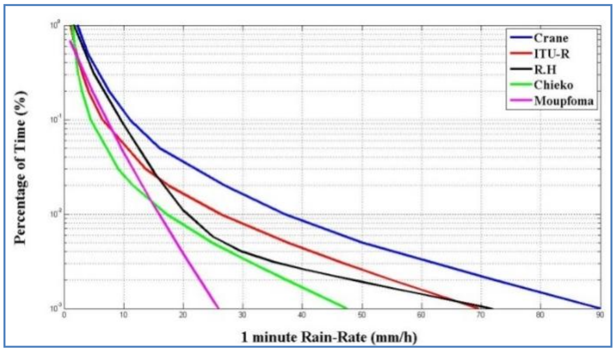

Fig. 5. Different rain-rate prediction models for Urmia

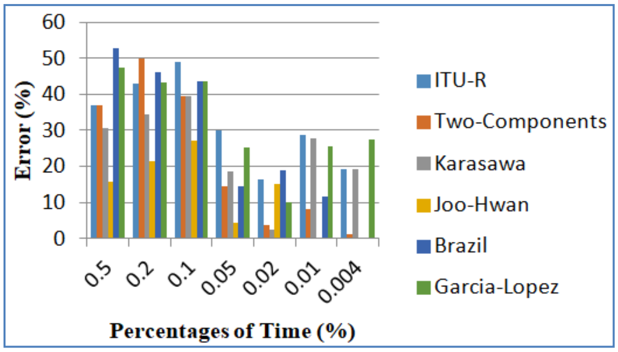

Fig. 7. Percentage of Error in different time percentages

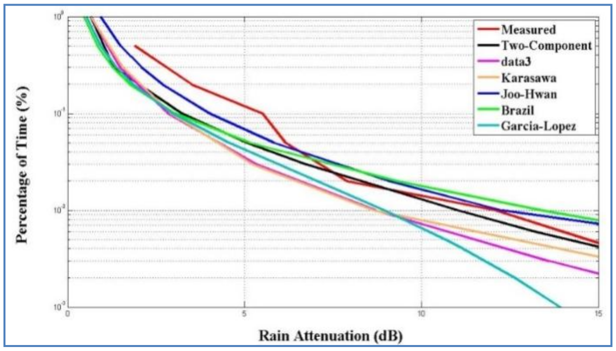

Fig. 6. Measured rain-attenuation for Yong-in and prediction models at 12.25 GHz

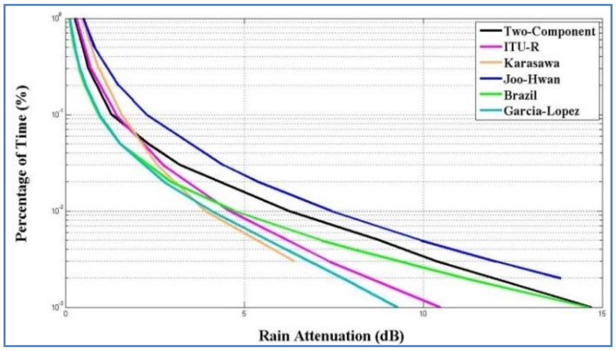

Fig. 8. Different rain-attenuation prediction models for Urmia

operates near to the ITU-R model with acceptable accuracy, but the accuracy of RH, Moubpfouma and Chieko models are not sufficient yet.

Fig. 5 represents the predicted values of rain-rate for the Urmia-site by the all five models. By generalizing the results of Yong-in site, the best rain-rate prediction model for Urmia-site is the ITU-R model. Therefore, in the following, to investigate the amount of rain-attenuation in both sites, the predicted values of rain-rate by the ITU-R model are chosen as the input.

4.3. *Comparison of rain-attenuation prediction models*

Fig. 6 provides the comparison of the six aforementioned rain-attenuation predicted models (in Section 4.2) with the measured rain attenuation in Yong-in. Fig. 7 evaluates the performance of prediction models according to the percentage of error in different percentages of time. According to the results, the performance of the ITU-R model for Yong-in is not appropriate and follows the measured diagram by a mean of 32% error because this model is highly influenced by the rain characteristics, which vary over time and space.

The Garci-Lopez model is a simple model with some coefficients that are constant around the world. Therefore, this model does not have appropriate accuracy for worldwide usage and, as can be seen from the results diagram, it is divergent for a time percentage smaller than 0.01. The Brazil model is converging with time-percentage reduction, where for the time lower than 0.05%, the mean error is 15%. The performances of the Two-component and Karasawa models are almost identical with acceptable accuracy. However, in all the percentages of time, the Joo-Hwan model, which is the modified version of ITU-R for South Korea, follows the measured diagram with mean of 12% error.

Table 6 presents the mean error, standard deviation and r.m.s. between the measured and the predicted values of rain-attenuation in Yong-in. As the results show, the Brazil model with 37% r.m.s. is the worst model because this model is the modified version of ITU-R model for tropical regions. On the other hand, the Two-Component and Karasawa models have lower r.m.s. in comparison with the Brazil model, but they do not have sufficient accuracy yet. Finally, the Joo-Hwan model, which modified the slant path adjustment factor of the ITU-R model for South Korea, is the most accurate rain

TABLE 6

Comparison of rain-attenuation prediction models by mean error, standard deviation and r.m.s. for Yong-in

Model	Mean	St. dev	r.m.s. (%)
ITU-R	-0.3188	0.1183	34.01
Two-Com	-0.2098	0.21	29.68
Karasawa	-0.2467	0.1234	27.59
Joo-Hwan	-0.0895	0.1563	18.01
Brazil	-0.2111	0.3115	37.63
Garcia-Lopez	-0.3183	0.1347	34.56

TABLE 7

Estimation of specific rain-attenuation in different frequency band at 0.01% of exceeding time for Urmia

Frequency band (GHz)	10	20	30	40	50
Attenuation (dB/km)	1.35	5.71	11.03	16.12	20.43

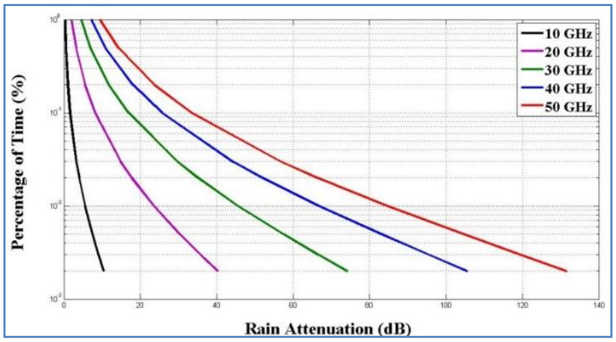

Fig. 9. Rain-attenuation in different frequency band for Urmia, based on the Joo-Hwan model

attenuation prediction model for Yong-in with 18% r.m.s. Therefore, by generalizing the results of Yong-in, the Joo-Hwan model would predict the rain-attenuation for the Urmia-site with higher accuracy. Fig. 8 shows the results of the six different rain-attenuation prediction models which were applied to Urmia.

4.4. *Evaluating rain attenuation at different frequency bands*

The raindrops absorb and scatter the electromagnetic waves. Therefore, for frequency-bands above 10 GHz, it can significantly attenuate the propagated signals. On the other hand, since the Joo-Hwan model is a frequency dependent model with the range of applicability of 4-55 GHz (ITU-R, 2007), the amount of rain-attenuation in different useful frequency-band is investigated for the Urmia-site. As the results of Fig. 9 and Table 7 show, by increasing the carrier-frequency, the wave length decreases and thereby absorption and scattering of propagated signals by raindrops will increase, which consequently result to higher attenuation in higher frequency bands.

5. Conclusion

In order to find the most accurate rain-rate and rain-attenuation prediction model for the earth-space link in the Urmia-site in Iran, we used meteorological skills to find a homogeneous site with available experimental measurements. Therefore, by utilizing the long-term observation of monthly rainfall and temperature of Urmia, we chose the Yong-in site in South Korea as the homogeneous area. Then the most common prediction methods were applied to Yong-in and compared with the available experimental values of rain-rate and rain-attenuation. The results show that, for time percentages lower than 0.01%, the Chieko model provides the best estimation for rain-rate, particularly in 0.01% of time (with an accuracy of 99.4%). However, the ITU-R rain-rate model provides more accurate estimations over all time percentages with 34% r.m.s. A comparison of rain-attenuation prediction models in Yong-in shows that the Joo-Hwan model provides the most accurate prediction, with 18% r.m.s.

Afterward, all the considered prediction models were applied to the Urmia and by generalizing the results of

Yong-in, the most accurate rain-rate and rain-attenuation prediction models for Urmia were revealed as ITU-R and Joo-Hwan, respectively. Finally, based on the Joo-Hwan model, the amount of rain-attenuation in different frequency bands (10-50 GHz) was investigated for Urmia. We believe that the utilized methodology can give an optimal strategy to find an accurate rain-rate and rain-attenuation prediction model for areas which do not have the required information of experimental measurements.

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