Variability and trends in rain height retrieved from GPM and implications on rain-induced attenuation over Nigeria

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ABSTRACT

To meet the rising demand for uninterrupted high-speed broadband internet services, the deployment of high-frequency bands for the transmission of radio signals is inevitable. Unfortunately, attenuation due to raindrop-laden remains the most challenging factor impeding effective radio wave propagation especially in earth-space satellite links operating at Ka and V bands. It is important to understand the attenuation and the parameters that determine its magnitude in order to provide an effective solution to this problem. Rain height as one of the attenuation input parameters was examined in detail. A study of its temporal evolution reveals that seasonal variation is insignificant while the spatial variation shows that it increases from the Sahel to the Coastal Zone of Nigeria. The work provides comprehensive rain height and rain-induced attenuation contour maps. These maps are expected to serve as a database for link budget calculations for different areas in Nigeria. Rain-induced attenuation maps for 1%, 0.1%, and 0.01% of time exceedance are provided at 20 GHz and 40 GHz for Ka and V band signals respectively.

1. Introduction

Over the years, satellite communication has remained the easiest and most affordable means for long-distance communication especially in point-to-multipoint networks. Although in the recent decades, optical fiber has found relevance in long-distance communication, the wireless mode of interconnectivity in satellite communications is inevitable and remains the most widely used in wireless technology. However, satellite links operating at a frequency of 10 GHz and above are usually subjected to signal degradation due to atmospheric disturbances such as gaseous attenuation, cloud and fog attenuation, and scintillation [1,2]. Among all the atmospheric factors, rain poses the greatest threat to radio wave propagation. Raindrops distort satellite signals mostly by either scattering or absorption. Hence, the major challenge with satellite communication lies in its reliability during heavy rainfall or when there is an obstruction along the earth-space propagation path [3]. The scarcity and paucity of these location-dependent parameters have led to their generalization of propagation parameters for different regions of the world as provided by the International Telecommunication Union - Radiocommunication Section (ITU-R). Rain path length which is a function of rain height and rate both play a vital role in the estimation of rain-induced attenuation in any location. For instance, the rain height recommended by ITU-R for tropical regions where there are no local data stands at 4.86 km [4]. Although subsequent recommendation provides location-dependent rain height data on a grid resolution of 1.5° by 1.5° [5], several empirical experimental studies have revealed that these values either underestimate or overestimate rain height in some tropical areas such as Malaysia [6, 7, 8] and Nigeria [7, 8, 9, 10, 11]. Accurate prediction of rain-induced attenuation is important to make provision for appropriate rain fade margin and secure optimum performance of radio links during rainstorms. Thus, high-resolution data retrieved from the Global Precipitation Measurement (GPM) have been used to process rain-induced attenuation contour maps over Nigeria.

2. Climatology of research location and data collection

Sixteen stations spread across Nigeria were selected for the research. The stations as well as their characteristics are presented in Figure 1 and Table 1. Nigeria is a country located in the equatorial zone and categorized under the tropical region in the ITU...
classification [12,13]. It shares borders with the Sahara Desert in its northern part and the Gulf of Guinea in the Atlantic Ocean in the south. The western and eastern parts of the country are bordered by the Republic of Benin and Cameroon respectively [14].

Generally, Nigeria experiences two major seasons throughout each year. The wet season runs from March till late October while the dry season reigns between November to March. These weather patterns are driven by the movement of inter-tropical discontinuity (ITU) between the north and south. The coastal areas are usually dominated by the rainy season and may extend beyond the season limit. This is due to the proximity of the Atlantic Ocean which results in frequent and prolonged rainfalls. The magnitude and occurrence rate of rain-induced attenuation on high-frequency radio links (Ka and V bands) in this area cannot be overemphasized. Hence the need for extensive studies on rain fade margin and its input parameters such as attenuation, rain rate, rain height, mean sea level height e.t.c. Based on critical evaluation of the climate, Nigeria is commonly subdivided into four geoclimatic zones known as Sahel, Midland Savannah, Guinea Savannah, and Coastal region as shown in Figure 1 [15].

Four stations were selected to represent each of the geoclimatic zones. The stations are listed in Table 1 ranging from the Sahel to the Coastal region.

The data employed in this research is the archived Global Precipitation Mission (GPM) data provided by the National Aeronautics and Space Administration (NASA) Japan Aerospace Exploration Agency (JAXA).
The GPM is a constellation of multi-level precipitation observatory satellite launched in 2014 to replace the TRMM after its mission might have ended in 2015 by default [16]. The GPM is an improved version of TRMM with several advantages such as better file naming convention, improvement on rain rate integration time, merging of level 2 and 3 datasets, extended capability to measure light rain (<0.5 mm/hr), solid precipitation and the microphysical properties of precipitating particles. While TRMM provides data on a grid spatial resolution of 5° by 5° [17], GPM has a better resolution of 0.25° by 0.25° [18]. The GPM provides precipitation parameters such as rain rate, zero degree isotherm height \( h_0 \), Bright Band Height, liquid water content, etc. The data provided by GPM are not only useful in the design of wireless communication systems, It also helps farmers, ranchers, and policymakers to plan for a period of drought, flooding, and other extreme weather [16]. GPM has a better resolution of 0.25° by 0.25° [18]. The GPM provides precipitation parameters such as rain rate, zero degree isotherm height \( h_0 \), Bright Band Height, liquid water content, etc. The data provided by GPM are not only useful in the design of wireless communication systems, It also helps farmers, ranchers, and policymakers to plan for a period of drought, flooding, and other extreme weather [16]. This work utilizes \( h_0 \) and rain rate data provided by GPM to compute the rain height and rain-induced attenuation for the selected locations in Nigeria. Further details on the procedure and algorithm for conversion of TRMM to GPM data can be found in [19].

3. Methodology

The local average rain height for each station was computed using Eq. (1) as recommended by [5].

\[
H_r = h_0 + 0.36
\]  

(1)

where \( h_0 \) are the zero degree isotherm heights above mean sea level obtained from the GPM and ITU-R database ITU-R P.839-4 [5]. The derived rain heights were classified into monthly, seasonal, and annual values for further analysis. Rain data of 30 minutes integration time collected from NASA for the 9 years (2006–2014) study duration were sorted and the percentage of time exceeded for the average year was calculated. The rain rates were converted to equivalent rain rates of 1 min integration time since it is the most suitable for calculating rain-induced attenuation and rain fade margins [5]. In this case, 1 min and 30 mins rain rates were taken as the equiprobable rain rates, and their relationship is given by the conversion factor-power equation known as the Segal method [20].

\[
R_{\text{min}}(p) = a p^b R_{30\text{min}}(p)
\]  

(2)

where \( R_{30\text{min}} \) is the rain rate of 30 minutes integration time at the percentage of exceedance \( p \). \( a \) and \( b \) are the regression coefficients obtainable through empirical data analysis. The Segal method is an improved version of the famous power-law model. This method was adopted because it has been proved to be the most effective conversion model in this tropical region i.e Nigeria [21,22]. Rain rates of 30 min integration time were employed due to the scarcity of 1 min rain rate data across all the study stations. The regression coefficients for the various study locations have been provided by [23].

The rain attenuations for 0.01% of time exceedance and attenuations exceeded for other percentages were calculated using the procedures below [24,25].

i. The slant path \( L_s \) between the ground station antenna and rain height is given as;

\[
L_s = \frac{H_r - h_0}{\sin \theta} \text{ for } \theta \geq 5^\circ
\]  

(3)

where, \( h_0 \) and \( \theta \) are the rain height, station height above mean sea level and elevation angle respectively.

ii. The horizontal projection \( L_{H} \) of the slant path length is

\[
L_H = L_s \cos \theta
\]  

(4)

iii. The rain rate \( R_{0.01} \) for 0.01% of time obtained was used to calculate specific attenuation using the power-law relationship as recommended by ITU-R P.618-13 [25].

\[
\tau_{0.01} = a R_{0.01}^b (\text{dB/km})
\]  

(5)

where \( a \) and \( b \) are frequency-dependent parameters obtained from ITU-R recommendation [26].

iv. The horizontal reduction factor \( r_{0.01} \) for 0.01% of time was computed using Eq. (6)

\[
r_{0.01} = \frac{1}{1 + 0.78 \sqrt[3]{\frac{\text{Rain}}{0.38(1 - e^{-2\theta})}}}
\]  

(6)

While the vertical adjustment factor \( v_{0.01} \) was obtained using the conditions below;

\[
\xi = \tan^{-1} \left[ \frac{H_r - h_0}{L_{Hr_{0.01}}} \right]
\]  

For \( \xi > \theta \) \( L_E = \frac{L_{Hr_{0.01}}}{\cos \theta} \text{ (km)} \)

Else \( L_E = \frac{(H_r - h_0)}{\sin \theta} \text{ (km)} \)

If \( |\psi| < 36^\circ \) \( \chi = 36 - |\psi| \) \( \text{Else } \chi = 0^\circ \)

\[
v_{0.01} = \frac{1}{1 + \sqrt{\sin \theta (31(1 - e^{-1/(1+\theta)}))} (\sqrt{\gamma_{H}L_{E}} / f^2 - 0.45)}
\]  

(9)

where \( \phi \) is the latitude of the earth station in degrees.

v. The effective path length \( L_E \) is given by

\[
L_E = L_{Hr_{0.01}}
\]  

(10)

vi. Finally, the attenuation \( A_{0.01} \) for 0.01% of time in decibel (dB) for an average year rainfall was estimated Eq. (11)

\[
A_{0.01} = r_{0.01} A_E \text{ (dB)}
\]  

(11)

The long-term rain attenuation \( A_E \) exceeded for other percentages of time \( p \) for an average year is calculated according to the following conditions;

If \( p \geq 1 \% \) \( \text{or } |\psi| \geq 36^\circ \) then \( \beta = 0 \)

If \( p < 1 \% \) \( \text{or } |\psi| < 36^\circ \) and \( \theta > 25^\circ \) then \( \beta = -0.005(|\psi| - 36) \)

Otherwise \( \beta = -0.005(|\psi| - 36) + 1.8 - 4 \times 2.5 \sin \theta \)

\[
A_E = A_{0.01}(p\%0.01) (0.655 + 0.03d(1-p) - 0.045 \ln(A_{0.01}) - 0.09(1-p) \sin \theta)
\]  

(12)

The derived rain heights and attenuations for all study stations were used to generate contours maps. The contour maps were developed using Kriging method which plots the data at their respective coordinate on a gridded map. This method uses geostatistical interpolation to spread spatial data over different spatial support using function \( Z_0 \) defined as;

\[
Z_0 = \sum_{i=1}^{n} \lambda_i Z_i
\]  

(13)

where \( Z_0 \) is the estimated rain height by kriging, \( Z_i \) is the known rain height or attenuation at point i with a weighted parameter \( \lambda_i \). \( n \) is the number of available data points. The value to be assigned to each point of the field without data does not depend on all the values available \( n \), but only on those observed in the closest points. These methods are commonly used in geosciences because they give a good estimate for
spatial distribution. The weight is determined to ensure that the estimator is unbiased and that the estimation variance is minimal [27].

4. Results and discussion

4.1. Temporal variation of rain height

The temporal variation investigates the behaviour of rain height over time. Several studies have revealed that $H_r$ is location-dependent hence the localized values are most preferred for estimation of rain-induced attenuation and fade margin [6]. Extensive studies were carried out to investigate the seasonal variability of $H_r$. The time scales employed in this study are Quad seasonal variation, Dual seasonal variation, and Year-wise variation.

4.1.1. QUAD seasonal variation of rain height

For the study of $H_r$ variation at high temporal resolution, the two main seasons in Nigeria were divided into four periods, namely; onset of rainy seasons (mid-March-May), intense rainy season (June-mid September), cessation period (mid-September-November), and mid dry season (December-mid March). Generally, $H_r$ begins to decline at the onset of the rainy season and attain minimum value when rain occurrence is at its peak i.e intense rainy season. At cessation period, $H_r$ begins to rise gradually till mid-dry season when it approaches its peak value.

However, the spatial studies have revealed that this trend is not absolutely governed by the seasonal rainfall pattern. For instance, $H_r$ rises gradually from June to August in all the stations in the Sahel zone as shown in Figure 2a. This period is associated with high precipitation in this zone [28] and the consequence is expected to be decreasing $H_r$. The maximum monthly $H_r$ was observed in the month of November for Sahel, Guinea, and Midland savanna while the peak occurred in February for both Coastal zone. Statistically, the range of the monthly $H_r$ in each station is less than 0.17 km with maximum standard deviation of 0.06 observed in Calabar. This implies that the annual mean $H_r$ discussed in subsequent paragraphs are reliable and recommendable throughout the year.

Figure 2. Monthly variation of Rain Height for (a) Sahel, (b) Midland Savanna, (c) Guinea Savanna, (d) Coastal Zone.
4.1.2. Dual seasonal variation of Hr

Since Nigeria experiences two extreme weather conditions annually, the variation of Hr height during the two seasons was also studied. The seasonal variation of Hr aligns with that of ho as discussed by [29]. The monthly plots in figure 2a-d indicate that rain height varies slightly with the seasonal rainfall pattern. The wet months were observed to possess higher Hr relative to the dry months in the Sahel [30]. However, the seasonal variation in the Midland, Guinea Savannah and Coastal Zone indicates that rain heights are lower in the rainy months when compared with the dry months as depicted in figures 2b - d. The coastal zone has the widest seasonal variation while the Sahel has the least. This is because the Sahel zone is bordered by the hot Sahara Desert while the coastal zone shares the country border with the cool Atlantic Ocean. Higher rain height values prevail in the dry months while the values are low in the wet months. The bumps at the ninth month in Figure 2d could be attributed to the famous august-break associated with the guinea savannah and coastal zone [15].

Figure 3a and b show the 9 years dry and wet season contour maps respectively. During the dry season, Hr over Nigeria varies between 5.178 km and 5.309 km while the wet season values span from 5.135 to 5.361 as depicted in figures 3a and b. However, it could be deduced from the maps that the seasonal values are closely the same in the Midland and Guinea Savannah while faint variation could be observed at the Sahel and Coastal Zones. The annual mean of the Hr for each location was computed and used to generate contour maps for Nigeria as shown in Figure 3c. According to the map, Hr decreases from about 5.254 km in the Coastal zone (Southern Nigeria) to about 5.153 km in the Sahel (Northern Nigeria). The map is highly recommended for the studies of spatial variation of Hr in Nigeria.

4.1.3. Year wise variation of Hr

The annual variation of Hr was computed for 9 years in all the study locations based on geoclimatic classifications. Figures 4a-d shows that Hr exhibit neither an increasing nor decreasing trend over the studied years in all the stations. Generally, Hr rises from 2006 to 2007 after which it falls to all-time low values in 2008 in all the stations. This was followed by a gradual increase from 2009 until it attains maximum values in 2010. The Hr begins to fall after the astronomical increase in 2010 except for year 2014 which experiences a slight increment when compared with the preceding year. The four stations representing the Sahel zone possess their minimum annual Hr in 2008 ranging from Sokoto at 5.12 km, Katsina at 5.14, Maiduguri at 5.15 km, and Kano at 5.15 km. Maximum annual Hr were observed in 2010 with Kano, Maiduguri, Katsina, and Sokoto having 5.31 km, 5.30 km, 5.30 km, and 5.26 km respectively. The minimum annual Hr in the Midland savannah stations also occurred in 2008 except for Abuja where the value for 2013 is slightly lower with a negligible difference of 0.009 km. Bauchi recorded its lowest value of 5.14 km, Jalingo has 5.16 km, Jos recorded 5.22 km while a minimum of 5.15 km was observed for Abuja station in 2013. It is worthy to note that 2010 has the highest amount of rainfall not just in all the study locations but throughout Nigeria as reported by [28]. The excess rainfall actually suppressed other Hr-determining factors and resulted in increased Hr in all stations. Hence, Maximum Hr was observed in 2010 in all the geoclimatic zones. The annual peak values are 5.32 km at Jos, 5.30 km at Abuja, 5.29 km at Jalingo, and 5.28 km at Bauchi. In the Guinea savannah, the minimum and maximum annual Hr were also observed in 2008 and 2010 respectively for all the stations. It was noted that the annual variation of Hr in the Savannah (Midland and Guinea Savannah) zone is moderately between 5.15 km and 5.30 km except for Jos whose range is influenced by the height of the station above the sea level. This is simply because the two savannah zones are the middle zones between the Sahel and coastal regions. They experience neither extreme hot weather like the Sahel nor extreme cool weather like the coastal zone. Lokojia and Makurdi both have the lowest Hr of 5.14 km and 5.16 km in 2008 while Akure and Ilorin possess highest values of 5.30 km in 5.29km in 2010. The annual trend of Hr in the coastal zone follows the same pattern as described in other zones. Apart from the year 2010 which experienced a surge in the amount of precipitation nationwide, the annual variation in the coastal zone actually lies between 5.15 km and 5.22 km as depicted in Figure 4d.
4.2. Spatial variation of Hr

In addition to the monthly, yearly and seasonal variation of rain height, this research also studies and reports the variability of rain height relative to the location of the study stations in Nigeria. Rain height varies significantly across all the studied stations due to the changes in the topographical and climatological properties. The results, as depicted in Figure 5, shows that rain height increases from the Sahel zone (Northern Nigeria) towards the Coastal zone (Southern Nigeria) except for Jos where a peak value of about 5.25 km was observed in the Midland Savannah. It is fairly constant between 5.20 and 5.23 km in the Guinea Savannah and Coastal zones. Lowest prevail in the Sahel region due to the latitudinal dependence of rain heights. It is interesting to note that Sokoto which has the highest latitude among all the studied stations recorded the lowest of about 5.15 km, thus the average value for the Sahel zone is 5.18 km. The plot of stations latitude against rain height presented in Figure 5 gives a correlation coefficient of -0.5. The weak correlation implies that do not depend solely on the earth station latitude but also on other factors which include zero degrees isotherm height, temperature, humidity, rainfall amount as established by [11,31,32]. The prevalence of low in the Sahel zone could also be attributed to the dominance of tropical continental (cT) air masses which usually result into the extended dry season for about 6–8 months every year. Several research works have reported an inverse relationship between rain height and latitude [33, 34, 35, 36, 37]. This report, therefore, verifies the previous claims by these researchers.

The sinusoidal swing could be attributed to the non-uniformity of changes in the topography and climate of the stations. For instance, the high elevation of Jos is responsible for its extremely high rain height of 5.25 km as it is expected to be lower than the in low-latitude stations such as Ilorin, Akure, Makurdi, Lokoja etc. Although, Jos has the highest of 5.25 km as a result of its elevation, considerably high are dominance in the Coastal and Guinea Savannah zones due to the weak latitudinal dependence of rain height. The average annual rain height in the Midland and Guinea Savannah are 5.22 km and 5.21 km respectively. Although the latitudinal variation of was invalidated between the two

![Figure 4. Annual variation of Rain Height in (a) Sahel zone, (b) Midland zone (c) Guinea Savannah (d) Coastal zone.](image)

![Figure 5. Spatial distribution of Rain Height across the station and their latitudes.](image)
geoclimatic zones, this is due to the presence of a plateau in the Jos station. The Coastal stations possess higher when compared with the Sahel and Midland Savannah zones. The annual rain height for Lagos, Port Harcourt, Calabar and Warri were estimated to be 5.22, 5.20, 5.21 and 5.20 km, respectively thus, the annual mean rain height for the Coastal Zone is about 5.21 km. The overall mean rain height derived for Nigeria is 5.21 km with a standard deviation of 0.06. The result implies that the annual mean of 4.80 km recommended by ITU-R P.839-4 for Nigeria underestimates $H_r$ by 7.86%.

4.3. Estimation of rain-induced attenuation

The input parameters used in the computation of rain-induced attenuation are the rain height (ITU and derived values), converted 30-to-1 min rain rate from NASA GPM, Ka-Band downlink frequency (20 GHz), V-Band downlink frequency (40 GHz), and other ground station parameters. The elevation angles used for each of the study stations were those that correspond to NigComSat-1R (also known as NigeriaSat-2) as provided in Table 1 [38]. The NigComSat-1R is the only indigenous Nigerian satellite providing broadband internet services to the country with a footprint covering some West African and few European countries. The procedures for estimating rain-induced attenuations had been explained in the methodology section.

4.4. Dependence of rain-induced attenuation on $H_r$

Rain remains the most severe factor among all the atmospheric disturbances militating the propagation of radio signals. Rain poses a serious threat to radio signals especially at frequencies above 10 GHz. Different sizes of raindrops are capable of either encapsulating (absorption) or diffracting (scattering) radio signals [39]. The scarcity of directly measured rain attenuation at higher frequencies such as Ka and V bands has necessitated several models for its prediction. The ITU-R P.618-12 recommendation remains the most efficient model provided locally measured input parameters are employed. The magnitude of rain-induced attenuation along earth-space links depends on several factors such as look-up angle, latitude of the earth station, transmission frequency, rain rate, rain height among others. This section investigates the influence of $H_r$ on attenuation by comparing its values using the ITU-R recommended rain heights and newly derived rain height from GPM data. The typical annual mean rain heights deduced for the study stations, the geoclimatic rain height, as well as the ITU-R rain heights, were used to compute attenuation at Ka and V bands, and the corresponding results obtained are presented in Figures 6 and 7 respectively. The geoclimatic rain height refers to the average $H_r$ in the four study stations representing each geoclimatic region. The two stations with the most and least deviated $H_r$ values from the geoclimatic $H_r$ are featured in Figures 6 and 7.

At the Ka-band, the variation of rain heights has an insignificant ($p$-value $> 0.05$) effect on attenuation in all the stations at a higher percentage of time exceedance, say 0.5% and above. This is evident from the referenced figures 7a-d as the attenuations obtained between 0.5 – 1% exceedance using different rain heights have produced the same results. However, at a lower percentage of time exceedance i.e $p < 0.5\%$, which translates to a higher period of signal availability, the rain height influences the level of attenuation in all stations. At the Sahel zone, the ITU-R $H_r$ completely underestimates attenuation in all the stations. Although the attenuation obtained for Sokoto is slightly close to that of ITU-R $H_r$-based attenuation, this is obviously due to the low value of the derived $H_r$ (5.15 km) when compared with other stations. For instance, at 0.01%, the ITU-R $H_r$-based attenuation is 32.3 dB while that of Sokoto-$H_r$ is 33.5 dB resulting in a percentage difference of 3.6 %. At the same exceedance

Figure 6. Rain induced attenuation at Ka band for (a) Sahel, (b) Midland Savanna, (c) Guinea Savanna, (d) Coastal zone.
level, Katsina has a corresponding attenuation of 36.6 dB which results in a percentage difference of 11.8%. The p-value in both cases is less than 0.05 which implies that rain height plays a significant role in attenuation magnitudes at a low percentage of time exceedance. At the Midland savannah, the ITU-R *Hr*-based attenuation performed well for all the four stations except at Jos stations where very low attenuation was observed throughout. The Jos-*Hr* based attenuation at 1%, 0.1% and 0.01% are 3.1 dB, 14.0 dB and 30.9 dB respectively whereas the corresponding ITU-*Hr* based attenuation are 4.0 dB, 17.5 dB and 37.7 dB. This suggests that the localized *Hr* is the most suitable for predicting attenuation and rain fade depth. Although the Geoclimatic *Hr* recommended for the Midland savannah zone is 5.22 km, the weird elevation of Jos settlement indicates that *Hr* of 5.25 km is more preferred.

The influence of *Hr* on attenuation in the Guinea savannah region remains minimal when compared with other geoclimatic zones. The ITU-*Hr*-based values only underestimate attenuation with a percentage difference of about 12.1% from 0.1% exceedance and below in Akure, while the percentage difference for Guinea savannah *Hr*-based attenuation is 9.5%. The rain-induced attenuation derived for Lokoja has the highest difference of about 4.1% at 0.001% exceedance level compared with the geoclimatic attenuations. In the coastal zone, the Lagos *Hr*-based attenuation is approximately the same with that of ITU-*Hr*-based at all percentages of time exceedance but remain at variant with other stations as depicted in Figure 6d. This indicates that the Lagos *Hr* attenuation is in agreement with the ITU-*Hr* attenuation. However, the location-dependent *Hr* attenuations for other stations show that ITU-*Hr*-based values grossly underestimate attenuation significantly. The influence of the prevailing high rain rate of about 140 mm/*Hr* at 0.01% exceedance is responsible for the all-time high attenuation observed in PH even with a lower *Hr* of 5.21 km. The average rain height for the coastal zone is 5.21 km which results in moderate attenuation of 5.4 dB, 23.8 dB, 48.8 dB at 1%, 0.1%, and 0.01% exceedance respectively.

The attenuations at V-Band for the stations in the four geoclimatic zones are as presented in Figures 8a-d. The behavior of attenuation values at V-band is not different from that of Ka-Band except that the values are higher due to increased frequency. These data are crucial for the planning and design of efficient earth-space V-Band links. The attenuation at various percentages of exceedance shows that radio signals operating at V-Band could suffer severe degradation with signal loss up to 139 dB at 0.01% in the coastal zone. The average attenuations at 0.01% of time exceedance are 102.8 dB at Sahel, 102.5 dB at Midland savannah, and 118.6 dB at Guinea savannah. The corresponding values obtained by [40] for some stations in each geoclimatic zone are quite lower because they employed the ITU-R P839-3 rain height (4.86 km) throughout the study stations. The Midland Savannah has the least deviation from the ITU values followed by the Sahel and Guinea savannah while the Coastal zone is the most deviated.

The Ka-Band attenuation at 1%, 0.1%, and 0.01% for the study stations have been used to generate contour maps in figures 8a, b, and c respectively. Similarly, figures 9a, b, and c show the contour map for

![Figure 7](https://example.com/figure7.png)

**Figure 7.** Rain induced attenuation at V band for (a) Sahel, (b) Midland Savanna, (c) Guinea Savanna, (d) Coastal zone.
V-Band attenuation at 1%, 0.1%, and 0.01% respectively. It could be conveniently established from the map that attenuation increases from the northern part of the country towards the south. Although only a few areas anomalous variation contrary to the northward trend, this is mostly due to the height of such stations above sea level. These maps would serve as a robust database for radio link budget and design across Nigeria.

Figure 8. Attenuation Contour Map for the study location at (a) 1% (b) 0.1% and (c) 0.01% exceedance for Ka-band frequency (20 GHz).

Figure 9. Attenuation Contour Map for the study location at (a) 1% (b) 0.1% and (c) 0.01% exceedance for V-band frequency (40 GHz).
4.5. Conclusion

Rain heights for the study stations have been derived from GPM data and compared statistically with ITU-R P.839-4 recommendations. Rain height is location-dependent and varies seasonally. The seasonal variation is quite minimal hence, the annual mean values are suitable for use. The study reveals that the ITU-R recommendations underestimate $H_r$ in all the study stations. The annual mean values of $H_r$ obtained for the Sahel, Midland Savannah, Guinea Savannah, and Coastal zones are 5.18 km, 5.22 km, 5.21 km, and 5.21 km respectively. This imply that the ITU $H_r$ is lower than the geoclimatic values. The influence of the rain height on rain-induced attenuation at ka and V-bands was also examined. Statistical analysis reveals that the relationship between rain height and attenuation is significant at lower percentages of time exceedance. It was observed that the attenuations calculated based on ITU $H_r$ grossly underestimate attenuation values in most stations. The attenuations based on the location-dependent rain heights have been used to generate contour maps for the entire country. To achieve 99.99% signal availability i.e 0.01% exceedance level, it is highly recommended that suitable fade mitigation techniques that can compensate for signal fade depth up to $52 \text{ dB}$ and $150 \text{ dB}$ at Ka and V-bands should be deployed.

Declarations

Author contribution statement

Y.B. Lawal: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Contributed reagents, materials, analysis tools or data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

J.S. Ojo: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

S.E. Falodun: Conceived and designed the experiments.

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Data availability statement

Data associated with this study is available at https://disc.gsfc.nasa.gov/datasets?keywords=GPM_2APRamp;page=1 and https://apps.eomwf.int/datasets/data/interim-full-moda/levtype=sfc/.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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