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0°C isotherm height distribution for Earth-space communication satellite links in Nigeria

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For an optimum performance of Earth-space satellite communication links, a number of meteorological parameters are needed to be considered along the Earth-space path for specific locations and the height of the 0°C isotherm (freezing level height) is among such parameters. Information regarding this parameter is always based on the recommendation of ITU-RP-839 in the form of contour maps. Since the meteorological parameters are location dependent, there is a need for the establishment of these parameters for specific locations. In addition, ITU-R model uses an yearly averaged constant rain height for the attenuation estimation, which may not be appropriate for tropical regions. In the present paper, the 0°C isotherm (ZDI) height has been established using two years of data collected on-board the precipitation radar of the Tropical Rain Measuring Mission (TRMM) satellite. The result shows the seasonal dependence of the 0°C isotherm height. It is observed, among other things, that the height is higher during the wet season as compared to the dry season. Rain induced attenuation at frequencies above 10 GHz is also estimated using the 0°C isotherm height derived for each of the locations over the elevation angle of the NIGCOMSAT-1R in Nigeria.

Keywords: Zero degree isotherm height, Freezing level height, Rain height, Rain attenuation, Earth-satellite link

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1 Introduction

Earth-space satellite communication links operating at 10 GHz and above are attenuated greatly by hydrometeors, like rain, hail, clouds, fogs, etc. However, rain poses the maximum threat to the link[1]. As the rain rate and frequency increase, the level of signal attenuation also increases[2,3]. For proper planning and design, it is important to have appropriate propagation data and prediction techniques as recommended by the International Telecommunications Union[4] (ITU-R). The prediction techniques take into account a number of parameters in estimating the fade margin required for link availability and one of these is the average 0°C isotherm height. During stratiform type of rain, the point, where the frozen water or ice begins to melt and forms rain, is the 0°C isotherm height[5]. Due to the differences in propagation characteristics of radio waves in ice and water, this parameter gives an effective boundary between the regions where the attenuation estimations are performed differently[6]. The ITU-R[7] provides information needed regarding this height during periods of precipitations. It gives a global map of 0°C isotherm height above mean sea level (km) with a resolution of 1.5° by 1.5° in latitude - longitude and encourages this information to be used in regions of the world where no specific information is available. It also provides a relation to estimate the rain height from the 0°C isotherm height. Recommendation ITU-R[4] uses this information and gives a general method to predict attenuation due to precipitation along a slant propagation path. However, the major inaccuracy in the prediction of rain attenuation over Earth-satellite links has been found to arise from the ambiguity in the structure of the rainfall over the path and uncertainty in estimating the attenuation due to melting layer[8,9].

It is found that the diurnal variation of 0°C isotherm height is negligible over the tropics and temperate locations but not the monthly and seasonal variations[6,10]. Rainfall events in the tropical and equatorial regions are more intense and usually associated with convective cells and thunderstorm with a vertical dimension reaching altitudes much higher than the 0°C isotherm height[3,11].

Thurai & Iguchi[12], in their earlier work on rain height information from TRMM Precipitation Radar (PR), studied the latitude dependence of freezing level heights in some tropical and sub-tropical regions using data on-board the TRMM satellite. They were able to establish the annual average of the melting layer heights and their seasonal variation using two years of data. However, this study was limited to a few locations.

In this paper, the annual average of 0°C isotherm height is presented over some locations in Nigeria using two years of precipitation data from the precipitation radar on-board the Tropical Rain Measuring Mission (TRMM) satellite. The rain height is also estimated based on the result, which has been used to calculate the attenuation level of radio waves due to rain over these locations at different frequencies (10 GHz and above) and over the chosen elevation angle of the Nigeria Communications Replacement Satellite-1 (NIGCOMSAT-R1) of 42.5°. Typical statistical values, like the rainfall rate of 0.01% with integration time of one minute and the average 0°C isotherm height recommended by ITU-R are used for the attenuation estimation

2 Nigerian climate and Data

Nigeria is located at 7.62°N and 6.97°E and in West Africa. It has two distinct seasons: the dry season, which is influenced by the Northwest trade wind and runs normally from November to March; and the wet/rainy season, which runs from April to October and is influenced by the South-East trade winds. The wet/rainy season is always associated with heavy rainfall, which is sometimes accompanied by thunderstorms. Nigeria, being a tropical country, experiences abundant sunshine throughout the year. There are four climate types and are distinguishable as one move from the southern part of the country to the northern part through the middle belt.

The 0°C isotherm height is derived from TRMM-PR observations taken over six locations in Nigeria; These are: Abuja (9.04°N, 7.28°E), Akure (7.18°N, 5.12°E), Bauchi (10.18°N, 9.46°E), Enugu (6.24°N, 7.24°E), Kaduna (10.32°N, 7.25°E), and Port Harcourt (PH) (4.43°N, 7.02°E). Each of the locations chosen represents different climatic regions of the country. The characteristics of each of the locations used for the study are presented in Table 1. The TRMM-PR is the first space borne rain radar and the only instrument on TRMM that can directly observe vertical distributions of rain. The operating frequency of the instrument on TRMM-PR is 13.8 GHz. The PR can achieve quantitative rainfall estimation over land as well as the ocean. The PR can also provide rain height information, which is useful for the radiometer based rain rate retrieval algorithms. The footprint size of PR is small enough to allow for the study of inhomogeneous rainfall effects upon the comparatively coarse footprints of the low frequency microwave radiometer channels[13,14]

During the normal observation mode, PR antenna beam scans in the cross-track direction over ±17° to have 220 km swath width from end to end. The antenna beam width of the PR is 0.71° and there are 49 observation angle bins within the scanning angle of ±17°. The horizontal resolution (footprint size) is 4.3 km at nadir and about 5 km at the scan edge when TRMM takes the nominal altitude of 350 km. The range resolution of TRMM-PR is 250 m, which is equal to the vertical resolution at nadir. The radar echo sampling is performed over the range gates between the sea surface and the altitude of 15 km for each observation angle bin. For nadir incidence, the mirror image is also collected up to the altitude of 5 km[14].

The PR-2A23 is one of the algorithms 2A23 censored by the TRMM-PR for event classification. The event classification is on the basis of the vertical reflectivity structure as well as the horizontal distribution of the reflectivity factor. It, further, identifies each measured profile (4.3 × 4.3 pixels) as stratiform, convective or other precipitation type. The algorithm is also tested whether a bright band exists in rain echoes and determines the bright band height if it exists[6,15,16]. It also detects isolated warm rain whose height is below the 0°C isotherm height. As the 13.8 GHz frequency band selected for the TRMM-PR is heavily attenuated by rain, the compensation of this rain attenuation becomes the major subject in the rain retrieval algorithms. Two years (2010 and 2011) data of TRMM 2A23 precipitation radar is used to obtain the 0°C isotherm heights.

Table 1 – Characteristics of the sites

Location	Coordinates °N	°E	Altitude, m	Climatic region	Average rainfall, mm h^{-1}
Abuja	9.04	7.28	334	Guinea Savanna	106.80
Akure	7.18	5.12	303	Rain Forest	112.67
Bauchi	10.18	9.46	451	Sahel Savanna	90.46
Enugu	6.24	7.24	139	Tropical Savannah	114.49
Kaduna	10.32	7.25	605	Sudan Savanna	97.78
Port Harcourt	4.43	7.02	18	Coastal	129.00

The rain height information is extracted according to the TRMM-PR algorithm which classified the rain type based on the two methods as explained by Thurai & Iguchi[12] and TRMM[14]. These methods are named vertical profile method (V-method) and horizontal pattern method (H-method). V-method detects the existence of bright band while H-method examines the horizontal pattern of reflectivity at a given height. Valid and invalid data are identified based on this algorithm. Valid values are used in this work. Analyis of the data involves computing the mean value for each day, then mean values of the days in a particular location are taken to get the average value for the height being considered at either the bright band height or freezing level height. The data is averaged daily to get the monthly value and the average of this gives the annual value for the parameter being considered.

3 Results and Discussion

3.1 Seasonal distribution of 0°C isotherm height over Nigeria

Figure 1 presents the monthly variation of the mean values of 0°C isotherm height averaged over two years of observations. It is observed that the highest values are recorded during the wet/rainy months of the year (April – October). This is in agreement with the earlier report by Mandeep[9] that during period of enhanced shower activities, the 0°C isotherm height is higher than during the dry months (November – March) due to the convective heating. For example, the months between June and September depict the peak of the rainy season in Nigeria. The results also show strong seasonal dependence of rain height as earlier reported by Thurai *et al.*[6]. It could also be observed that the 0°C isotherm height shows the slight location dependence with no two locations having the same value. However, the presence of annual oscillation (AnO) component could be observed at the 0°C isotherm height, although the actual values of the oscillation changes may be due to wave-wave of the precipitation, which occur at different periods and intensities.

3.2 Rain height

Rain height is the level up to which water drops with diameter larger than 0.1 mm during periods of precipitation. It is assumed that rain is uniform from the ground to the rain height according to the simple vertical structure and the rain height is quoted to be that level up to which raindrops have diameters of 0.1 mm or more[17].

Since the physical height of rain is not easily measurable, the simplest approximation for rain height is to use the level of the 0°C isotherm during rainy conditions as recommended by ITU-R[7] using the relation:

$$h_r = h_0 + 0.36 \text{ km} \qquad \dots (1)$$

where, h_r, is the rain height; and h_0, the height of the 0°C isotherm in km above mean sea level. The ITU puts the h_0 over all the locations in Nigeria at 4.5 km, which gives h_r as 4.860 km (predicted value) by using Eq. (1). The h_r of 4.697 km, 4.682 km, 4.686 km, 4.684 km, 4.695 km, and 4.676 km was also obtained for Abuja, Akure, Bauchi, Enugu, Kaduna, and Port Harcourt, respectively. This puts the average, h_r, value over Nigeria at 4.687 km above mean sea level. A percentage error of about 3.69 is calculated using the predicted h_r.

Table 2 presents the comparison of the rain height between the present study and other countries (tropical and temperate climate), where the values of

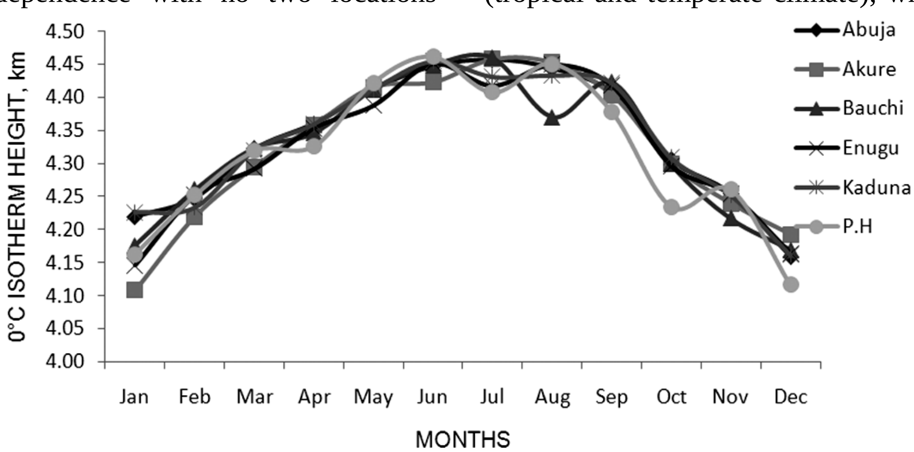

Fig. 1 – Monthly variation of average 0°C isotherm height over the six locations

Table 2 – Comparison of rain height between present study and other countries (tropical and temperate climate)

Source	Location	Coordinates	Climatic region	Average h_r, km
Ajayi & Barbaliscia[10]	Santa Rosa, Argentina	64.16°W, 36.34°S	Temperate	3.45
Ajayi & Barbaliscia[10]	Roma, Italy	12.2°E, 41.8°N	Temperate	2.31
Ajayi & Barbaliscia[10]	Dares Salam, Tanzania	39.7°E, 6.88°S	Tropical	4.65
Mandeep[9]	Subang, Malaysia	101.33°E, 3.07°N	Tropical/Equatorial	5.02
Mondal *et al.*[21]	Calcutta, India	88.20°E, 22.32°N	Tropical/Equatorial	5.9
Present study	Abuja, Nigeria	7.28°E, 9.04°N	Tropical	4.697
Present study	Akure, Nigeria	5.12°E, 7.18°N	Tropical	4.682
Present study	Bauchi, Nigeria	9.46°E, 10.18°N	Tropical	4.686
Present study	Enugu, Nigeria	7.24°E, 6.24°N	Tropical	4.684
Present study	Kaduna, Nigeria	7.25°E, 10.32°N	Tropical	4.695
Present study	Port Harcourt, Nigeria	7.02°E, 4.43°N	Tropical	4.676

h_r are taken from other sources. In a temperate region, h_r is significantly smaller than the tropical climate values. For locations in Nigeria, h_r was found to be slightly less than h_r values from locations in Malaysia and India. However, the value of h_r for location at Tanzania is slightly similar to the values obtained from locations in Nigeria.

3.3 Rain induced attenuation of radio waves

The recommendation ITU-R[4] makes use of point rainfall rate at 0.01% probability level to estimate the attenuation due to rain. The steps needed for the estimation of the long term statistics of the slant-path rain attenuation at a specific location for frequencies up to 55 GHz are:

Step 1: Determine the rain height, h_r as given in Recommendation ITU-R[7]. Table 3 presents the input parameters used in the estimation of rain attenuation.

Step 2: For θ ≥ 5°, compute the slant-path length, L_s (in km), using the rain height as:

$$L_S = \frac{(h_r - h_s)}{\sin} \quad \ldots (2)$$

For θ < 5°, slant-path length, L_s (in km) can be computed using:

$$Ls = \frac{2(h_r - h_s)}{\left(sin^2\theta + \frac{2(h_r - h_s)}{R_e}\right)^{1/2} + \sin} \quad \ldots (3)$$

where, R_e, is the effective radius of the earth (8,500 km); h_s, the height above mean sea level of the earth station (km); and θ, the elevation angle (degrees).

If (h_r-h_s) is less than or equal to zero, the predicted rain attenuation for any time percentage is zero and the following steps are not required.

Table 3 – Input parameters used in the estimation of rain attenuation

Locations	h_s	h_0	h_r	$R_{0.01}$,%
Akure	0.303	4.322	4.682	106.80
Abuja	0.334	4.337	4.697	112.67
Bauchi	0.665	4.326	4.686	90.46
Enugu	0.139	4.324	4.684	114.49
Kaduna	0.605	4.335	4.695	97.78
Port Harcourt	0.018	4.316	4.676	129.00

Step 3: Calculate the horizontal projection, L_G (in km), of the slant-path length using:

$$L_G = L_s \cos\theta \quad \ldots (4)$$

Step 4: Obtain the rainfall rate, $R_{0.01}$, exceeded for 0.01% of an average year with an integration time of 1 min. If this long-term statistics cannot be obtained from local data sources, an estimate can be obtained from the maps of rainfall rate given in Recommendation ITU-R[18]. If $R_{0.01}$ equals zero, the predicted rain attenuation is zero for any time percentage and the following steps are not required.

Step 5: Obtain the specific attenuation, $_R$ (dB km^{-1}), using the frequency-dependent coefficients given in Recommendation ITU-R[18] and the rainfall rate, $R_{0.01}$, determined from Step 4, using:

$$_R = k\,(R_{0.01}) \quad \ldots (5)$$

where, k and are constants and are frequency dependent. Table 4 gives the values for these constants for frequencies between 10 and 40 GHz. The $R_{0.01}$ is the point rainfall rate for the location for 0.01% of an average year (mm h^{-1}).

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

Table 4 — Regression coefficient for estimating specific attenuation[19]

Frequency, GHz	K_h	α_h	K_v	α_v	k	α
10	0.0121	1.2571	0.0112	1.2156	0.01172	1.23704
12	0.0238	1.1825	0.0245	1.1216	0.02420	1.15148
20	0.0916	1.0568	0.0961	0.9847	0.09389	1.01961
30	0.2403	0.9485	0.2291	0.9129	0.23465	0.93098
40	0.4431	0.8673	0.4274	0.8421	0.43518	0.85482

$$r_{0.0.1} = \frac{1}{1+0.78\sqrt{\frac{L_G \quad R}{f}} - 0.38(1-e^{-2L_G})} \quad \ldots (6)$$

where, *f*, is frequency (Hz).

Step 7: Calculate the vertical adjustment factor, ***v0.01***, for 0.01% of the time:

$$= \tan^{-1}\left(\frac{h_r - h_s}{L_G \, r_{0.01}}\right) \quad \text{(degrees)} \quad \ldots (7)$$

For $\zeta > \theta$, $L_R = \frac{L_G \, r_{0.01}}{\sin\theta}$ (km)

Else $L_R = \frac{(h_r - h_s)}{\sin\theta}$ (km)

If $|\varphi| < 36°$, $\chi = 36 - |\varphi|$ (degrees)

Else $\chi = 0$ (degrees)

where, φ, is the latitude of the earth station location (degrees); and L_R, radio path length.

Step 8: The effective path length is:

$$L_E = L_R \, v_{0.01} \quad \text{(km)} \quad \ldots (8)$$

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

$$A_{0.01} = \; _R L_E \quad \text{(dB)} \quad \ldots (9)$$

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

If $p \geq 1\%$ or $|\varphi| \geq 36°$, then $\beta = 0$

If $p < 1\%$ and $|\varphi| < 36°$ and $\theta \geq 25°$, then $\beta = -0.005(|\varphi| - 36)$

Otherwise, $\beta = -0.005(|\varphi| - 36) + 1.8 - 4.25 \sin\theta$ … (10)

$$A_P = A_{0.01}\left(\frac{p}{0.01}\right)^{-(0.655+0.033\ln(p)-0.045\ln(A_{0.01})-\beta(1-p)\sin\theta)} \quad \ldots (11)$$

where, β, is a constant that can be obtained from ITU-R[4]; p, the % of time of interest. The rain attenuation exceeded for different percentages of time is found by substituting for the percentages of time. This method provides an estimate of the long term statistics of attenuation due to rain.

Finally, the rain attenuation obtained using the h_r recommended by ITU-R[7] is compared with the value obtained using the measured h_r to obtain the predicted value error. The error using the two sets of data can be expressed as:

$$\Delta E \text{ (dB)} = A_p - A_m \quad \ldots (12)$$

where, E, is the % error; A_p, the predicted attenuation value based on the h_r recommended by the ITU-R; and A_m, the attenuation value obtained using the measured h_r.

For the estimation of rain induced attenuation, the point rain rate over each of the locations (Table 1) were used at different frequencies over the elevation angle of the NIGCOMSAT-1R of 42.5° using Eq. (11).

Figures (2-7) present the rain attenuation cumulative distributions at Ku and Ka-band frequencies over the six locations of study. Each of the figure for each location represents rain attenuation obtained using the h_r estimated from ITU-R value and the one estimated using the measured value, respectively. A direct proportionality between point rainfall rates and rain attenuation has been observed. Port Harcourt, having the highest value of point rainfall of 129 mm h^{-1} at 0.01% of time, recorded the highest values of attenuation as compared to the least values of attenuation recorded by Bauchi, having the least point rainfall of 90.46 mm h^{-1} at 0.01% of time. Attenuation also increased with increase in frequency[9]. It is also observed that rain induced attenuation becomes pronounced at frequencies above 10 GHz as earlier reported by Mandeep[9]. For example, the estimated values of rain-induced attenuation at 12 GHz between 0.1% and 0.001% probability levels needed for the design of low-margin Ka band communication systems and multimedia

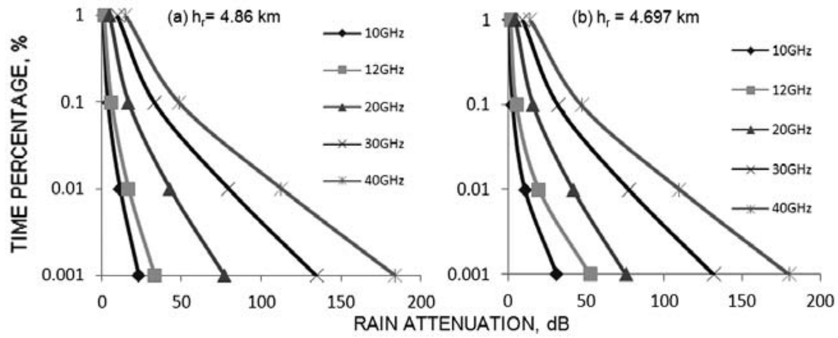

Fig. 2 – Rain attenuation distribution at different frequencies for Abuja (@ =42.5°) at: (a) h_r= 4.86 km and (b) h_r = 4.697 km

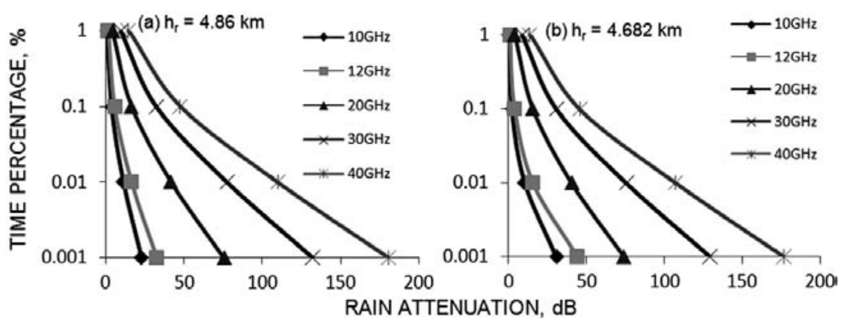

Fig. 3 – Rain attenuation distribution at different frequencies for Akure (@ =42.5°) at: (a) h_r= 4.86 km and (b) h_r = 4.682 km

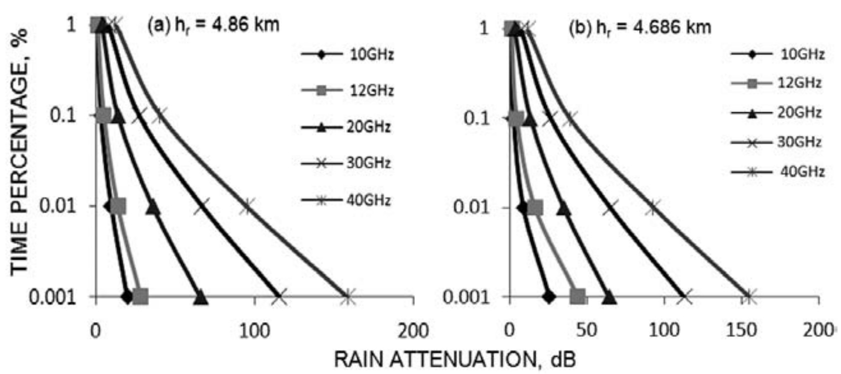

Fig. 4 – Rain attenuation distribution at different frequencies for Bauchi (@ =42.5°) at: (a) h_r= 4.86 km and (b) h_r = 4.686 km

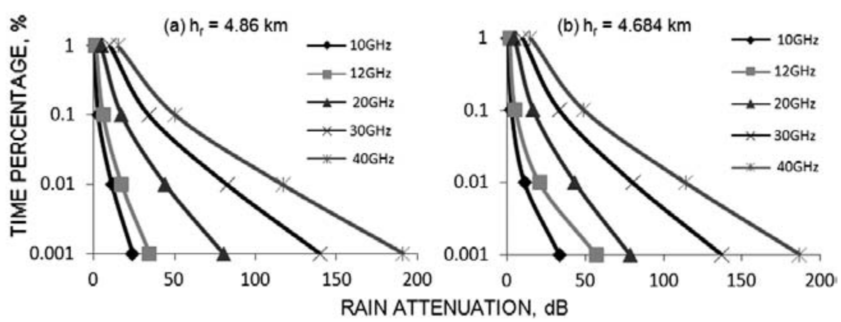

Fig. 5 – Rain attenuation distribution at different frequencies for Enugu (@ =42.5°) at: (a) h_r= 4.86 km and (b) h_r = 4.684 km

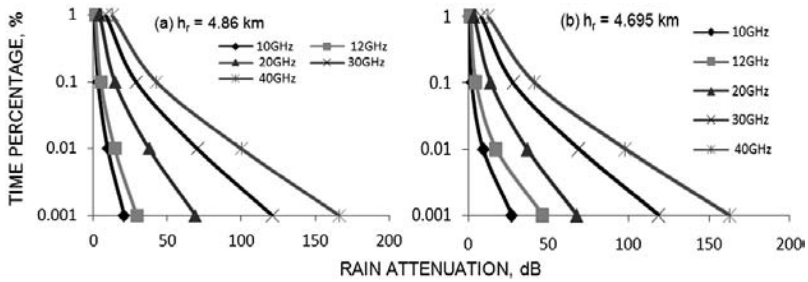

Fig. 6 – Rain attenuation distribution at different frequencies for Kaduna (@ =42.5°) at: (a) h_r= 4.86 km and (b) h_r = 4.695 km

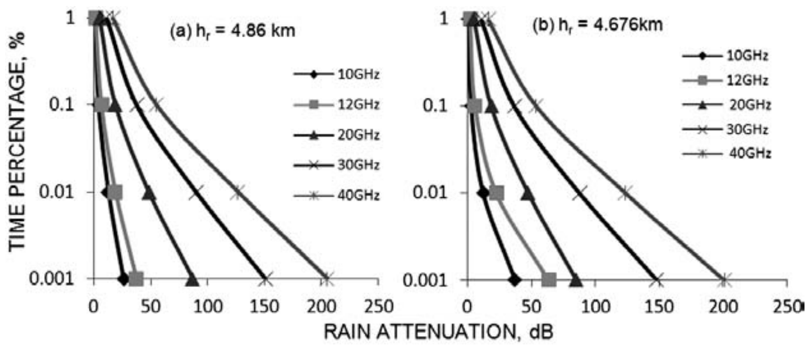

Fig. 7 – Rain attenuation distribution at different frequencies for Port Harcourt (@ =42.5°) at: (a) h_r= 4.86 km and (b) h_r = 4.676 km

Table 5 — Comparison of rain attenuation using measured h_r over six stations and the ITU-RP 839-3 (2001) value of h_r at elevation angle of 42.5°

Location	Rain attenuation/Error	Frequency					
		10 GHz	12 GHz	20 GHz	30 GHz	40 GHz	% of Time
Abuja	Rain attenuation, dB at h_r = 4.697	0.87	1.41	4.40	9.34	14.23	1
		3.67	5.68	16.11	32.04	47.07	0.1
		10.88	16.16	41.54	77.44	109.74	0.01
		22.72	32.38	75.48	131.91	180.30	0.001
	Rain attenuation, dB at h_r (ITU-R) = 4.86	0.89	1.44	4.51	9.59	14.62	1
		3.75	5.80	16.48	32.81	48.25	0.1
		11.08	16.46	42.39	79.12	112.22	0.01
		23.09	32.92	76.86	134.47	183.94	0.001
	Error, dB for different % of time	0.02	0.03	0.11	0.24	0.39	1
		0.07	0.12	0.36	0.77	1.17	0.1
		0.20	0.30	0.85	1.68	2.47	0.01
		0.37	0.54	1.38	2.56	3.64	0.001
Akure	Rain attenuation, dB at h_r = 4.682	0.86	1.38	4.30	9.11	13.95	1
		3.61	5.59	15.78	31.30	46.22	0.1
		10.72	15.91	40.76	75.82	107.93	0.01
		22.41	31.93	74.20	129.44	177.64	0.001
	Rain attenuation, dB at h_r (ITU-R) = 4.86	0.88	1.42	4.42	9.37	14.36	1
		3.69	5.71	16.17	32.12	47.48	0.1
		10.93	16.24	41.67	77.62	110.59	0.01
		22.81	32.52	75.69	132.19	181.56	0.001
	Error, dB for different % of time	0.02	0.03	0.12	0.26	0.42	1
		0.08	0.13	0.39	0.82	1.26	0.1
		0.22	0.33	0.91	1.80	2.66	0.01
		0.40	0.59	1.49	2.75	3.92	0.001

(*Contd.*)

Table 5 (*Contd.*) — Comparison of rain attenuation using measured h_r over six stations and the ITU-RP 839-3 (2001) value of h_r at elevation angle of 42.5°

Location	Rain attenuation/Error	Frequency					
		10 GHz	12 GHz	20 GHz	30 GHz	40 GHz	% of Time
Bauchi	Rain attenuation, dB at h_r = 4.686	0.72	1.17	3.68	7.86	12.07	1
		3.08	4.79	13.69	27.38	40.50	0.1
		9.26	13.85	35.83	67.15	95.75	0.01
		19.66	28.20	66.11	116.09	159.56	0.001
	Rain attenuation, dB at h_r (ITU-R) = 4.86	0.74	1.20	3.79	8.10	12.44	1
		3.15	4.91	14.04	28.11	41.63	0.1
		9.46	14.14	36.66	68.79	98.18	0.01
		20.03	28.73	67.48	118.63	163.17	0.001
	Error, dB for different % of time	0.02	0.03	0.10	0.23	0.37	1
		0.07	0.11	0.35	0.74	1.13	0.1
		0.19	0.30	0.83	1.64	2.42	0.01
		0.37	0.54	1.37	2.54	3.62	0.001
Enugu	Rain attenuation, dB at h_r = 4.684	0.93	1.50	4.65	9.82	14.93	1
		3.90	6.01	16.94	33.55	49.17	0.1
		11.48	17.01	43.48	80.74	114.17	0.01
		23.83	33.89	78.62	136.94	186.80	0.001
	Rain attenuation, dB at h_r (ITU-R) = 4.86	0.95	1.53	4.77	10.09	15.35	1
		3.98	6.14	17.34	34.38	50.44	0.1
		11.70	17.33	44.39	82.55	116.82	0.01
		24.24	34.48	80.11	139.69	190.70	0.001
	Error, dB for different % of time	0.02	0.04	0.12	0.27	0.42	1
		0.08	0.13	0.40	0.83	1.26	0.1
		0.22	0.33	0.92	1.81	2.66	0.01
		0.40	0.59	1.49	2.75	3.89	0.001
Kaduna	Rain attenuation, dB at h_r = 4.695	0.75	1.21	3.80	8.08	12.36	1
		3.18	4.94	14.06	28.05	41.37	0.1
		9.55	14.24	36.72	68.65	97.62	0.01
		20.21	28.90	67.58	118.41	162.35	0.001
	Rain attenuation, dB at h_r (ITU-R) = 4.86	0.76	1.24	3.90	8.31	12.73	1
		3.25	5.06	14.41	28.79	42.50	0.1
		9.74	14.53	37.55	70.29	100.04	0.01
		20.57	29.44	68.95	120.94	165.95	0.001
	Error, dB for different % of time	0.02	0.03	0.10	0.23	0.37	1
		0.07	0.11	0.35	0.74	1.13	0.1
		0.19	0.30	0.83	1.64	2.42	0.01
		0.37	0.54	1.37	2.53	3.60	0.001
Port Harcourt (PH)	Rain attenuation, dB at h_r = 4.676	1.05	1.68	5.18	10.88	16.45	1
		4.35	6.67	18.69	36.83	53.74	0.1
		12.67	18.69	47.52	87.87	123.73	0.01
		26.04	36.89	85.15	147.72	200.77	0.001
	Rain attenuation, dB at h_r (ITU-R) = 4.86	1.07	1.72	5.31	11.18	16.91	1
		4.44	6.82	19.13	37.75	55.13	0.1
		12.91	19.06	48.53	89.85	126.63	0.01
		26.48	37.54	86.77	150.71	204.99	0.001
	Error, dB for different % of time	0.02	0.04	0.13	0.30	0.47	1
		0.09	0.14	0.44	0.92	1.39	0.1
		0.24	0.36	1.01	1.98	2.90	0.01
		0.44	0.64	1.62	2.98	4.22	0.001

applications are about 5.4, 19.7 and 52.7 dB, respectively, whereas at 40 GHz, values of attenuation are about 47.1, 109.8 and 180.3 dB over Abuja, Nigeria. The same trend could be observed in other locations although with different values.

Table 5 shows a comparison of rain attenuation using the measured rain height and the predicted (ITU) rain heights at elevation angle of 42.5°. The level of rain attenuation obtained using the ITU-R[7] (predicted) values are higher than the rain height estimated from the TRMM data (measured). This shows that the value given by the ITU-R does not reflect the true local rain height characteristics for Nigeria because the 0°C isotherm height in Nigeria shows seasonal variation, rainfall types and location dependence. Attenuation of radio waves is higher at 0.001% of time than other percentages of time considered. The error values in dB between the actual values of attenuation and the ITU-R predicted values are obtained using Eq. (12) and are found to vary from a minimum value of 0.02 dB to a maximum value of about 5 dB. Generally, the error increases with frequency and the percentage of time. For example, in Abuja (Nigeria) at higher frequency band of 40 GHz, the error increases between 0.4 and 4 dB. The same trend could be observed in other locations at different frequencies although with different error values. The lower the altitudes of the location above sea level, the more likely the attenuation because the radio wave will encounter more path length and rain cells[20]. Port Harcourt has the least elevation angle and hence, highest level of rain attenuation could be observed from the location.

4 Conclusions

Two years of precipitation data from the precipitation radar on-board the TRMM satellite over some locations in Nigeria have been analyzed to estimate rain height based on 0°C isotherm height. It is observed that the 0°C isotherm height in Nigeria displays a strong seasonal dependence and the distribution over various locations shows very slight differences. A direct proportionality appear to exist between rain rate and rain attenuation, Port Harcourt with the highest value of point rainfall rate recorded the highest values of rain attenuation as compared to the least values recorded by Bauchi having the least point rainfall rate. Rain induced attenuation becomes more pronounced at frequencies above 10 GHz, between 0.1 and 0.001% probability levels, which are needed for the design of low margin Ka band communication systems and multimedia applications. It is also observed that the rain height values needed for rain attenuation estimation suggested by ITU-R do not reflect the true values for Nigeria. Hence, attenuation values may be overestimated by system designers if ITU-R values are used. These results are vital to system designers to achieve improvement on communication satellites and better availability of signals to end users.

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