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ESTIMATION OF ATTENUATION AT TRMM PRECIPITATION RADAR CHANNEL

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Abstract

The Tropical Rainfall Measuring Mission (TRMM) satellite is a novel mission to observe rainfall from space. The precipitation radar onboard the TRMM operates at 13.8 GHz. It measures several parameters which help to understand the cloud microphysics, viz. the characteristics of the melting layer, rainfall intensity, etc. However, at such a high frequency, the raindrops cause absorption and scattering of the signal leading to attenuation. Thus, the signal strength reduces, causing degradation of the signal. The knowledge of attenuation is of immense importance to the link designers. Besides, it has its applications in defense. The knowledge of attenuation is also necessary for climate study as it gives an insight into drop-size distribution. In this paper, the authors have attempted to estimate attenuation from the ITU-R model by using the TRMM-retrieved rainfall as an input. They have validated the attenuation measured by the TRMM against that estimated using the ITU-R model. The study includes a few locations in the Indian subcontinent, namely, Bangalore (12.97°N, 77.59°E), Guwahati (26.14°N, 91.74°E), Chennai (13.08°N, 80.27°E), Delhi (28.70°N, 77.10°E), Kakdwip (21.87°N, 88.18°E), Kolkata (22.57°N, 88.36°E), Karaikal (10.92°N, 79.83°E), Mumbai (19.07°N, 72.87°E), Panjim (15.49°N, 73.82°E), Puri (19.81°N, 85.83°E), Machilipatnam (16.19°N, 81.13°E), Vishakhapatnam (17.68°N, 83.21°E), Salem (11.66°N, 78.14°E), Trivandrum (8.52°N, 76.93°E), and Mangalore (12.91°N, 74.85°E). Some of the locations so chosen lie along the East and West coasts of India. The period of study includes 1998-2002. The study shows that over Trivandrum and Kakdwip, the two matches very well. However, over other locations, sometimes the TRMM-estimated attenuation values overestimate. At times, these underestimate. The RMS error over these locations varies between 0.177 at Trivandrum to 22.004 at Bangalore. Besides, the investigation shows that the rainfall versus attenuation relationship is not always a power relation as accepted globally. Instead, the relationship between the two varies from one location to another.

Keywords:

Attenuation, Rainfall, Tropical Rainfall Measuring Mission, ITU-R Model, Elevation Angle

1. INTRODUCTION

High frequencies are suitable for communication as these can penetrate the ionosphere. However, at high frequency, the signal is attenuated by the atmospheric components, viz. rain, snow, atmospheric gases, and water vapour, etc. Of all these components, rain is the most hazardous. Above 10 GHz, the attenuation due to rain is so severe that it causes a significant signal loss. Thus, knowledge of attenuation is of immense importance in communication, and defense. However, the measurement of attenuation is scanty. So, a rainfall versus rain-induced relationship is useful to estimate attenuation at the data-sparse regions. Thus, the establishment of a correct relationship between the two is of prime concern. In the existing literature, the rainfall intensity and the rain-induced attenuation relationship is shown to be a power relation. However, by considering the dependence of rainfall dynamics on geography, rain drop-size distribution, and climatological conditions, it appears that the rainfall versus attenuation relationship cannot be a universal one, rather it should vary from one location to another. The relationship between the two also appears to vary with season. This paper aims to seek a functional relationship between the two, over a few tropical and extra-tropical locations in India, and check if it varies from one location to another. A relationship between the two will also help in estimating rainfall from the attenuation at places, where measurement of rainfall is not available. Thus, the benefit of the establishment of rainfall versus attenuation is two-fold. In the context of climate change, the knowledge of rainfall is of significant importance. Change in rainfall patterns is one of the major manifestations of climate change. Because of the change in rainfall patterns, several places all over the globe are facing a flood or flood-like situations, while many places are facing drought. Thus, the present article addresses an issue that is of crying need. Several researchers [1-3] all over the world have been investigating this issue. Mandeep et al. [4] have found that the modified ITU-R model [5] is a better choice for estimation of attenuation. Mandeep [6] has found a good agreement between the measured and the estimated attenuation over Malaysia. A study by Mukesh et al. [7] shows that the ITU-R model is not a good choice to predict attenuation at high frequency. Parth and Joshi [8] have found that a hybrid model, consisting of the advantages of the Garcia-Lopez model [9] and the simple attenuation model [10] yield attenuation that is in agreement to the measurement both at high and low frequencies.

In this paper, the authors have attempted to find out the correlations between rainfall and the rain-induced attenuation over a few selected locations in India, over a period 1998-2002. They have used the path integrated attenuation (PIA) from the data product 2A25 of the precipitation radar onboard the Tropical Rainfall Measuring Satellite (TRMM).

2. DATA AND METHODOLOGY

The path integrated attenuation (PIA), i.e. the attenuation along the slant path from the Tropical Rainfall Measuring Mission satellite (TRMM) to the receiver on the ground, are obtained from the data product 2A25 [11] of the precipitation radar (PR) onboard the Tropical Rainfall Measuring Mission satellite (TRMM). The data are obtained in Hierarchical Data Format (HDF) and are converted to ASCII before further analysis. The PIA values have been obtained over a few tropical and extra-tropical locations in India as mentioned in Table.1. It is noteworthy some of the locations like Chennai, Karaikal, Kakdwip, Kolkata, Machilipatnam, Puri, and Vishakhapatnam lie along the east coast of India. The locations, like Mumbai, Panjim, Mangalore, and Trivandrum lie along the west coast, while Delhi, Guwahati, Salem, and Bangalore are continental locations. The investigation has been carried over 1998-2002. It is noteworthy that the TRMM has an overpass at a station once a day, or very rarely, twice. Hence, many rainy events were overlooked by the TRMM.

Table 1. Latitude, longitude, height from mean sea level, and geography of the locations

Station	Latitude	Longitude	Station height (m)	Geography
Bangalore	12.971	77.594	920	Land
Chennai	13.082	80.270	6.7	Coast
Delhi	28.704	77.102	216	Land
Guwahati	26.144	91.736	55	Land
Kakdwip	21.876	88.185	4	Coast
Karaikal	10.925	79.838	8	Coast
Kolkata	22.572	88.363	9.14	Coast
Machilipatnam	16.19	81.136	11	Coast
Mangalore	12.914	74.856	22	Coast
Mumbai	19.076	72.877	14	Coast
Panjim	15.49	73.827	7	Coast
Puri	19.813	85.831	0.1	Coast
Salem	11.664	78.146	289	Land
Trivandrum	8.524	76.936	18	Coast
Vishakhapatnam	17.686	83.218	24	Coast

The swath of the precipitation radar (PR) onboard the Tropical Rainfall Measuring Mission (TRMM) satellite is 220 km with 49 beams [12]. The vertical resolution of PR is 250 m. The precipitation radar scans every 250 m along the slant range and stores the rainfall intensity in 80 range bins. It operates at 13.8 GHz. The radar reflectivity from 1C21, rain type, freezing level height, and bright band height from 2A23, and rain attenuation from 2A21 are the input data files for the 2A25 algorithm [12]. By using these files, the rainfall rate for every resolution cell is estimated and correction of the rain attenuation is achieved. The 2A25 estimates path integrated attenuation for three cases: finally adjusted PIA, PIA between the surface and near-surface range bins, and the PIA from 2A21. The estimated PIA values are stored in dB. The rainfall intensity is multiplied by 100 and stored as a 2-byte integer in mm/hr. The finally adjusted PIA and the rainfall rate from 2A25 products from 1998-2002 are used in this study.

The rainfall values over the locations have also been obtained from the India Meteorological Department (IMD). The authors have estimated the attenuation using the ITU-R model [13] by considering these rainfall values as an input and have compared the same with the measured PIA derived from the TRMM. They have also used the TRMM–retrieved rainfall values as input to the ITU-R model [13] to estimate attenuation over the selected locations.

To find out a functional relation between the attenuation, and the rainfall, the authors have fitted the two parameters for the entire period 1998 through 2002 at the same probabilities to various models, viz. linear, logarithmic, quadratic, cubic, compound, power, logistics, exponential, inverse, growth, and sigmoid. The validity of the model is judged by the F test at a 5% level of significance.

The ITU-R model [13] is used to estimate rain-induced attenuation is described below.

Step 1: Rain height for all 15 Indian stations are calculated from Eq.(1) based on ITU-R P.839.4 model [14]:

$$h_R = h_0 + 0.36 \text{ km} \tag{1}$$

where, h_R - rain height in km and h_0 is the mean annual 0°C isotherm height. The values of h_0 are obtained from ITU-R P.839.4 model [14].

Step 2: Slant path length L_s is computed from Eq.(2):

$$L_s = (h_R - h_S)/\sin\theta \text{ km if } \theta \geq 5° \tag{2a}$$

$$L_S = \frac{2(h_R - h_S)}{\left(\sin^2\theta + \frac{2(h_R - h_S)}{R_e}\right)^{0.5} + \sin\theta} km \text{ if } \theta < 5^\circ \tag{2b}$$

where, L_s is the slant path length, h_R is the rain height, h_S is the station height from mean sea level, θ is the Earth station elevation angle, and R_e is the effective radius of Earth (8500 km).

Step 3: The horizontal projection (L_G) is calculated from Eq.(3):

$$L_G = L_S \cos\theta \text{ km} \tag{3}$$

where, L_G is the horizontal projection.

Step 4: The rainfall rate $R_{0.01}$% is computed from Eq.(4) [15]:

$$R_{0.01} = aR_{5H} \tag{4}$$

where, R_{5H} is the mean of first five largest values during 1998-2002. The value of a is 2.3 for locations in India [14].

Step 5: Specific attenuation (γ_R) is calculated from Eq.(5):

$$\gamma_R = kR_{0.01}^{\alpha} \text{ dB/km} \tag{5}$$

where, γ_R is the specific attenuation and the constant value k and α are based on ITU R P.838-3 model [16].

Step 6: Horizontal reduction factor ($r_{0.01}$) for 0.01% of time is obtained from Eq.(6):

$$r_{0.01} = \frac{1}{1 + 0.78\sqrt{\frac{L_G\gamma_R}{f}} - 0.38\left(1 - e^{-2L_G}\right)} \tag{6}$$

where, f is the frequency (13.8 GHz), and $r_{0.01}$ is the horizontal reduction factor.

Step 7: Vertical adjustment factor ($v_{0.01}$) for 0.01% of time is obtained from Eq.(7):

$$v_{0.01} = \frac{1}{1 + \sqrt{\sin\theta}\left(31\left(1 - e^{-\left(\frac{\theta}{1+\chi}\right)}\right)\sqrt{\frac{L_G\gamma_R}{f}} - 0.45\right)} \tag{7}$$

where, L_R is adjusted rainy path length, $v_{0.01}$ is the vertical adjustment factor and ζ is the polarization angle in degree.

L_R is obtained from Eq.(8)-Eq.(9):

$$\zeta = \tan^{-1}\left(\frac{h_R - h_S}{L_S r_{0.01}}\right) \text{degrees} \tag{8}$$

$$L_R = \begin{cases} L_G r_{0.01} km & if\ \zeta > \theta \\ L_S\ km & otherwise \end{cases} \tag{9}$$

$$\chi = \begin{cases} 36 - |\varphi| & if\ |\varphi| < 36^\circ \\ 0 & otherwise \end{cases}$$

where, φ is Earth station latitude.

Step 8: The effective path length (L_E) is calculated from Eq.(10):

$$L_E = L_R v_{0.01} \text{ km} \tag{10}$$

Step 9: Attenuation exceeded for 0.01 % of time of year is obtained from Eq.(11):

$$A_{0.01} = \gamma_R L_E \text{ km} \tag{11}$$

Step 10: Attenuation exceeded for 0.001-5% is calculated from Eq.(12):

$$A_p = A_{0.01}\left(\frac{p}{0.01}\right)^{\left(0.655+0.033\ln(p)-0.045\ln(A_{0.01})-\beta(1-p)\sin\theta\right)} \tag{12}$$

The value of β is computed based on the following conditions:

$$\beta = \begin{cases} 0 & p \geq 1\% \text{ or } |\varphi| \geq 36^\circ \\ -0.05\left(|\varphi| - 36^\circ\right) & p < 1\% \text{ and } |\varphi| < 36 \\ -0.005\left(|\varphi| - 36^\circ\right) + 1.8 - 4.25\sin\theta & \text{otherwise} \end{cases}$$

The root mean square error is calculated using Eq.(13):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(P_i - O_i\right)^2}{n}} \tag{13}$$

where, P_i is the attenuation measured from TRMM; O_i is the attenuation calculated using ITU-R model and n is the number of data points.

3. RESULTS AND DISCUSSIONS

The Fig.1 represents the variations of rainfall intensity with the percentage of time over the locations studied. The Fig.1 shows that as the percentage of time increases, the rainfall intensity decreases. This is because high-intensity rainfall is short-lived, while a low-intensity rainfall persists over a longer duration.

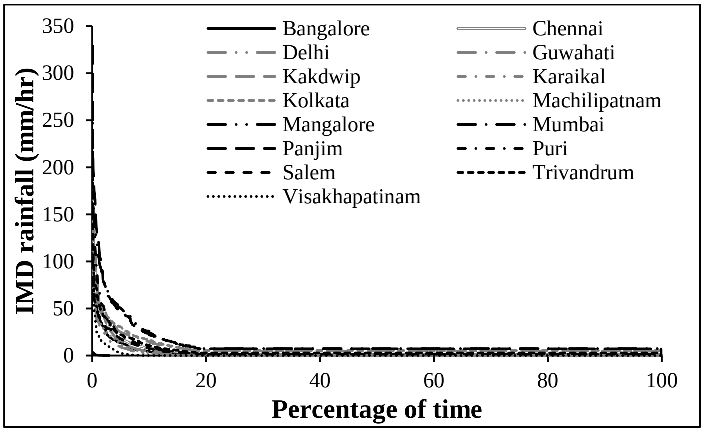

Fig.1. Cumulative distribution of IMD rainfall over locations in India (1998-2002)

The Fig.2-Fig.16 show the attenuation over the selected locations. These reveal that over all the locations, the attenuation estimated using the ITU-R model is much higher than measurement. The TRMM-retrieved PIA is underestimated by the other two over all locations, except Guwahati, Kolkata, and Puri, where the estimated attenuation using the TRMM-retrieved rainfall underestimates the other two. Thus, it appears that the TRMM-retrieved attenuation is underestimated over most of the locations. It must be because the TRMM overlooks most of the rainy events. It has an overpass at a location, only once a day, or very rarely, twice. Besides, Fig.2-Fig.16 reveal the following observations:

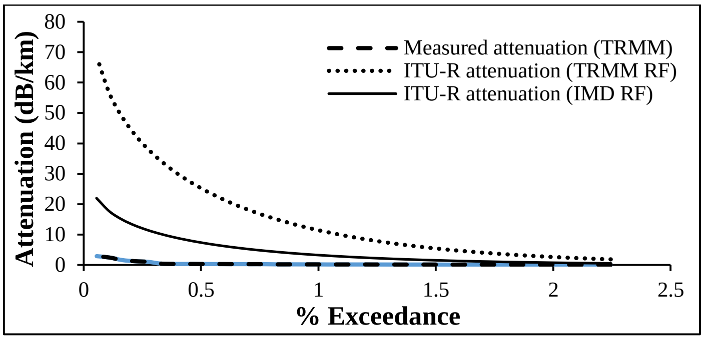

Fig.2. Attenuation versus percentage exceedance of time over Bangalore (1998-2002)

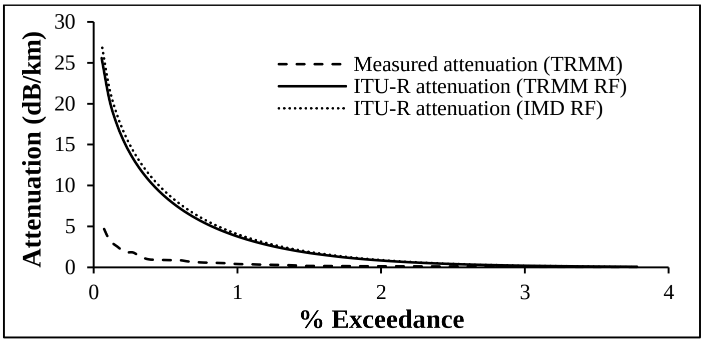

Fig.3. Attenuation versus percentage exceedance of time over Chennai (1998-2002)

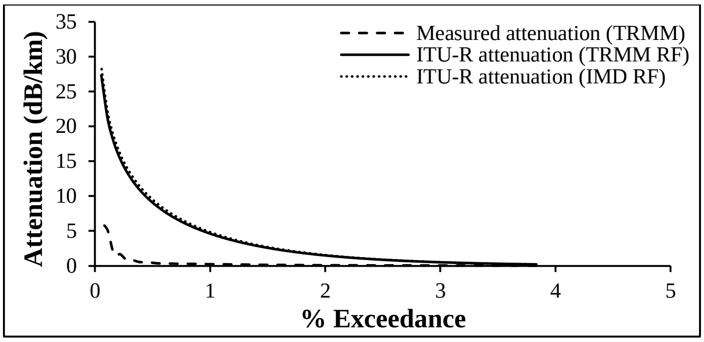

Fig.4. Attenuation versus percentage exceedance of time over Delhi (1998-2002)

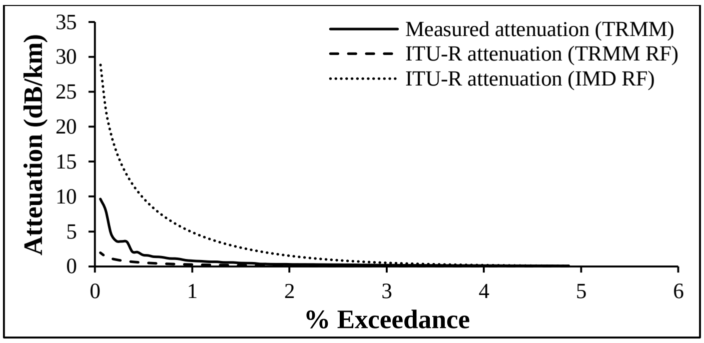

Fig.5. Attenuation versus percentage exceedance of time over Guwahati (1998-2002)

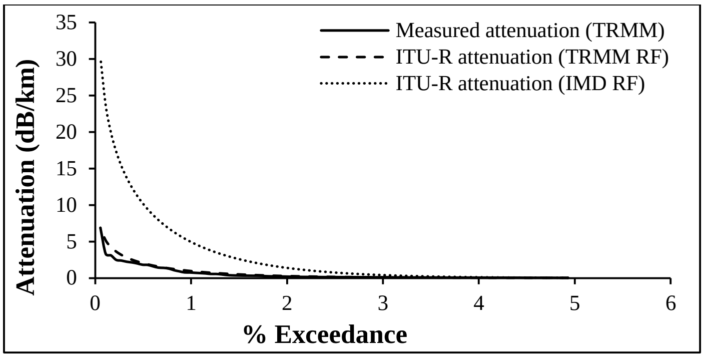

Fig.6. Attenuation versus percentage exceedance of time over Kakdwip (1998-2002)

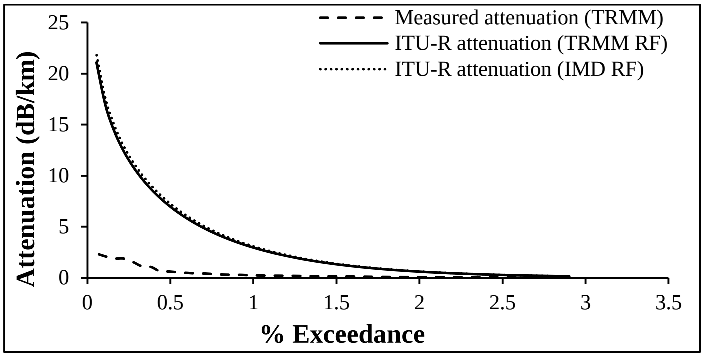

Fig.7. Attenuation versus percentage exceedance of time over Karaikal (1998-2002)

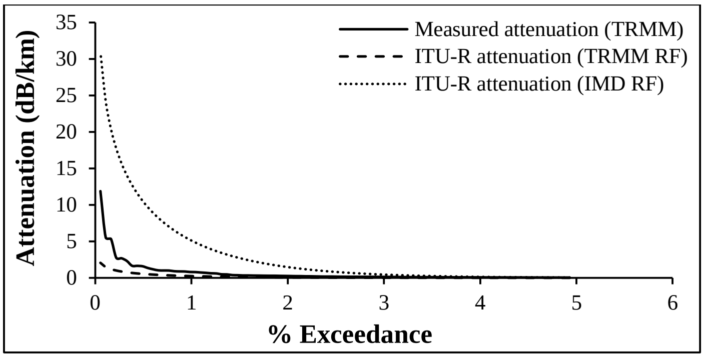

Fig.8. Attenuation versus percentage exceedance of time over Kolkata (1998-2002)

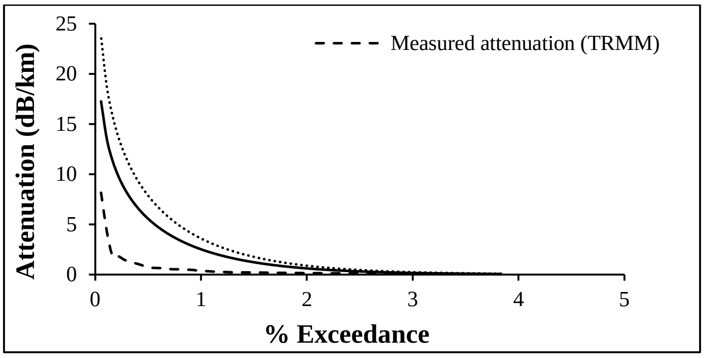

Fig.9. Attenuation versus percentage exceedance of time over Machilipatnam (1998-2002)

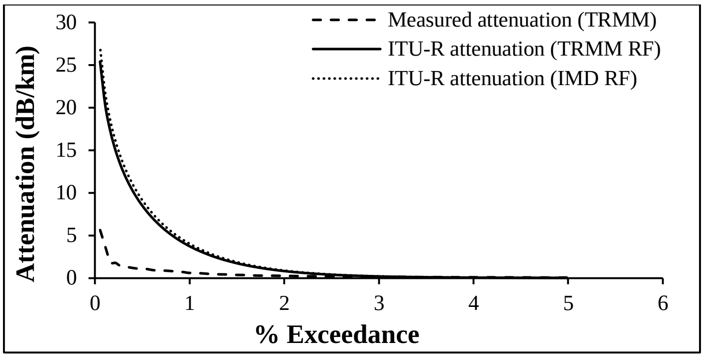

Fig.10. Attenuation versus percentage exceedance of time over Mangalore (1998-2002)

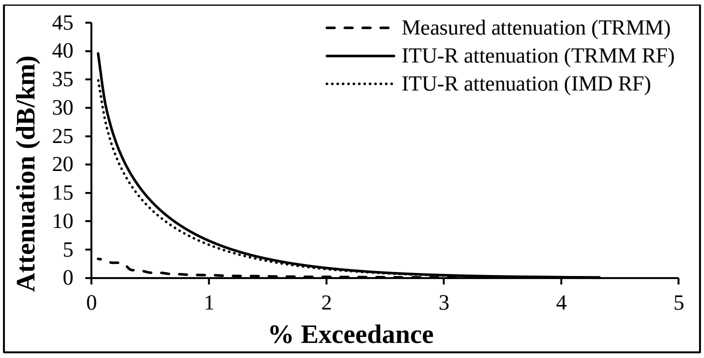

Fig.11. Attenuation versus percentage exceedance of time over Mumbai (1998-2002)

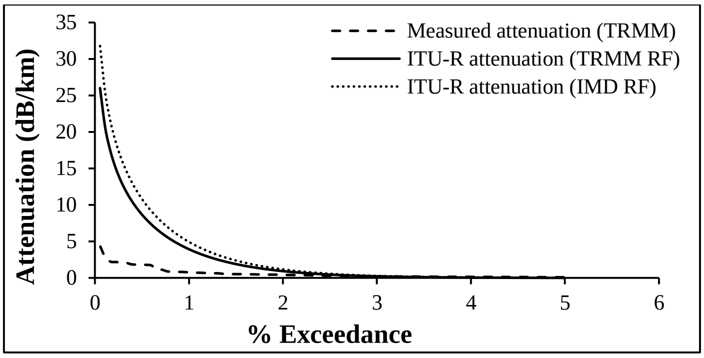

Fig.12. Attenuation versus percentage exceedance of time over Panjim (1998-2002)

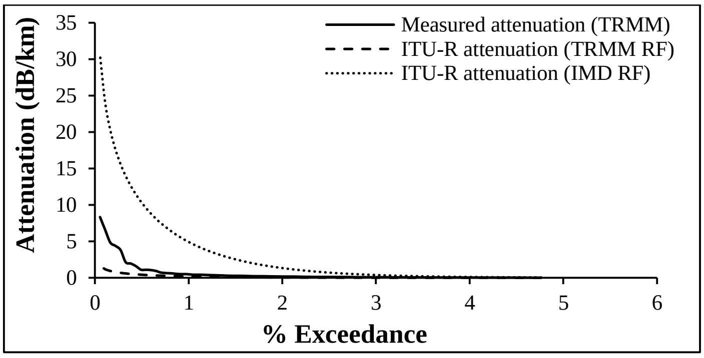

Fig.13. Attenuation versus percentage exceedance of time over Puri (1998-2002)

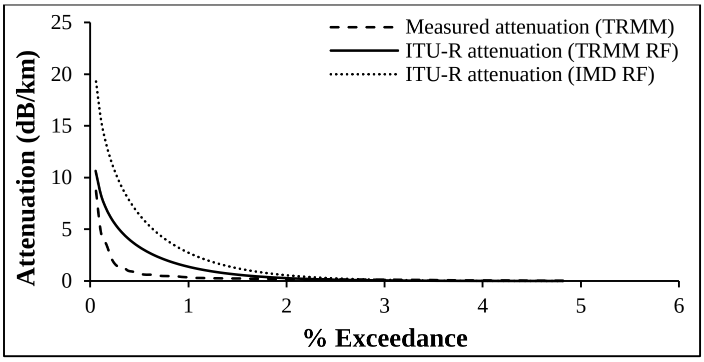

Fig.14. Attenuation versus percentage exceedance of time over Salem (1998-2002)

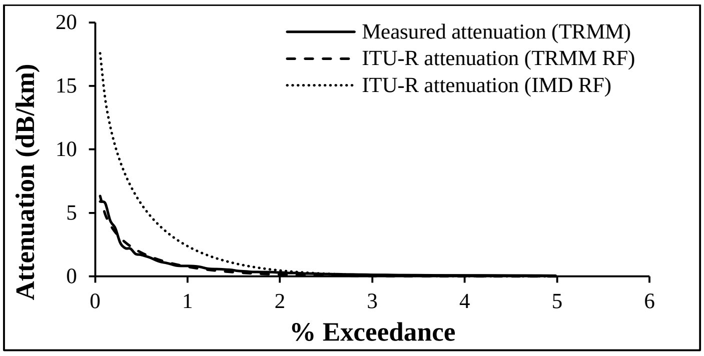

Fig.15. Attenuation versus percentage exceedance of time over Trivandrum (1998-2002)

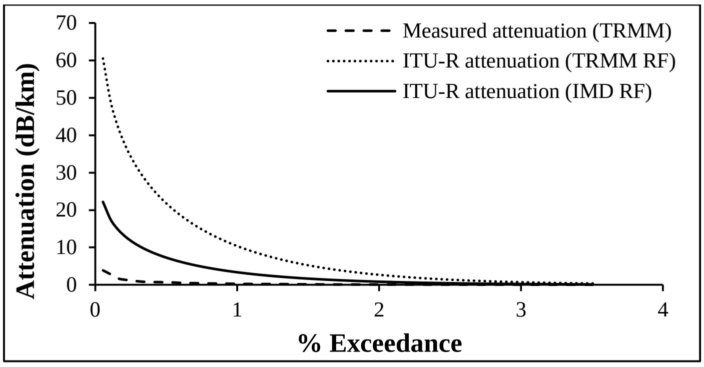

Fig.16. Attenuation versus percentage exceedance of time over Vishakhapatnam (1998-2002)

The TRMM-retrieved PIA shows good agreement with the estimated attenuation using the ITU-R model when the TRMM-retrieved rainfall is used as input to it over Guwahati, Kakdwip, Puri, and Trivandrum.

The TRMM-retrieved PIA shows good agreement with the estimated attenuation using the ITU-R model when the IMD rainfall is used as input to it over Bangalore and Kolkata.

Over Machilipatnam, Mangalore, Mumbai, Panjim, Karaikal, Chennai, and Delhi, the TRMM-retrieved PIA does not match with the estimated values in either case-TRMM-retrieved rainfall or IMD rainfall as an input to the ITU-R model. However, over these locations, good agreement is seen between the estimated values when the IMD rainfall and the TRMM-retrieved rainfall is used as input to the ITU-R model.

The Fig.2-Fig.16 also reveal that as the percentage of time increases, the agreement of the measured PIA with the estimated values using the ITU-R model increases. At 2% and above probability values, a good agreement is seen between them.

The Table.2 shows the RMS error between the TRMM-retrieved PIA and the estimated attenuation. The Table.2 shows that over Trivandrum the measured attenuation shows the maximum agreement with the estimated value using the ITU-R model with TRMM-retrieved rainfall as the input to it, while over Bangalore, the agreement is the least between the two.

Table.2. Comparison of RMS error in attenuation estimation

Station	TRMM attenuation and ITU-R attenuation using TRMM RF	TRMM attenuation and ITU-R attenuation using IMD RF	ITUR attenuation using TRMM RF and ITUR attenuation using IMD RF
Bangalore	22.604	6.266	15.73
Chennai	5.535	5.9892	0.4541
Delhi	5.86	6.1909	0.3314
Guwahati	1.379	4.7291	6.024
Kakdwip	0.3078	5.506	5.2629
Karaikal	5.337	5.588	0.2517
Kolkata	1.332	5.193	6.337
Machilipatnam	3.025	4.612	1.599
Mangalore	4.821	5.244	0.424
Mumbai	8.863	7.805	1.058
Panjim	4.67	5.989	1.321
Puri	1.268	5.425	6.602
Salem	1.271	3.291	2.086
Trivandrum	0.174	2.545	2.537
Vishakhapatnam	15.567	4.967	10.601

The agreement between the measured PIA and the estimated values using the ITU-R model, with the IMD rainfall as an input is the highest over Trivandrum and the least over Mumbai. The Table.2 also shows that the measured PIA matches well with the estimated attenuation values using ITU-R when the TRMM-retrieved rainfall is used as an input in comparison to that of IMD rainfall.

The disagreement between the measured and estimated attenuation may be attributed to the rain height model suggested by the ITU-R. Besides, the ITU-R model assumes a power-law relation between the specific attenuation and rainfall. Also, the assumption of the rainfall at 0.01% of the time as a standard one in the specific attenuation versus rainfall relation appears to be unrealistic and, in turn, questionable. Instead, measured attenuation and rainfall values will elevate the understanding of rainfall versus attenuation dynamics.

The Table.3(a)-Table.3(b) show the functional relationship between rainfall and attenuation at the same probabilities. Table 3a reveals that over Bangalore, Delhi, Guwahati, and Salem, a quadratic relation exists between the measured PIA and IMD rainfall, while over other locations, a sigmoid relation is seen.

Table.3(a). Functional relationship between measured TRMM attenuation and IMD rainfall at the same probabilities (1998-2002) at 13.8 GHz

Station	R^2	Functional relationship
Bangalore	0.939	y=0.868-0.044x+0.001x^2
Chennai	0.937	y=exp(1.189-122.172/x)
Delhi	0.934	y=0.805-0.057x+0.001x^2
Guwahati	0.957	y=1.874-0.123x+0.002x^2
Kakdwip	0.882	y=exp(0.773-106.306/x)
Karaikal	0.985	y=exp(2.074-222.284/x)
Kolkata	0.975	y=exp(2.378-173.073/x)
Machilipatnam	0.947	y=exp(1.80-108.835/x)
Mangalore	0.959	y=exp(2.190-289.548/x)
Mumbai	0.962	y=exp(1.451-222.947/x)
Panjim	0.983	y=exp(1.468-186.822/x)
Puri	0.911	y=exp(1.198-125.691/x)
Salem	0.945	y=1.576-0.097x+0.002x^2
Trivandrum	0.941	y=exp(1.959-130.803/x)
Visakhapatnam	0.979	y=exp(0.747-80.393/x)

Table.3(b). Functional relationship between ITU-R attenuation using TRMM rainfall and TRMM-retrieved attenuation at the same probabilities (1998-2002) at 13.8 GHz

Station	R^2	Functional relationship
Bangalore	0.941	Y=-24.795+16.556log(x)
Chennai	0.951	Y=0.409+0.107x
Delhi	0.917	Y=0.112$x^{1.156}$
Guwahati	0.989	Y=-0.032+0.004x
Kakdwip	0.953	Y=0.003$x^{1.395}$
Karaikal	0.914	Y=0.058$x^{1.203}$
Kolkata	0.916	Y=0.016+0.004x
Machilipatnam	0.949	Y=0.027$x^{1.281}$
Mangalore	0.960	Y=exp(2.284-38.358/x)
Mumbai	0.978	Y=0.043+0.183x
Panjim	0.978	Y=-1.095+0.102x
Puri	0.958	Y=0.010+0.003x
Salem	0.892	Y=exp(1.078-21.749/x)
Trivandrum	0.987	Y=-0.160+0.020x
Visakhapatnam	0.991	Y=-0.980+0.559x-0.001x^2

The Table.3(b) reveals that over Delhi, Kakdwip, Karaikal, and Machilipatnam, a power relationship exists between the measured attenuation, and the estimated one, using the ITU-R model when the TRMM-retrieved rainfall is used as an input to it. The two bear a quadratic relation over Vishakhapatnam. Over Chennai, Guwahati, Kolkata, Mumbai, Panjim, Puri, and Trivandrum, a linear relation is found between the two. Over Salem and Mangalore, a sigmoid relation exists between the two. Thus, Table.3(a)- Table.3(b) shows that the relationship between rainfall and attenuation varies from one location to another. A study by Das et al. [17] shows that attenuation appears to vary from one location to another.

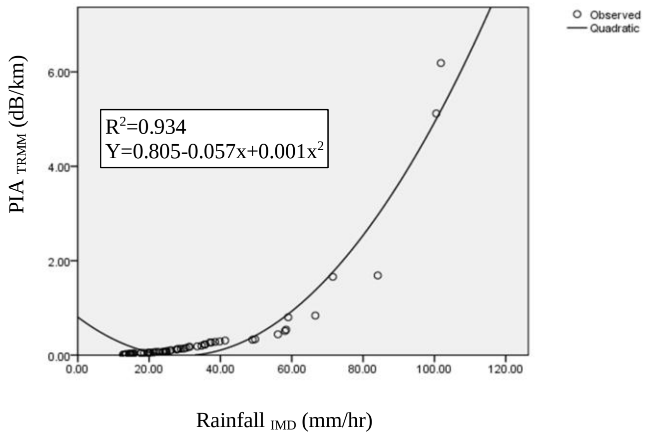

Fig.17. Variation of attenuation $_{TRMM}$ with rainfall $_{IMD}$ over Delhi (1998-2002) at the same probabilities

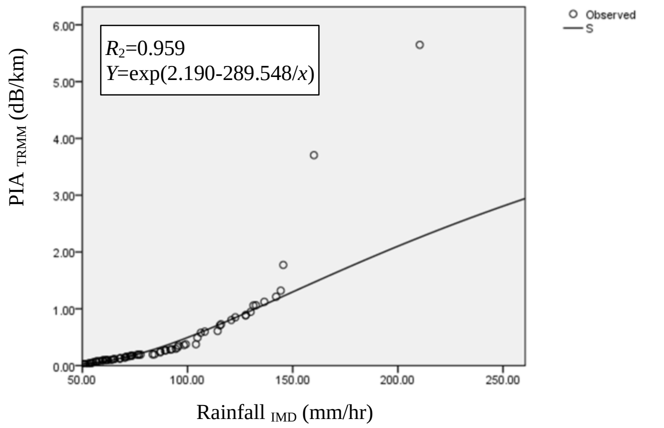

Fig.18. Variation of attenuation $_{TRMM}$ with rainfall $_{IMD}$ over Mangalore (1998-2002) at the same probabilities

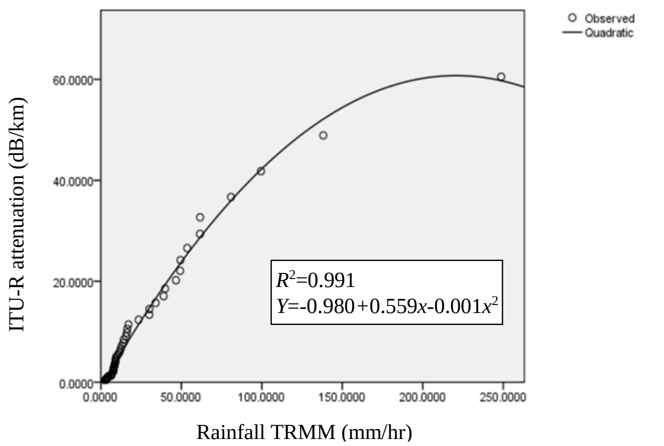

Fig.19. Variation of ITU-R attenuation with rainfall $_{TRMM}$ over Vishakhapatnam (1998-2002) at the same probabilities

The Fig.17-Fig.18 respectively shows the TRMM-retrieved PIA and IMD rainfall over Delhi, and Mangalore. The Fig.17-Fig.18 shows that over Delhi the relation between the two is quadratic, while a sigmoid relation exists over Mangalore. The relationships over the other locations are seen in Table.3(a).

The Fig.19-Fig.20 respectively shows the correlation between the TRMM-retrieved rainfall and the attenuation estimated using the ITU-R model, using the former as an input to the model over Vishakhapatnam and Trivandrum. Over Vishakhapatnam a quadratic relation is seen, while over Trivandrum a linear relation exists between the two. The relationships over the other locations are shown in Table.3(b).

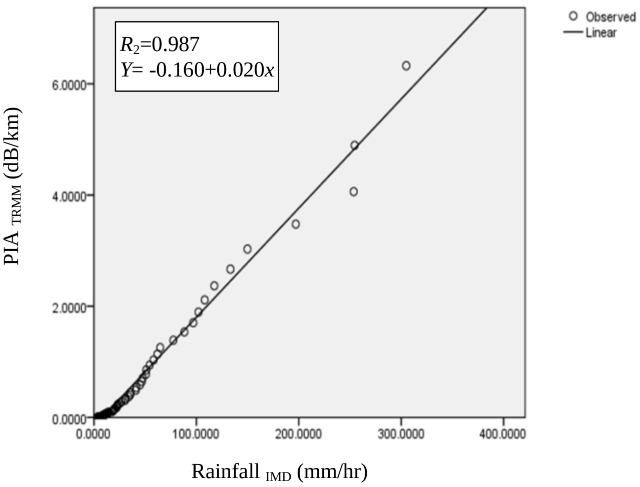

Fig.20. Variation of ITU-R attenuation with rainfall $_{TRMM}$ over Trivandrum (1998-2002) at the same probabilities

4. CONCLUSION

The investigation reveals that the attenuation versus rainfall relation varies from one location to another. Thus, the relation appears to depend on geography. The TRMM-retrieved PIA is underestimated in comparison to the estimated values using the ITU-R model over most of the locations, except Kolkata, Guwahati, and Puri. The agreement between the measured and the estimated attenuation increases as the percentage of time increases and is significant at a probability of 2% and above.

The study shows that instead of trying to estimate the rain-induced attenuation using a model, it is advisable to install collocated facilities for attenuation and rainfall intensity measurement over locations covering varied geographical aspects and over seasons.

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