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RAIN RATE AND RAIN ATTENUATION PREDICTION FOR SATELLITE COMMUNICATION IN KU AND KA BANDS OVER NIGERIA

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Abstract—Rain rate and rain attenuation predictions are one of the vital steps to be considered when analyzing a microwave satellite communication links at the Ku and Ka bands. In this paper, tools for the prediction of rain rate and rain attenuation are presented in the form of contour maps for Nigeria using a massive rainfall data bank of 30 years which are taken from measurements made from the coast to the arid region of Nigeria. Rain-rate maps for the country of Nigeria were developed using the models purposely designed for tropical zones while ITU-R models were used for the rain-attenuation maps. The information from these maps will be a good preliminary design tools for both terrestrial and earth-satellite microwave links and also provide a broad idea of rain attenuation for microwave engineers.

1. INTRODUCTION

Atmospheric effects play a major role in the design of satellite-to-earth links operating at frequencies above 10 GHz. Raindrops absorb and scatter radio waves, leading to signal attenuation and reduction of the system availability and reliability. The severity of rain impairment increases with frequency and varies with regional locations [4]. Hence

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the incidence of rainfall on radio links becomes even more important for frequencies as low as about 7 GHz particularly in the tropical and equatorial climates, where intense rainfall events are common [20]. It is therefore very important when planning both microwave and terrestrial line-of-sight system links; to make an accurate prediction of rain induced attenuation on propagation paths [27]. Initially, attenuation prediction attempts involved extrapolation of measurements to other locations, frequencies, and elevation angles; however, the complex nature and regional variability of rain make this approach highly inaccurate [28].

The method for the prediction of rain attenuation on microwave paths has been grouped into two classes: the empirical method which is based on measurement databases from stations in different climatic zones within a given region and the physical method which make an attempt to reproduce the physical behaviour involved in the attenuation process. However, when a physical approach is used not all the input parameters needed for the analysis is available. Empirical method is therefore the most used methodologies [10, 13].

For the empirical methodology, an appropriate distribution of rainfall rate at 1-minute integration time is needed for the site under studied in order to predict accurate rain attenuation for the location. This input is sometime provided by meteorological and environmental agencies, universities, and independent researchers. Study has revealed that daily rainfall accumulations are universally recorded and hourly data are fairly available by national weather bureaus/environmental agencies [27]. There is still dearth of rainfall rate of 1-minute integration time necessary for the study of rain induced impairment to telecommunication especially in the tropical region (Nigeria) [1]. This is because global national weather services are established to satisfy more traditional requirements such as those for agriculture, hydrology and forest management. A method for converting the available rain rate data to the equivalent 1-minute rain rate cumulative distribution is therefore necessary.

The critical role of the propagation impairment on communication systems cum lack of rain-measurement data from tropical regions for verification for modeling purposes has been the concern of many organizations like, the International Telecommunication Union (ITU), European Space Agency (ESA), and European cooperative program (COST) among others. This has become necessary because of the peculiarity of the tropical regions, which are characterized by high intensity rainfall, enhanced frequency of rain occurrence and the increased presence of large raindrops when compared with temperate climates [2]. Another very important effort towards gathering more information is through Tropical Rain Measurement Mission (TRMM) jointly developed by the United States and Japan, and the Global Precipitation Climatology Project (GPCP) of the World Climatic Research Programme (WCRP). As earlier stated, the data available from this mission can not directly be employed in system design, due to its long integration time.

The aim of this paper is to give additional tools to the system designers, in the form of contour maps of rain intensity and rain attenuation, for the design of satellite systems in the tropical countries and particularly in Nigeria. Nigeria has recently launched her first communication satellite, known as Nigerian Communication Satellite (NIGCOMSAT-1). It is the first Africa geosynchronous communication satellite and is positioned at 42.5° E. NIGCOMSAT1 has an expected service life of 15 years and can operate at C, Ku, Ka and L band. It is committed to effective delivery of secure, qualitative and value-added satellite services to Africans, while the Ka-band transponders will also cover part of Italy. Nigeria is expected to launch another satellite communication (NIGCOMSAT-2) in the year 2010. Hence the tools from this work will be used for preliminary design of the satellite microwave links, satellite-payload design (satellite-coverage analysis), Earth-segment design and a broad idea of rain attenuation for microwave engineers. The tools are also applicable to other regional and hemispherical broadband access systems.

Rain-rate and rain attenuation maps for the country of Nigeria were developed using the models purposely designed for tropical zones by *Moupfouma and Martins* [22] (which is a mix between a log-normal distribution for low rain rates and a gamma distribution for high rain rates) and that of *J. Chebil's* [3] model for the estimation of point rain rate, and the ITU model for rain attenuation prediction method prediction method [16].

The climatic mapping of rain-rate and rain-attenuation has naturally attracted a great deal of attention — for instance this kind of work has earlier been carried out for USA [12], Europe [12, 14, *Gunes et al.*, 1994], Malaysia [3], Colombia [13] and on global scale by *ITU-R* [10], *Salonen and Baptisa* [16], *Crane*, 1996. Efforts has also been made by Ajayi and Ofoche [2] to obtain 1 minute rain rate map for Nigeria using Rice-Holmberg model however the model overestimates rain rates in the high-availability range (0.01%), and underestimates in the range between 0.1% to 1% [26]. These percentages unavailability of time are crucial for communication purposes, hence the need for this work [21].

2. OVERVIEW OF SOME EXISTING MODELS FOR RAIN-ATTENUATION AND RAIN-RATE

As earlier mentioned, a lot of methodologies exist for the prediction of rain-rate and rain-attenuation. In this section an overview of some of the important models and their results are considered.

2.1. Rain-rate Prediction Models

Rainfall of high intensity is difficult to record and measure experimentally, as well as being highly variable from year to year. However, in system design it is the highest rainfall rates which are frequently of great interest. Short integration-time rainfall rate is the most essential input parameter in the prediction models for rain attenuation [27].

Several models exist for the prediction of point rainfall-rate cumulative distribution; this include the work of *Crane* [9] which has considerably influenced the zonal models of the ITU-R and have been used extensively in the United States, although to a lesser extent in other parts of the world, the limit of the model being the number of station-years of measurements available and not all stations fulfilled the one minute integration time requirement. The results reported by *Segal* [27] also influenced the ITU-R zonal models, and provided a systematic approach for obtaining a specified number of rain zones in country such as Canada. Watson *et al.* [29] later mapped rain rates exceeded for 0.1% and 0.01% of an average year based on data for 400 locations within Europe. This approach has been excellent in providing high quality estimates of rain intensity and was used to update the ITU-R rain zones in Europe. The drawback of this approach is that it requires a relatively high density of short integration-time point precipitation measurements or measurements from which these can be derived. The topography is also not explicitly taken into account, therefore requiring a high spatial resolution for the measurement data. This approach cannot be easily used on global data due to the low spatial resolution of point measurements on a global scale and the errors that would arise from the spatial interpolation of precipitation rates for fixed annual probability levels.

Holmberg and Rice [24] also developed a model for obtaining rain-rate values for use in fading calculations known as Rice-Holmberg's model. The model requires certain parameters like; highest monthly rainfall accumulation observed in a set of 30-year period, number of thunderstorm days expected in an average year and the average annual accumulation. The thunderstorm ratio is not always readily available from local weather agencies. The model was later modified by *Dutton* *and Dougherty* [11] to make it depend on four parameters, two of which are used to estimate the fraction of thunderstorm rain. However, it has been acknowledged that the Rice-Holmberg method overestimates rain rates in the high-availability range (0.01%), and underestimates in the range between 0.1% and 1% [26].

Recent analysis suggests that the rain rate distribution is better described by a model which approximates a log-normal distribution at the low rates, and a gamma distribution at high rain rate. This kind of model was developed by *Moupfouma and Martins* [21]. The model is good for both tropical and temperate climate and can be expressed as:

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

where r (mm/h) represents the rain rate exceeded for a fraction of the time, $R_{0.01}$ is the rain intensity exceeded during 0.01 percent of time in an average year (mm/h) and b is approximated by the following expression:

$$b = \left(\frac{r - R_{0.01}}{R_{0.01}}\right) \ln\left(1 + \frac{r}{R_{0.01}}\right) \tag{2}$$

The parameter u in Equation (1) governs the slope of rain rate cumulative distribution and depends on the local climatic conditions and geographical features. For tropical and sub-tropical localities

$$u = \frac{4 \ln 10}{R_{0.01}} \exp\left(-\lambda\left[\frac{r}{R_{0.01}}\right]^{\gamma}\right) \tag{3}$$

where $\lambda = 1.066$ and $\gamma = 0.214$.

Thus, the Moupfouma model requires three parameters; λ, γ and $R_{0.01}$. The first two parameters have been provided. To estimate $R_{0.01}$, the use of J. Chebil's model [3] appears suitable, it allow the usage of long-time mean annual accumulation, M, at the location of interest. The power law relationship of the model is given by

$$R_{0.01} = \alpha M^{\beta} \tag{4}$$

where α and β are regression coefficients. Chebil has made a comparison between some models based on measured values of $R_{0.01}$ and M in Malaysia, Indonesia, Brazil, Singapore and Vietnam. He showed that his model is the best estimate of the measured data [3]. The regression coefficient α and β are defined as

$$\alpha = 12.2903 \quad \text{and} \quad \beta = 0.2973 \tag{5}$$

Thus, using the refined Moupfouma model and Chebil model, the 1 min rain-rate cumulative distribution is fully determined from the long-term mean annual rainfall data.

2.2. Rain-attenuation Prediction Model

A number of rain attenuation prediction models have been published which claim global applicability. Attenuation predictions require first the estimation of a surface rain rate distribution and second the prediction of the radiowave attenuation value distribution, given by the rain rate distribution. Several workers have proposed different models for calculation of attenuation along a path. Way back in 1946, *Ryde* presented a rain attenuation model. After three decades, Crane looked afresh at the model predictions and compared them with the measured values taking the data available and new data published after that. He found an average matching between model predictions and measurements [6, 7]. He later proposed another model called, two-component model, followed by the revised version [8]. Several other models also include: simple attenuation model by Stutzman and Dishman, Dutton et al. model, Excell model, Misme Waldteufel, Garcia model, ITU-R model, Bryant model, Flavin model, DHA model, Moupfouma Model among others. Details of these models can be obtained from *COST 255* [5].

To develop the map for rain attenuation over Nigeria, ITU rain attenuation model of ITU rain attenuation model of [16] was used. It has been reported that the ITU rain attenuation prediction model result were close to the average prediction of a set of results obtained from the application of eight different methodologies [23]. The input parameters needed for the model are: point rainfall rate for the location for 0.01% of an average year (mm/h), height above sea level of the Earth station (km), elevation angle, latitude of the Earth station (degree), frequency (GHz) and effective radius of the Earth (8500 km).

The step by step procedure for calculating the attenuation distribution is given below:

Step 1: Freezing height during rain H_r (km) is calculated from the absolute value of station latitude ϕ (degrees) as

$$\begin{aligned} H_r &= 5.0 \quad \text{for} \quad 0^\circ \leq \phi < 23^\circ \\ H_r &= 5.0 - 0.075(\phi - 23), \quad \text{for} \quad \phi \geq 23^\circ \end{aligned} \tag{6}$$

Step 2: The slant-path length, L_s, below the freezing rain height is obtained

$$L_s = \frac{H_r - H_s}{\sin\theta}\,(\text{km}) \tag{7}$$

where θ is the elevation angle and H_s is the station height in km. For elevation angles less than 5°, a more accurate path length estimate can be made using:

$$L_s = \frac{2\,(H_r - H_s)}{\left[\sin^2\theta + \dfrac{2\,(H_r - H_s)}{Re}\right]^{0.5} + \sin\theta} \text{ (km)} \quad Re = 8500\,\text{km} \tag{8}$$

Step 3: The horizontal projection, L_G, of the slant path length is found from:

$$L_G = L_s \cos\theta \tag{9}$$

Step 4: The rain intensity, $R_{0.01}$ (mm/h), exceeded for 0.01% of an average year is then obtained from the 1 minute integration rain rate data, and is used for calculating the specific attenuation, $\gamma 0.01$ (dB/km):

$$\gamma_R = kR_{0.01}^{\alpha} \tag{10}$$

The parameter k and α depend on frequency, raindrop size distribution, rain temperature, and polarization. They can be obtained from [17].
Step 5: The horizontal path adjustment factor, $r_{0.01}$, for 0.01% of the time is also given as:

$$r_{0.01} = \frac{1}{1 + 0.78\sqrt{\dfrac{L_G \gamma_R}{f}} - 0.38\left[1 - e^{-2L_G}\right]} \tag{11}$$

Step 6: Calculate the adjusted rainy path length, L_r, [km], through rain:

$$\begin{aligned} &L_r = \frac{L_G r_{0.01}}{\cos\theta} \text{ for } \xi > \theta \quad L_r = \frac{H_r - H_s}{\sin\theta} \text{ for } \xi \leq \theta \\ &\text{where} \quad \xi = \tan^{-1}\left(\frac{H_r - H_s}{L_G r_{0.01}}\right) \end{aligned} \tag{12}$$

Step 7: The vertical reduction factor, $rv0.01$, for 0.01% of the time is also given by:

$$rv_{0.01} = \frac{1}{1 + \sqrt{\sin\theta}\left[31\left(1 - e^{-\theta/[1+\chi]}\right)\dfrac{\sqrt{L_G \gamma_R}}{f^2} - 0.45\right]} \tag{13}$$

where $\chi = 36 - |\phi|$, for $|\phi| < 36°$ and $\chi = 0$, for $|\phi| \geq 36°$.
Step 8: The effective path length through rain, Le [km], is given by:

$$Le = L_r r v_{0.01} \tag{14}$$

Step 9: The predicted attenuation exceeded for 0.01% of an average year may then be obtained from:

$$A_{0.01} = \gamma_R Le \, (\mathrm{dB}) \tag{15}$$

Step 10: The estimated attenuation to be exceeded for the other percentages of an average year, in the range 0.001% to 10%, may then be estimated from the attenuation to be exceeded for 0.01% for an average year by using:

$$A_p = A_{0.01} \left(\frac{p}{0.01}\right)^{-[0.655+0.033\ln(p)-0.045\ln(A_{0.01})-z\sin\theta(1-P)]} \tag{16}$$

where p is the percentage probability of interest and z is given by

$$\begin{array}{l} \text{For } p \geq 1\%, \quad z = 0 \\ \text{for } p < \ 1\% \quad z = 0 \quad \text{for } \ |\phi| \geq 36° \end{array} \tag{17}$$

$$\begin{array}{l} z = -0.005\,(|\phi| - 36) \ \text{ for } \theta \geq 25° \text{ and } \ |\phi| < 36° \\ z = -0.005\,(|\phi| - 36) + 1.8 - 4.25\sin\theta, \\ \qquad \text{for } \theta < 25° \text{ and } \ |\phi| < 36° \end{array} \tag{18}$$

3. DEVELOPMENT OF RAIN-RATE AND RAIN ATTENUATION CONTOUR MAPS

Daily rainfall data were collected from the Nigerian Meteorological Station for 26 locations which cut across the coastal to arid region of Nigeria for a period of 30 years for most of the stations. Figure 1 presents the topographical map of Nigeria, showing the most important tropical climate zones of the country as well as the altitude of the stations where rain data were collected for this work. The south-south area is the coastal region with an annual average rainfall of about 3000 mm; the south west of the country belongs to the rain forest zone, with an average accumulation of 1500–2000 mm. The middle belt region also receives about 1200 mm, while the northern area is the arid/savannah region, with an average accumulation less than 1000 mm.

3.1. Rain Rate Contour Maps

For the development of rain rate contour map, we have used Moupfouma model which approximates a log-normal distribution at the low rates, and a gamma distribution at high rain rate. The model was used in conjunction with the Chebil's model. Table 1 presents the local climatological parameters of the stations for this study. Thus, applying the methodologies described in Equations (1) to (5) (Moupfouma and Chebil's models), and using the parameters in Table 1 as input, the 1 min rain-rate contour maps of Figure 2 for 0.1% and Figure 3 for 0.01% was developed. The contour lines of Figures 2

Table 1. Local climatological parameters of the stations for this study.

Station	Longitude (°N)	Latitude (°E)	Average annual accumulation (mm/year)
Akure	5.18	7.17	1485.57
Ikeja	3.2	6.3	1425.207
Calabar	8.17	4.58	2864.907
Minna	6.33	9.36	1196.751
Kano	8.3	11.58	924.850
Makurdi	8.53	7.32	1337.371
Sokoto	5.13	13.04	567.206
Maiduguri	13.08	11.51	648.455
Dikwa	14.52	12.08	657.433
Adamawa	12.3	9.10	1012.398
Ile Ife	5	7.5	1215.27
Ilorin	4.5	8.5	1232.775
Port Harcourt	7	4.2	2803.104
Warri	5.44	5.29	2617.503
Enugu	7.27	6.25	1876.301
Abuja	9.25	7.1	1777.538
Saki	3.23	8.39	1097.968
Jos	8.5	9.5	1186.89
Gombe	11.11	10.16	746.805
Bauchi	9.5	10.18	849.397
Kaduna	7.26	10.33	1103.464
Zaria	7.41	11.04	801.879
Borno	12.45	11.59	574.488
Gusau	6.4	12.09	650.288
Nguru	10.25	12.59	451.586
Katsina	7.35	13	556.336

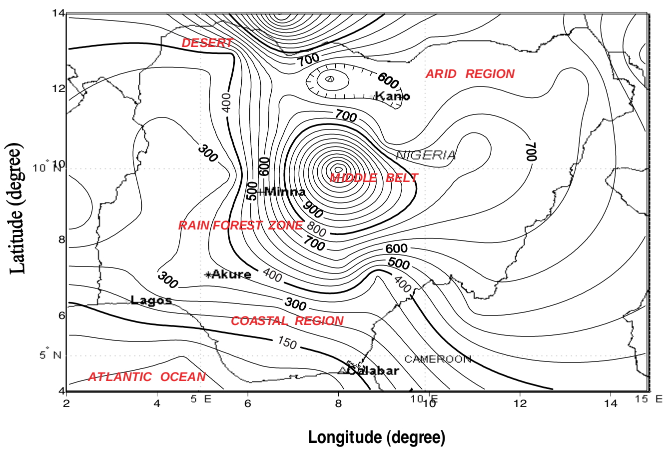

Figure 1. Topographic map of Nigeria, showing the most important tropical climate zones of the country as well as the altitude of the stations where rain data were collected.

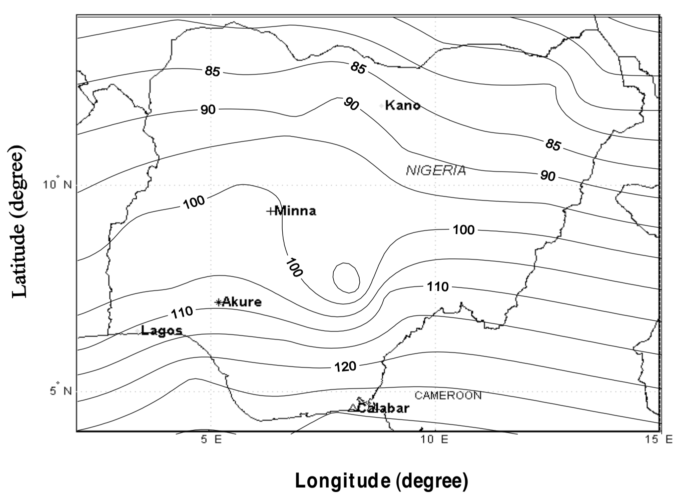

Figure 2. Rain rate (mm/h) contour maps for 0.01% of time in Nigeria.

and 3 were developed using the kriging method in a MATLAB program. ITU-R has classified Nigeria to be in rain climatic zone N and P and it has assigned a value of 65 mm/h and 145 mm/h for $R_{0.1}$ and $R_{0.01}$ respectively for a location like Warri and Calabar (coastal region) which belongs to zone P of the ITU. However, Figures 2 and 3 shows that in a location like Port Harcourt, Warri and Calabar with highest rain fall accumulation, the $R_{0.01}$ is $\sim$130 mm/h, while it is $\sim$50 mm/h for $R_{0.1}$. For area with lower average annual precipitation (arid area) such as Sokoto, Katsina, Nguru, Borno, Dikwa and Maiduguri, the $R_{0.01}$ ranges from about 65–80 mm/h depending on the location while $R_{0.1}$ is $\sim$30 mm/h. However, ITU has assigned a value of 95 mm/h for $R_{0.01}$ and 35 mm/h to the zone [19]. The mountainous zone like Jos Plateau with an altitude up to 1400 m has $\sim$100 mm/h for $R_{0.01}$, while it is $\sim$36 mm/h for $R_{0.1}$. The fact that ITU-R rain zoning overestimated rain rate values in Nigeria is clearly revealed with the help of this map [2].

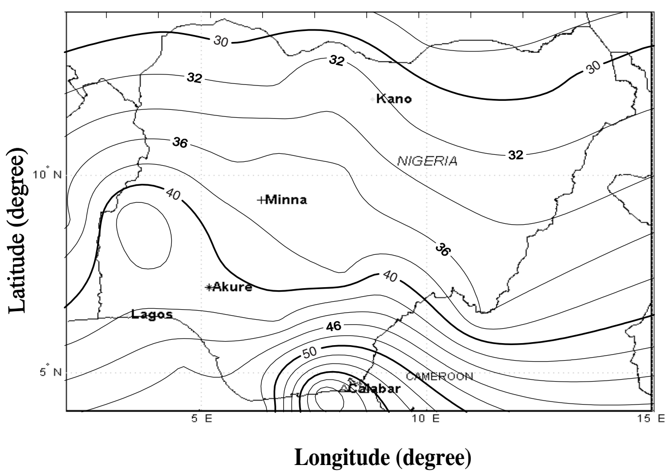

Figure 3. Rain rate (mm/h) contour maps for 0.1% of time in Nigeria.

3.2. Rain Attenuation Contour Maps

As earlier mentioned, the rain attenuation contour maps were developed using ITU rain attenuation model of [16]. The application consists of three methodologies: first is the calculation of the specific attenuation [17]; second, the calculation of rain height [18]; and third, the attenuation-calculation methodology [16]. The attenuation contour maps were developed for Ku and Ka band in order to meet today's active challenges in the rapid growth of satellite broadband networks. Efforts are being made to use Ka band rather than Ku band frequencies, due to the bandwidth requirements of the application they are expected to support. In addition Ka-band allow for a higher return-link data rate. In order to develop the rain attenuation for 0.1% and

0.01% of the time, rain rate from each contour line were applied to the ITU rain attenuation model described in Equations (6) to (18) in conjunction with the altitude obtained from Figure 1 and the latitude from Table 1. Other parameter used to draw the maps are; frequency of operation: 12.675 GHz for Ku and 19.45 GHz for Ka-band (these values were used because it corresponds to the center of the band for Ku and Ka-band downlinks respectively); Satellite orbital position: 42.5° E (NIGCOMSAT 1 orbital position).

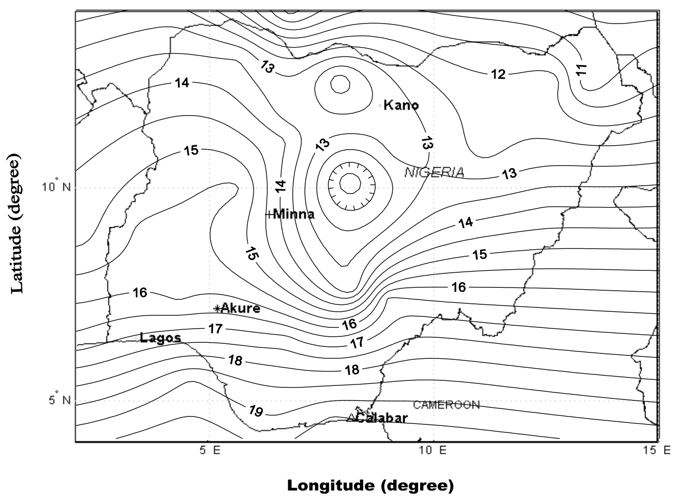

Figure 4. A 0.01% rain-attenuation (dB) contour map for the Ku band.

Figure 4 presents the contour map for 0.01% rain attenuation for Ku-band for Nigeria, while Figure 5 is for Ka-band. The results show a difference in both the Ku and Ka-band predicted attenuation values over each of the location. For a coastal region like Calabar with the highest average annual accumulation, the rain attenuation is as high as ∼37.8 dB for ka-band, while it is ∼19.6 dB for Ku-band, this show a difference of about 18.2 dB between the two frequency bands. The results of the rain attenuation prediction in the south western part of the country (area regarded as the rain forest zone) has a difference of ∼3 dB when compared with the coastal region for the Ku-band, while it is ∼6 dB for the Ka-band. The middle belt region shows a difference of ∼5 dB for Ku-band when compared with the arid region of the country, while it is up to ∼10 dB for ka-band. The magnitude of the average difference between the far Northern zones (desert area) was of the order of 1 dB for Ku-band and 2 dB for Ka-band.

Figures 6 and 7 also show the contour maps for 0.1% rain attenuation for Ku-band and Ka-band respectively. This section is very crucial to system designers, since it corresponds to an average-year propagation objective (99.9 availability of time). For Ku band,

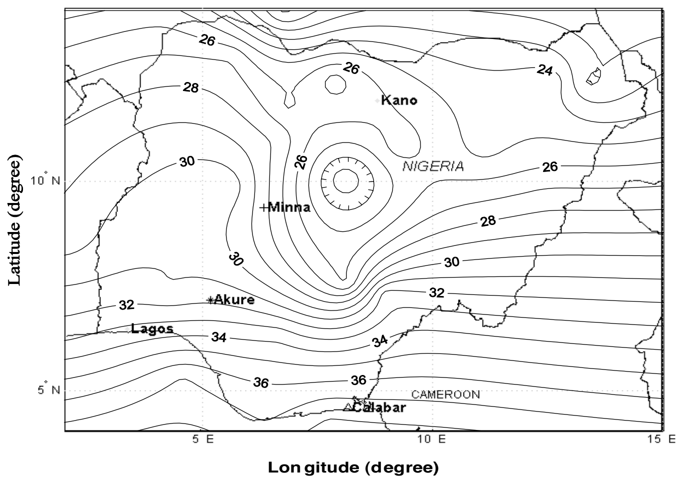

Figure 5. A 0.01% rain-attenuation (dB) contour map for the Ka band.

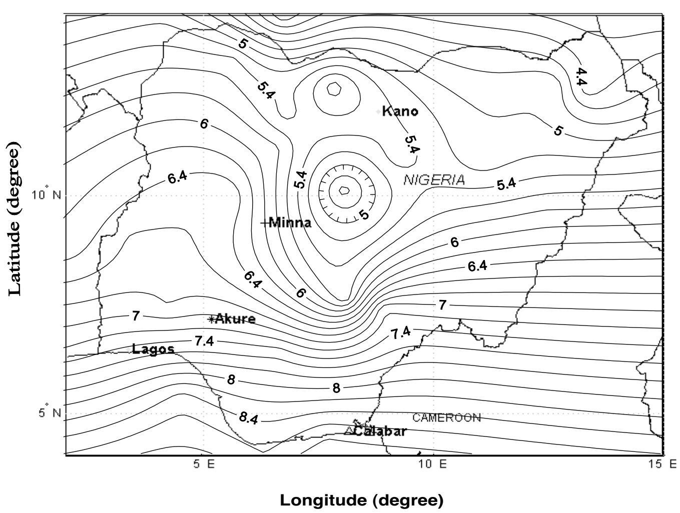

Figure 6. A 0.1% rain-attenuation contour map for the Ku band.

the magnitude of the attenuation prediction was of the order of 1 dB difference for the coastal region of the country due to the higher rain rates used as input data. However, for Ka band the magnitude is as high as 7 dB when compared the coastal region with other zones. The northern part of the country showed a moderate rain attenuation prediction due to low amount of rainfall intensity in the region. In general, predicted rain-attenuation value is lower for Ku-band when compared with the Ka-band.

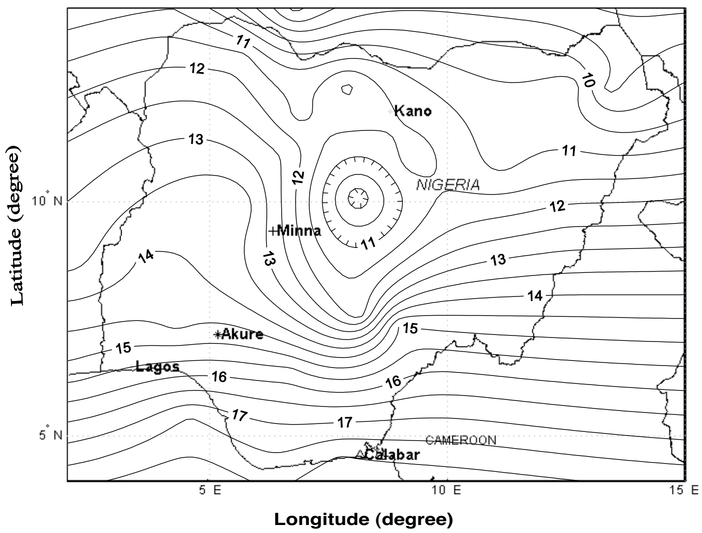

Figure 7. A 0.1% rain-attenuation (dB) contour map for the Ka band.

There is consistence larger increase in the rain-attenuation predictions in the southern part of the country and inferior in the northern part. Hence, system designers need to be aware of these differences because they represent an uncertainty in the design of each link. The uncertainty might lead to an over-cost, both in initial expenses and in periodic expenses [13]. Also, the differences and higher dB values in some locations often affects service availability and can lead to interruptions of communications link performance. It is therefore necessary to compensate for the differences via RF modifications (larger antennas, larger amplifiers). The terminal effects of these modifications are reflected in the service price.

4. CONCLUSIONS

Rain rate and rain attenuation contour maps have been developed for 0.1 and 0.01% of the time using the refined Moupfouma model for rain rate maps and ITU-R 618 for the rain attenuation maps over Nigeria. The 0.1% of time of rain attenuation is needed for very small aperture terminal (VSAT) network service-availability. The information from these maps will be useful in the preliminary design for both terrestrial and earth-satellite microwave links, and to provide a broad idea of rain attenuation to microwave engineers for the proposed launching of another satellite communication (NIGCOMSAT-2) in Nigeria.

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