Rain Height Statistics from GPM Data for Satellite Communication Systems in Nigeria

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Abstract. In this present era, the rising demand for seamless wide band internetwork services such as 5G network requires the propagation of radio waves at high frequency. Rain-induced attenuation poses a lot of dangers on Earth-Space satellite links operating at frequencies above 10 GHz. Although the magnitude of overall attenuation on any radio link is determined by various natural phenomena such as atmospheric gases, fog, mist, aerosol, ice, contribution by rain remains the most significant. This paper provides extensive study on the rain heights variability in Nigeria using data obtained from the Global Precipitation Mission (GPM). The result depicts an increasing trend of rain height from 4.92 km in the southern part of the country to about 5.23 km in the north. The results show that ITU-R recommended value underestimate rain height. The results also show seasonal dependence of rain height throughout the years of study. Analysis of the GPM data shows that freezing heights across all stations were underestimated by about 9% when compared with previous TRMM-based research. The present study has revealed the preference of GPM data over TRMM data for the estimation of rain height and rain-induced attenuation.

Keywords: Attenuation, Rain Height, Freezing Height, ITU-R, GPM, TRMM

1. Introduction
Wireless communication is subjected to several atmospheric disturbances as the radiowaves travel from transmitting antenna to receiving antenna. The extent to which radio signals are attenuated is collectively determined by many factors such as the frequency of the radio wave, polarization, elevation, rain height, rain rate, zero-degree isotherm height, e.t.c. Among these parameters rain rate and rain height are the most important factors which account for high value and significant variation in attenuation occurrence probability [1]. For earth-space satellite links, severe attenuation is usually experienced between the ground stations and a level within the troposphere known as the rain height $h_r$. According to the International Telecommunication Union - Recommendations (ITU-R), the $h_r$ is assumed to be 360 m higher than the top of the bright band i.e zero-degree isotherm height $h_o$ [2]. Rain height is the level up to which there are rain droplets with a diameter greater than 0.1 mm. It is the highest point level of rain region measured from sea level where supercooled melted ice begins to fall as precipitation. Rain height is a function of several weather parameters such as amount of rainfall, temperature, evapotranspiration rate amongst others which vary temporally and spatially.

In some areas where the height of earth’s surface above sea level is absolutely negligible, the effective rain height may be assumed to coincide with the zero-degree isotherm height $h_o$. However, it should be noted that earth stations with considerable height above the sea level possess significant difference between zero-degree isotherm height $h_o$ and rain height $h_r$. Generally, the mean annual rain height recommended by the ITU is determined as:
where \( h_0 \) is the zero-degree isotherm height above mean sea level obtainable from ITU-R P.839-4 map. The recommended map puts \( h_0 \) at 4.5 km for the tropical regions, Nigeria inclusive. This implies that the recommended \( h_r \) for Nigeria is 4.86 km. Several studies conducted by many researchers throughout the world have revealed that the ITU-Recommendation either underestimates or overestimates rain heights at different locations on the earth [3-9]. It should be noted that none of the previous works cited in this paper employ GPM data, thus the need for thorough comparison. Application of GPM data to determine rain height in Nigeria is what defines the uniqueness of this work.

2. Data source and Methods
The data used for this research is a 10-year (2008-2014) GPM data obtained from the archive of the National Aeronautical Space Agency (NASA) and Japan Aerospace Exploration Agency (JAXA). It is a level 2 product available at https://disc.gsfc.nasa.gov/datasets?keywords=GPM_2APR&page=1. The data which were directly measured by the Tropical Rain Measurement Mission – Precipitation Radar (TRMM PR) between 1997 and 2014 were reprocessed, improved for better accuracy and migrated into the GPM database using the new GPM algorithm. Purposely for the measurement of global precipitation, NASA and JAXA launched an international satellite known as GPM. It serves as a continuation of the TRMM mission which officially ended in the year 2015[10].The GPM data has several advantages over the natural TRMM data, such as better file naming convention, lower rain rate integration time, merging of level 2 and 3 datasets thus reduction in file sizes, migration from Hierarchical Digital Format 4 (HDF4) to HDF5 format, extended capability to measure light rain (< 0.5 mm/hr), and ability to measure solid precipitation [11]. Unlike, the TRMM/PR, the DPR consists of two rain radars that run at 13.6 GHz and 35.5 GHz channels. The full details of the Ku-band Precipitation Radar (KuPR) and Ka-band Precipitation Radar (KaPR) design specifications can be found in [12]. According to [12], a major source of error in the rainfall estimates from the TRMM/PR comes from the uncertainty in the conversion of radar reflectivity into rainfall rate. The anomaly has been identified to be the trends in the raindrop size distribution (DSD) based on region, season and the type of rainfall. An additional Ka-band frequency radar was added to the GPM sensor suite to provide DSD information which can be derived from non-Rayleigh scattering effects [12]. Thus, the GPM provides more accurate raindrop size distribution estimated from the Dual Precipitation Radar (DPR).

Product 2APR in the GPM dataset was downloaded from the NASA website mentioned above. The data is made up of several HDF files with each file representing daily values of precipitable water vapour, precipitation rate, freezing height, storm height etc. The freezing heights were extracted from the HDF files using the Matlab program. Data for sixteen stations were used with four stations representing each of the geoclimatic zones as presented in Table 1. Rain heights were determined based on monthly, seasonal, and spatial variation using equation (1).
Table 1: Details of study locations and their geoclimatic features

| Location | Latitude (°N) | Longitude (°E) | Height Above Sea Level (m) | Geoclimatic Zone | Geoclimatic Feature |
|----------|---------------|----------------|----------------------------|------------------|---------------------|
| Sokoto   | 13.006        | 5.248          | 318                        | Sahel            | where the tropical continental (cT) air mass predominates and the tropical maritime (mT) air mass invades for between 3 and 5 months at most |
| Katsina  | 12.514        | 7.611          | 519                        |                  |                     |
| Maiduguri| 11.831        | 13.151         | 320                        |                  |                     |
| Kano     | 12.002        | 8.592          | 488                        |                  |                     |
| Abuja    | 9.076         | 7.398          | 360                        | Mid-Land/Derived Savannah | predominantly highland, where the cT air mass dominates but where the topography effectively extends the length of the humid period because of localized convection and orographic effects |
| Jos      | 9.896         | 8.858          | 1,186                      |                  |                     |
| Bauchi   | 10.301        | 9.824          | 616                        |                  |                     |
| Jalingo  | 8.893         | 11.377         | 349                        |                  |                     |
| Akure    | 7.257         | 5.206          | 350                        | Guinea Savanna   | where mT air dominates for about 7 months and cT air dominates for the remaining 5 months. |
| Lokoja   | 7.802         | 6.733          | 53                         |                  |                     |
| Makurdi  | 7.732         | 8.539          | 104                        |                  |                     |
| Ilorin   | 8.479         | 4.542          | 320                        |                  |                     |
| Lagos    | 6.524         | 3.379          | 41                         | Coastal          | Domained by mT air for most of the year |
| Warri    | 5.554         | 5.793          | 6                          |                  |                     |
| Calabar  | 5.00          | 8.40           | 32                         |                  |                     |
| Rivers   | 4.745         | 6.823          | 65                         |                  |                     |

3. Results and Discussion

Nigeria is classified into four geoclimatic zones namely: Sub-Sahel, Derived Savannah, Guinea Savannah and the Coastal zones [13]. The monthly variation of freezing height in all the stations are presented in Figures 1 (a-d). The trend shows that freezing height rises gradually at the onset of the dry season and usually attain peak when the dust-laden harmattan is predominant. It decreases to minimum value during the wet months and begins to rise again towards the cessation of the raining season.

This result contrary to some previous literature which claim that zero-degree isotherm heights also known as freezing heights are generally low during dry season and posses high values in the wet months[14-17]. Although, none of the previous researches utilize GPM data, the critical comparison of results predicts significant different between TRMM and GPM data.
In the Coastal region, freezing height value drop sharply at the onset of raining season in the month of May from 4.89, 4.91, 4.90 and 4.91 km from Port Harcourt, Warri, Lagos and Enugu respectively. Although, a little spike was observed in the month of august which may be attributed to the famous august-break. The mean wet season of freezing heights are 4.78, 4.78, 4.79 and 4.78 km in the four stations respectively, thus the overall wet season average freezing height is 4.78 km while the corresponding average for the dry season value is 4.89 km. This implies that the average annual freezing height and rain height in the Coastal zone are 4.84 km and 4.92 km respectively. A similar seasonal trend was observed in Guinea and Derived Savannah zones. The mean wet season and dry season of 4.79 and 4.90 km respectively put the annual freezing height and rain height in the guinea savannah zone at 4.84 km and 5.05 km height. For the Derived savannah zone, the mean wet and dry seasons freezing height are 4.79 and 4.89 km respectively, while the annual freezing height and corresponding rain height are 4.84 and 5.47 km respectively. The variations between the wet and dry seasons values in the Sahel regions were insignificant (< 0.8 %). This minimal seasonal difference could be attributed to less amount of rainfall associated with Sahel region when compared with other zones of the country. The mean freezing...
heights during the wet and dry months of the seasons are 4.8 and 4.84 km respectively, hence, the corresponding annual freezing height and rain height are 4.82 and 5.23 km respectively. Figure 2 shows the seasonal values of freezing heights in all the study locations. Higher values prevail in the dry season while low values dominate throughout the raining season.

![Figure 2: Distribution of Zero Degree Isotherm Height over Nigeria during wet and dry seasons](image)

The freezing heights obtained for all the stations were compared with the TRMM-based research work of Omotosho and Oluwafemi [18] as presented in Table 2. The TRMM-based research underestimates freezing heights with percentage differences between 7.7 % and 9.5 % across the country. Similar trends were observed in other previous researches that utilized TRMM data for the same study locations [9, 16-18]. This implies that newly derived rain height is highly recommended for better prediction of rain-induced attenuation in Nigeria.

**Table 2: Comparison of Freezing Heights Obtained from GPM and TRMM Data**

| Station   | \( H_o \) using GPM Data (m) | \( H_o \) using TRMM Data (m) | Percent Diff (%) |
|-----------|-------------------------------|-----------------------------|-----------------|
| Kano      | 4835                          | 4410                        | 8.8             |
| Katsina   | 4821                          | 4410                        | 8.5             |
| Maiduguri | 4847                          | 4420                        | 8.8             |
| Sokoto    | 4800                          | 4430                        | 7.7             |
| Jos       | 4836                          | 4400                        | 9.0             |
| Jalingo   | 4849                          | 4390                        | 9.5             |
| Bauchi    | 4841                          | 4420                        | 8.7             |
| Abuja     | 4846                          | 4400                        | 9.2             |
| Makurdi   | 4855                          | 4400                        | 9.4             |
| Akure     | 4842                          | 4390                        | 9.3             |
| Ilorin    | 4834                          | 4420                        | 8.6             |
| Lokoja    | 4844                          | 4390                        | 9.4             |
| Port Harcourt | 4838 | 4380 | 9.5   |
| Warri     | 4835                          | 4380                        | 9.4             |
| Lagos     | 4845                          | 4400                        | 9.2             |
| Calabar   | 4841                          | 4400                        | 9.1             |
4. Conclusion

In this work, freezing height and rain height have been computed from GPM data which is the newly improved version of TRMM data. The results have shown that rain heights increase from the coastal zone (Southern Nigeria) towards the Sahel zone (Northern Nigeria) in both dry and wet seasons. The freezing heights observed during stratiform rainfall in the dry season are higher than those recorded in the wet months in all the zones but with minor differences in the Sahel. The freezing height obtained in this work is higher than earlier results obtained using TRMM data and the ITU recommended value for the tropical region. The statistical analysis of this research predicted an overall mean rain height is 5.11km for Nigeria. Further GPM-based research covering all regions of the world is encouraged as the GPM remains the latest satellite-borne global precipitation radar.

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