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Determination of the Calibration Factor for the Rain Rate Derived From TRMM Satellite Using MRR Data over Akure, Nigeria

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ABSTRACT

The ground based radar calibration of a space borne radar is an important means of testing the reliability of Tropical Rain Measuring Mission- Precipitation Radar (TRMM- PR) derived radar reflectivity factor (Z) and rain rate (R) values over a location. For this purpose, a well-calibrated ground based Micro Rain Radar (MRR) located at Department of Physics, The Federal University of Technology, Akure (Lat 5.3^{0}E, Long 7.3^{0}N) in south-western Nigeria was used to validate data from TRMM satellite data. The measurements of the vertical profile of reflectivity factor and rain rate were carried out using TRMM-PR satellite radar and a MRR simultaneously in 2008 and 2010 during the raining season. The data collected from 49 different range gates covering heights from 250 m -1225 m in 250 m steps from TRMM-PR and 30 different range gates covering height from 0 – 4800 m in 160 m steps for MRR were compared. From the two years data used, 28 days (overpasses) of significant rainfall at two different heights 1.5 km and 4.0 km for the two days of most significant rainfall were selected for analysis. The data analysis at the 1.5 km and 4.0 km height and for 28 days of overpasses show good correlation ranging from the maximum 0.99 to the least 0.53 at 4 km and 0.99 to the least 0.59 at 1.5 km. The 'b' parameter value of the power law $Z = aR^b$ empirically derived from MRR over Akure were used to calibrate TRMM-PR values for rain rate estimate, the mean difference of radar reflectivity factor at heights 4.0 km and 1.5 km were 2.4 dB and 2.5dB respectively. The results also show that the radar reflectivity (dBZ) derived from the PR data after attenuation correction agrees to within 2.0 dB when compared with that of the MRR with a relative variation of ±0.9 dB at different heights.

1. Introduction

The measurement of rainfall using radar system has a long time history of over 50 years (Remo, 2001 and Steven, 2000). In the tropics radar measurement of rainfall was not that popular until the recent time when the precipitation radar (PR) aboard the tropical Rain full measuring mission (TRMM) satellite was flown in to the space in November, 1997. (Simpson et al., 1996; Kummerow et al, 1998: Kozu et al. 2001; Liang et al; 2001). The problem with the measurement of rain rate from radar system has been the error and uncertainties in the accuracy of the data product so obtained when compared with the same data measurement using rain gauged on the ground.

The power return of the radar measured as reflectivity factor (Z) is usually converted to the estimated rain rate (R) by the use of Z-R empirical relation.

Remo, 2001; reported that, the problem associated with radar remote sensing of rainfall is the conversion of the radar reflectivity's measured a loft to rain rate measure at the ground. He also stated that, the manner which the conversion is carried out affect the precision of the radar rainfall estimation obtained.

The complexity of the non-linear relationship between the radar reflectivity and rainfall rate at the surface as reflected in the (Z-R) power law ($Z = aR^b$) has been ascribed as the major cause of the uncertainties and error in the radar data products (Steven, 2000).

The need for internal calibration of radar system to measure accurately rainfall was emphasized by (Crum et al,. 1993) as a means of reducing the introduction of uncertainties in radar results. It was also found out that, the internal variables of radar system such as the transmitted power and path loss of the receiver signal processor changes in values during operation.

Smith and Krajewski (1994) also discovered in Oklahoma, U.S.A. that the reflectivity factor (Z) difference found for WSR-88D's radar, was higher than 17% (percent) particularly with heavier rainfall and were systematic over long periods.

Also (Ricks et al,. 1995) reported average difference of reflectivity factor Z of about 3dB between the New Orleans and Mobile WSR-88D's for a rain storm about equidistance from each site.

Daviak and Zrnic 1984, reported the need for the correction of gaseous, rainfall, attenuation of the microwave return to and from the target from the radar. It was also found out that for s-band radar 50 dBZ rain would only attenuate the receive signal 1dB.

Anagnostou et al, 2001; Schumacher and Houze (2000); concluded that the most important types of external calibration is best done by comparing TRMM or precipitation radar PR –derived radar reflectivities with the estimable of the same quantify made with well calibrated ground based radar.

Therefore, Liang et al; (2001) reported the comparisons of TRMM-PR radar with a ground-based (WSR-88D) Doppler radar in Florida USA and concluded that, the comparisons with ground-based radars constitute a critical component in testing the accuracy of the TRMM-PR estimates of radar reflectivity and rain-rate.

Because of the important of TRMM-PR in the measurement of radar reflectivity and rain rate data made available in the Tropic and equatorial regions; especially in African where such data were not previously available, it is hence very important to also calibrate the TRMM-PR data in Akure Nigeria with external radar system for effective usage.

In this study a ground based Micro Rain Radar (MRR) located at The Federal University of Technology Akure, South-Western Nigeria was used to calibrate same data from TRMM-PR.

2.Material and Methodology

The spatial structure of precipitation is often studied using radar operating at a frequency of several GHz and taking into consideration the fact that precipitation will reflect, by backscattering, a part of the energy incident on it. This fact enables data to be captured from a precipitation target in the atmosphere.

2.1 Sources of Data

The data collected over two years from the Micro Rain radar (MRR) located at Department of Physics, The Federal University of Technology Akure (Lat 5°15'E, long 7°15'N), South-West Nigeria, and from TRMM at same location were compared. The location map is shown in Figure 3.0. The measurements of the vertical profile of reflectivity factor and rain rate have been carried out by the TRMM (PR) satellite radar and the MRR. The measurements were taken in 2008 and 2010 during the rainy season. The space-borne TRMM precipitation radar (PR) and the MRR operate by sending electromagnetic waves at 13.8 GHz and 24.1GHz respectively into the atmosphere. The data from the TRMM-PR were collected at 49 different range gates, that is, from 250 m-12.25 km in 250 m steps at six hour integration time for TRMM (PR) and at 30 different range gates, that is, from160 m- 4.8 km in 160 m steps at one minute integration time by the MRR. The reflectivity factor in dBZ from TRMM were accessed using WinZip and Mat Lab 2010[a] software programmes to unzip the data archived in HDF (Hierarchical Data Format) and then converted to Readable ASCII Data format. The two years (2008 and 2010) data of radar reflectivity factor Z(data product 2A25) and rain rate were obtained from Tropical Rainfall Measuring Mission (TRMM) and were marched with the same years' data from the ground based MRR at FUTA. The site characteristics is shown in Table 1

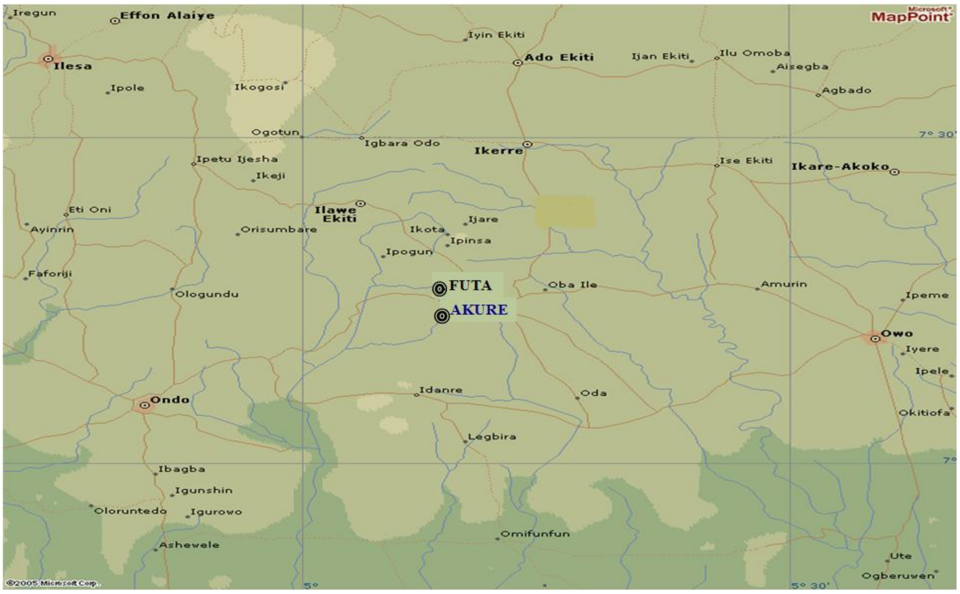

Fig 1: The location where data were taken for this work.

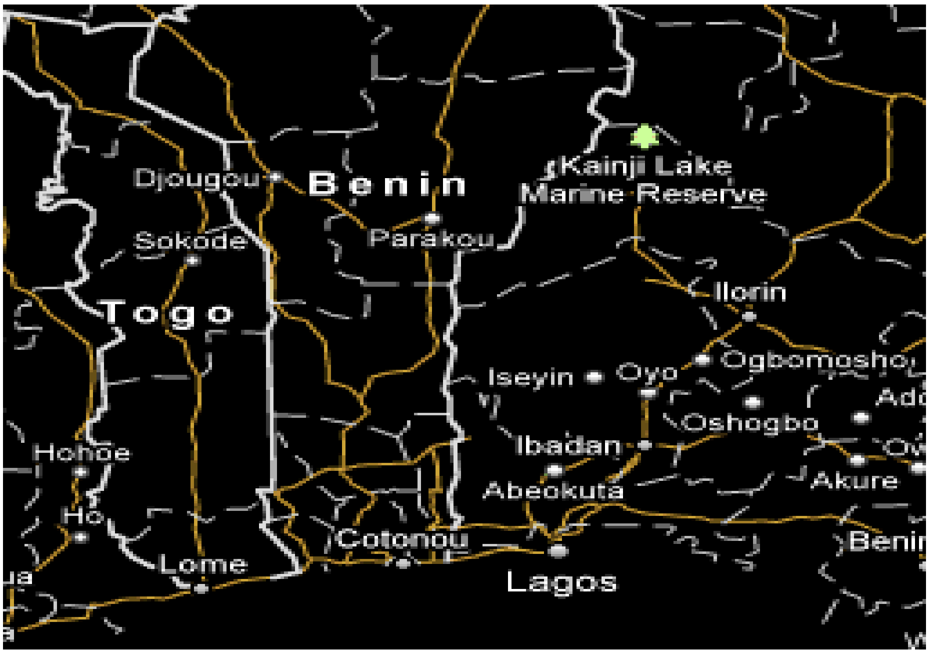

Fig 2: Coverage Area of TRMM (PR) Satellite Sensor Onboard during Measurement

Table 1: Site characteristics of the location (Akure).

Location	Latitude (degrees) (^oE)	Longitude (degrees) (^oN)	Altitude level	Climatic Region
Akure	5°15'	7°15'	250m	Rain Forest

2.2 Mode of Data Collection

The radar data were downloaded using the PC interface and software packages to read the data. The two data sets from TRMM used are radar reflectivity factor (dBZ) with and without attenuation correction. That is radar reflectivity measured (dBZ_m) and radar reflectivity with attenuation correction (dBZ).

2.3 TRMM Data

The TRMM data set (2A25) has a spatial coverage of between 38^0 north and 38^0 south, owing to the 35 degree inclination of the TRMM satellite. The orbit provides an extensive coverage in the tropics and allows each location to be covered at a different local time each day, enabling the analysis of the diurnal cycle of precipitation. The map of the different locations covered is shown in Figure 2. There are, in general, 9150 scans along the orbit, with each scan consisting of 49 rays. The scan width is about 220 km. The data are stored in the Hierarchical Data Format (HDF), which includes both core and product specific metadata applicable to the PR measurements. A file contains a single orbit of data with a file size of about 242 MB (uncompressed). The HDF "swath" structure is used to accommodate the actual geophysical data arrays. There are 16 files of PR 2A25 data produced per day.

The data products from the radars were compared for calibration. The precipitation radar (PR) from Tropical rainfall measuring mission (TRMM) satellite and the micro rain radar (MRR) located at the Federal University of Technology Akure, South-Western Nigeria. Rain-rate and reflectivity factor data from TRMM-PR and MRR where measured at rear simultaneously the same time when the TRMM–PR satellite passes over Akure during rainy season. The data set from both radar were re-sampled to match in space and time resolution. The mean and correlation coefficient of the data was examined to check for the accuracy. Also, the radar reflectivity (dBZ) data were group into attitudes. The reflectivity dBZ at high attitudes (4 km) can be; used to check how accurate the calibration of the radars. And at low attitude (1.5 km) the reflectivity dBZ can be used to assed the performance of error due to attenuation correction from TRMM-PR algorithm.

2.4 Data Analysis

The data used for the study are, one minute integration time reflectivity data (dBZ) and rain rate (mmh^{-1}) from TRMM and one hourly resolution time 2A25 radar reflectivity and rain rate data product from TRMM-PR over Akure Lat 5.3^0E long 7.3 ^{0}N. The measurement of the virtual profile of reflectivity factor and rain rate has been carried out by the TRMM-PR satellite radar and the MRR over Akure. The measurements were taken in 2008 and 2010 during the rainy season. The space-borne TRMM precipitation radar (PR) and the MRR operate by sending radio ware at the frequency of 13.8 GHz and 24:1 GHz respectively into the atmosphere. The data from the TRMM-PR were collected at 49 different range gates while from the same data from MRR were collected at 30 different range gates. Two attitudes were examined from the range gates of the radar (which were 4 km and 1.5 km). These attitudes were signification to this research because the bright band height over the location (Akure) has been found to be on average about 4km (http//:disc2.nascom.nasa.gov as at 25th December, 2010).

The bright band height indicates the melting point level below the freezing level before rainfall is just about to start over a location. Also high attitude such as 4 km was referred to as near storm attitude where the effect of attenuation of micro wave can be negligible (Liang et. al., 2001)

Recent research studies have shown that, The Standard and TRMM Science Data and Information System (TSDIS) product gives rain rate only at the lowest vertical level from the surface to 1.5 km (Liang et. al., 2001).

The days with highest precipitation during each rainy event were selected from the overall data. During the period of observation, the highest precipitation day occurred on the 6th of April, 2008 and on the 26th of August, 2010 as will be presented later. These data were obtained from overall data collected. The rain rate and reflectivity factor were then retrieved from TRMM and MRR. The data were made comparable by converting (logarithmic function) dBZ to Z data and re-sampling onto horizontal plane spaced 250 m apart, from where the various heights of measured data were examined. The heights considered are 1.5 km, and 4 km. The heights 250 m, 500 m 1.0 km and 1.5 km are called near the surface altitude, whose data provide an assessment of the performance of TRMM-PR attenuation correction algorithm and the heights 2 km, 3 km and 4 km are called the near storm altitude whose data are used to check the relative calibration accuracy of the radars (Liang Liao et al., 2001). For data in each plane, we performed interpolation and averaged the interpolated data at the specified height. The scatter diagram was plotted to determine their correlation. Also, the percentage agreements of the data were determined. The data were then divided into rainfall types to give a better picture of the data observation. For this paper only heights 4 km and 1.5 km were considered.

2.5 The Radar Reflectivity dBZ and dBZ$_m$ Relation

There are two data outputs in TRMM-PR measurement which were used for this study. The measured dBz$_m$ (without attenuation correction) and dBZ (with attenuation correction). The two quantities are related approximately by

$$Z(r) = z_m(r)\exp\left[0.2\ln 10\int_0^r \delta(s)\,ds\right] \qquad (1)$$

where Z(r) is radar reflectivity (dBZ) with attenuation correction, Z$_m$(r) is radar reflectivity measured (dBZm), δ(s) is the specific attenuation in dB/km and *r* is the range in km. But the power P(r) returned by the radar at range *r* is.

$$P(r) = \frac{c|k|^2 z_m(r)}{r^2} \qquad (2)$$

Combining equations (1) and (2), we have

$$P(r) = c|k|^2 \; z(r) \; \exp\frac{\left[-0.2\ln 10\int_0^r \delta(s)\,ds\right]}{r^2} \qquad (3)$$

where P(r) is the radar return power at range *r*, δ(s) is the specific attenuation (dBkm^{-1}), C is the radar constant and $/k/^2 \approx 0.93$ is the dielectric factor of water. The rain rate is usually estimated from the reflectivity factor Z using the power law relationship

$$Z = a\,R^b \qquad (4)$$

where *a* and *b* are coefficients that may vary from one location to the next and from one season to the next, but that is independent of *R* itself. These coefficients will in some sense reflect the climatological character of the particular location or season, or more specifically the type of rainfall (such as stratiform and convective,) for which they are derived.

The weighted mean of Z for all the overpasses was also calculated as $(dBZ)_{weighted}$, which is defined by:

$$(dBZ)w = \frac{\sum_{i=1}^{28} N_i (dBZ)_i}{\sum_{i=1}^{28} N_i} \qquad (5)$$

N_i is the number of common resolution elements in the ith overpass for which radar reflectivity factor (dBZ) >15dB and dBZgv >10dB as threshold values, where dBZgv is the ground validated radar reflectivity factor from MRR. The difference in the weighted means as a function of height can be expressed using the following notation:

$$\Delta\,(A, B) \equiv [A]_w - [B]_W \qquad (6)$$

For example;

$$\Delta\,(dBZ_m, dBZ_{gv}) = [dBZ_m]_w - [dBZ_{gv}]_w \qquad (7)$$

where $[dBZ_m]_w$ is the weighted mean of dBZ_m and $[dBZ_{gv}]_w$ is the weighted mean of dBZ_{gv}.

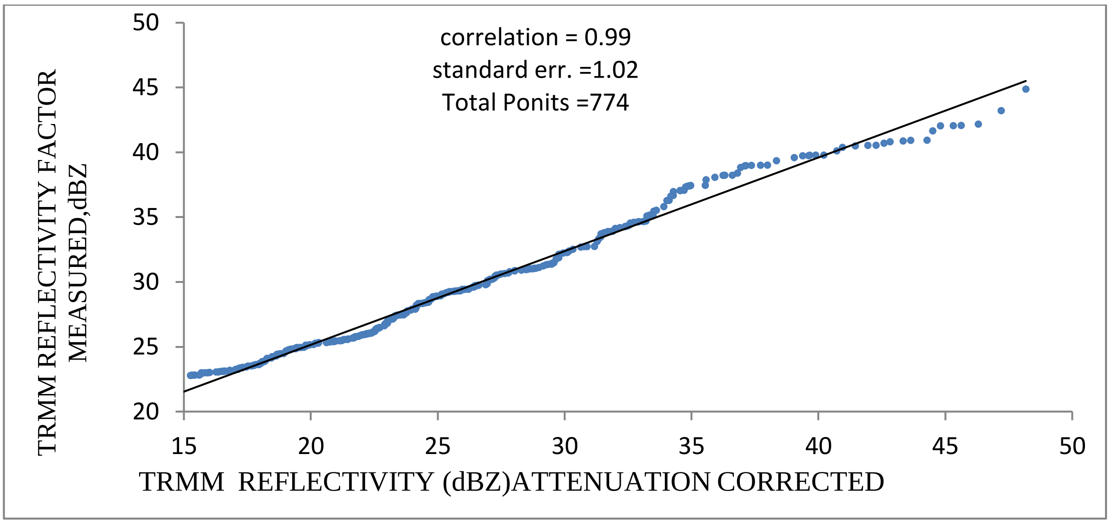

Fig 3: Scatter plots of TRMM (PR) dBZ vs. TRMM (PR) without and with Attenuation correction at 4km above sea level

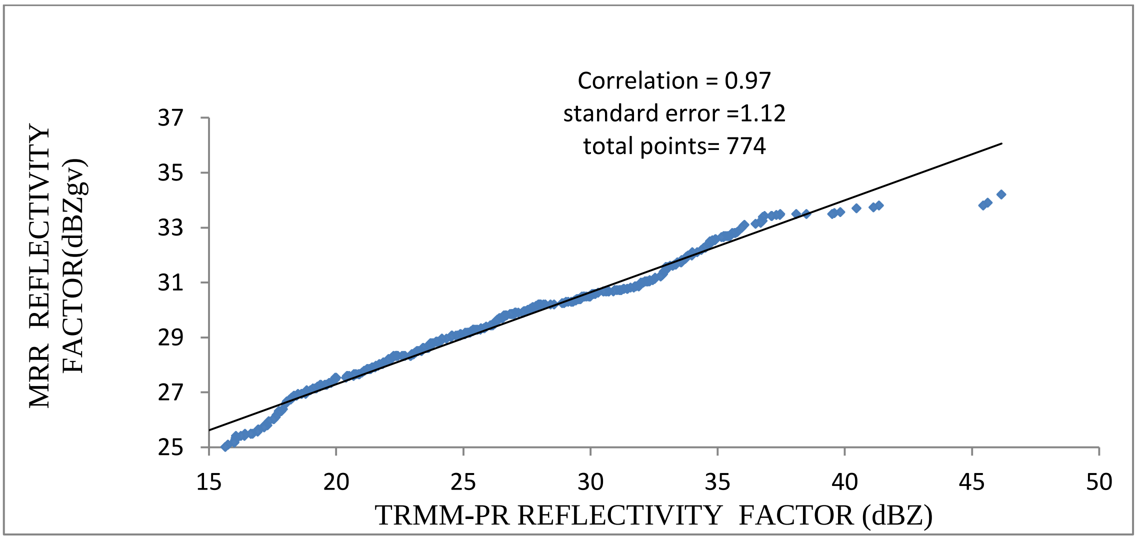

Fig 4: Scatter plots of MRR (dBZgv) vs TRMM dBZ with attenuation correction at 4km above sea level

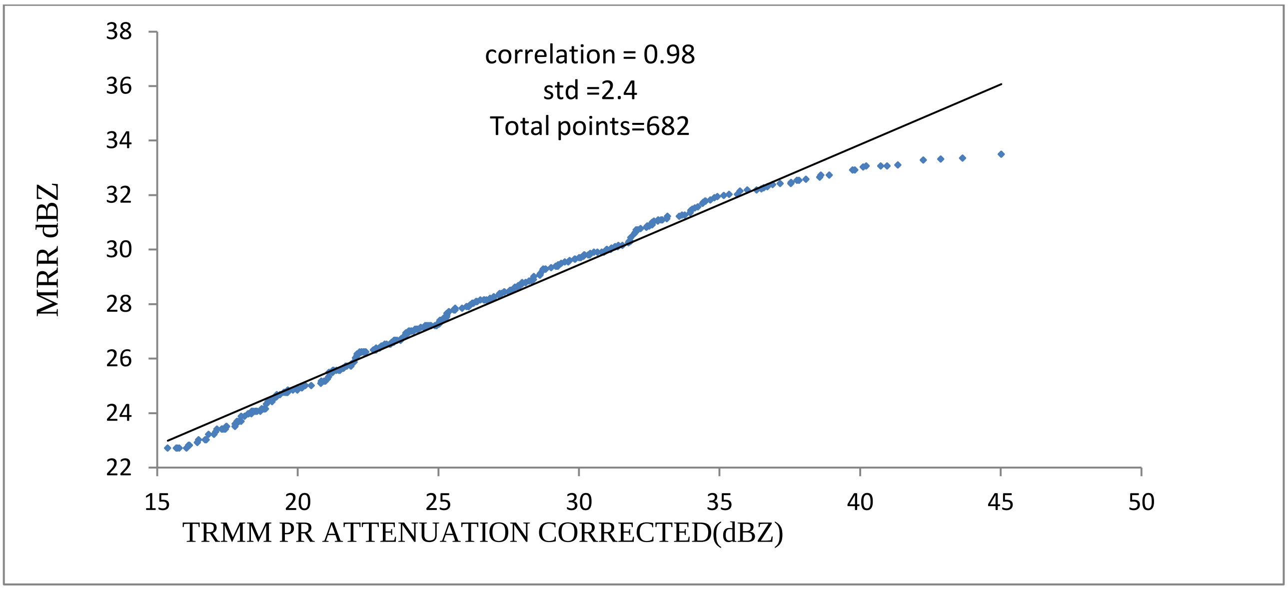

Fig 5: scatter plots of dBZ of MRR vs.TRMM with attenuation correction at 1.5 km above sea level.

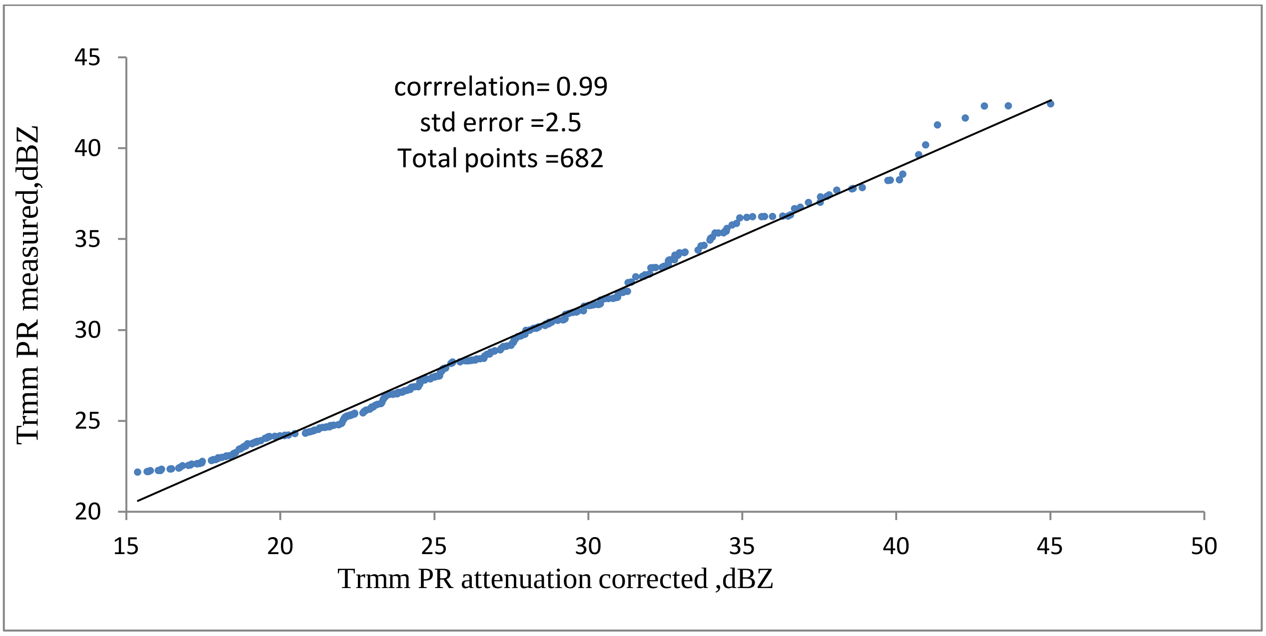

Fig 6: the scatter plots of TRMM (PR) dBZ vs. TRMM (PR) without and with attenuation at 1.5 km above sea level.

2.6 Discussion of Result

Tables 2 - 4 show the samples of the typical raw data pixel of the reflectivity factor without attenuation correction (dBZm), reflectivity factor with attenuation correction (dBZ) and the ground validated value from MRR (dBZgv) at some selected heights respectively. Each column represents various selected heights of 250 m, 500 m, 1 km, 1.5 km, 2 km, 3 km and 4 km. The difference between the data from the first and the last row of each column gives the maximum difference in reflectivity (dBZ). For example, Table 2 shows the magnitude of the variation of reflectivity dBZ values measured from TRMM-PR signal. The maximum differences of reflectivity dBZ values across the (range gates) columns is obtained during the measurement of reflectivity dBZ from the horizontal scan width. The maximum difference was derived by the deduction of the reflectivity dBZ value from the first row and the last row of each vertical height. The reflectivity dBZ values obtained ranges from 5.55 dB, 10.20 dB, 10.22 dB, 10.71 dB, 7.23 dB to 9.86 dB at 250 m, 500 m, 1 km, 1.5 km, 2 km, 3 km and 4 km respectively.

In Table 3, the attenuation correction made on the reflectivity dBZ data by the use of the TRMM-PR attenuation correction algorithm over the location, has the maximum difference which ranges from 10.90 dB, 9.49 dB, 12.69 dB, 14.70 dB, 13.39 dB, 13.63 dB to 10.74 dB at 250 m, 500 m, 1 km, 1.5 km, 2 km, 3 km and 4 km respectively which has higher values at the same altitudes than values in Table 2 without attenuation correction. Also, the maximum difference of dBZ values of the validated data from MRR is shown in Table 4, the values ranges from 12.2dB, 11.6dB, 11.1dB, 9.1 dB, 8.7 dB, 4.4 dB and 2.9 dB at 250 m, 500 m, 1 km, 1.5 km, 2 km, 3 km and 4 km respectively. These results show some discrepancies in reflectivity dBZ values within the data range gates of the radars, and also reveal the need for the calibration of the data over the location.

Tables 5 and 6 show the mean radar reflectivity factors; the ground validated MRR reflectivity (dBZgv) and the TRMM-PR reflectivity without (dBZm) and with (dBZ) attenuation correction for the 28 overpass cases with their overpass time. Each of the tables summarize the comparisons at heights 1.5 km and 4 km respectively, and gives a more complete picture of the TRMM-PR results relative to the MRR both with and without attenuation correction. The weighted mean values were derived from equation (5). It could be observed from the tables that, 6th April, 2008 and 26th August, 2010 had the most significant values both for rain rate (mm/h) and reflectivity factor Z (dBZ). The two days had the highest correlation coefficients and the highest value of N (number of points or common resolution). The difference between dBZ_m and dBZ is considered as an attenuation correction. This is because the latter dBZ_m has sensibility (the PR nominal threshold) to measure only data up to 18 dB and recording data below 18 dB as noise. While the former corrected this attenuation and can read data up to 15 dB only. This is what is referred to as attenuation corrected reflectivity data (dBZ).

The attenuation correction gives reflectivity (dBZ) values that are on the average 2.0 dBZ greater than its ground validated value dBZgv for MRR as presented in Table 5. The trend continues even as the height goes from to 1.5 km downward.

The TRMM-PR ground validation sites around the world such as in Florida, U.S.A, in Adelade, Australia have used the standard TRMM Science Data and Information System (TSDIS), and reported that the Standard TSDIS product gives rain rates only at the lowest vertical from the surface to 1.5 km (Liang Liao et al., 2001) and (http://disc2.nascom.nasa.gov as at 12th, December,2012).

The differences in the weighted means as a function of height were obtained by using equations (6) and (7). It could be observed that the relation Δ (dBZ, dBZgv) = (dBZ-dBZgv) gives 1.83 dB, 1.29 dB, 1.89 dB and 1.87 dB at heights of 4, 3, 2, and 1.5 km, respectively. This implies that the difference between the attenuation-corrected TRMM- PR derived radar reflectivity and the MRR reflectivity data is relatively insensitive to height and that the weighted means of the PR data are generally about 1-2 dB greater than the MRR with minor variation of 0.9dB. This reveals a good level of accuracy of TRMM (PR) data against MRR data over Akure.

In order to get an indication of the effect of attenuation correction on TRMM-PR results, we also considered the relation Δ (dBZ, dB*Zm*) that is, the difference between the reflectivity dBZ values from the TRMM-PR with and without attenuation correction. It was found out that Δ (dBZ, dB*Zm*) = 1.44 dB (4 km), 1.55dB (3 km), 1.67dB (2km) and 2.27dB (1.5 km); that is, the average attenuation correction goes from 1.44 dB at 4km to 2.27 dB at 1.5 km. This trend could also be observed in other heights. This again shows the variation of the two data (Amitai et al., 2000).

A case study was taken for the 6th April, 2008 as one of the most significant day of rainfall during measurement. Figures 3-4 show the scatter plot of reflectivity measured without attenuation correction (dBZm) versus reflectivity with attenuation correction (dBZ) and ground validated (dBZgv) versus reflectivity with attenuation correction (dBZ) at a height of 4 km respectively. It could be observed that, the two quantities are nearly identical and that the attenuation from the storm top to a 4 km height is usually negligible even with the intense rain on that day. On the other hand, Figures 5-6 show the increased apparent attenuation that TRMM-PR suffers while descending from 4 km, (near storm heights) down to 1.5 km. For further considerations on the specified day, heights 4 km and 1.5 km were taken for example.

Also the attenuation correction gives reflectivity dBZ values that on average are 6.1 dB greater than those obtained from the MRR reflectivity (dBZgv). The mean values of the day (6th April, 2008) over 4 km as indicated in Table 6 is presented using brackets to denote the mean, as shown (dBZm (h = 4 km)) = 35.30 dB, (dBZ (h = 4 km)) =33.15 dB and (dBZgv (h = 4 km)) =27.08 dB. This trend continues as the height is change from 4 to 1.5 km.

At the height of 1.5 km (Figures 5 and 6), the maximum difference between the data is nearly 15 dB. Despite the presence of strong attenuation, the corrected reflectivity dBZ values are well correlated with reflectivity dBZm values, R^2 = 0.99 whereas the correlation co-efficient between reflectivity dBZgv and reflectivity dBZ is 0.98 . These plots give a better correlation 0.99 and 0.98 respectively when compared with Table 5 values. This trend continues in the other heights examined.

A further observation in Table 5 shows that, the reflectivity dBZ attenuation correction is over 4.9 dB larger than the derived from the dBZgv of MRR. This is indicated by the notation; (dBZm (h =1.5 km)) =35.2dB, (dBZ (h=1.5 km)) =33.5 dB and (dBZgv (h = 1.5 km)) =28.6 dB. Some of the discrepancies between dBZgv and dBZ can be attributed to the non–Rayleigh scattering effects at the higher frequency, different viewing geometries and attenuation effects in the MRR which operates at 24.1GHz (1.25 cm wavelength) frequency. Increases in the radar reflectivity factor are usually associated with an increase in the number of concentration of large particles, the backscattering section of which can be significantly different for the wavelength of the MRR and that of (2.17 cm wavelength) the TRMM-PR. The non-Rayleigh scattering effect is usually estimated using measured DSDs (Liang et al., 200l).

Another reason for discrepancies may be due to the inaccuracies in the geolocation of the TRMM-PR. The location of a particular TRMM-PR radar volume along the beam is obtained from the latitude and longitude of the estimated surface range gate, which is normally taken as the gate where the return power is maximum. Errors in these data and variation in the topography contributes to the uncertainties in the location of the TRMM-PR radar volume to that of the ground validation (gv) volume.

Table 2: A typical raw sample of radar reflectivity factor data pixel measured from TRMM-PR (dBZm)* at some selected heights

++Heights	250 m	500 m	1 km	1.5 km	2 km	3 km	4 km
	REFLECTIVITY FACTOR VALUES (dBZm)						
	43.04	48.58	47.85	46.85	46.00	44.37	47.65**
	42.96	47.82	46.16	46.16	45.24	42.91	43.93
	42.96	45.18	45.02	45.02	44.90	41.28	43.50
	42.53	41.75	44.18	44.18	44.53	41.00	41.65
	41.75	40.97	43.88	43.88	43.74	40.94	41.64
	40.98	40.59	43.53	43.53	43.03	40.58	41.64
	40.97	40.39	43.04	43.04	43.01	40.54	41.60
	40.65	39.78	42.27	42.27	42.49	39.80	40.87
	40.62	39.51	41.29	41.29	41.45	39.52	40.48
	40.57	39.44	41.15	41.15	41.02	39.51	40.12
	40.26	39.43	40.41	40.41	40.74	39.44	40.12
	40.00	39.13	39.63	39.63	39.57	38.76	39.78
	39.77	39.05	39.61	39.61	39.27	38.73	39.70
	39.45	39.05	39.54	39.54	38.88	38.70	39.39
	39.09	39.04	39.36	39.36	38.76	38.69	39.32
	39.09	38.69	39.26	39.26	38.40	38.6	39.29
	39.04	38.69	39.23	39.23	38.37	38.51	39.29
	39.03	38.67	39.21	39.21	38.35	38.35	38.96
	38.96	38.67	38.48	38.48	38.07	38.33	38.56
	38.23	38.66	38.46	38.46	37.96	38.33	38.55
	38.19	38.66	38.20	38.20	37.96	37.92	38.50
	38.19	38.65	38.19	38.19	37.85	37.91	38.32
	38.17	38.65	38.12	38.12	37.71	37.89	38.17
	38.15	38.29	38.08	38.08	37.67	37.72	38.06
	37.95	38.28	38.07	38.07	37.58	37.56	37.97
	37.88	38.27	38.07	38.07	37.55	37.54	37.95
	37.49	37.88	37.67	37.67	37.29	37.14	37.79

*(dBZm) is the measured reflectivity factor values without attenuation correction.

++Each column represents the selected vertical range gate heights.

**Each row represents the horizontal scan width of the radar beam at 4 km (horizontal distance) each for the selected height

Table 3: A typical raw sample of radar reflectivity factor data pixel measured from TRMM-PR (dBZ)* at some selected heights

++Heights	250 m	500 m	1 km	1.5 km	2 km	3 km	4 km
	REFLECTIVITY FACTOR VALUES (dBZ)						
	47.38	44.91	49.43	50.44	49.29	49.13	46.16**
	45.87	42.67	48.94	48.94	45.58	42.54	45.62
	44.77	42.26	48.01	48.01	45.44	42.18	45.45
	43.55	40.84	47.46	47.46	45.36	41.67	41.35
	43.28	40.31	44.15	44.16	44.43	41.24	41.13
	42.69	39.68	43.83	43.82	43.98	41.13	40.46
	42.51	39.65	42.57	42.57	43.57	41.12	39.83
	41.28	39.48	42.56	42.56	43.15	40.93	39.59
	41.26	39.30	42.21	42.21	42.88	40.90	39.51
	40.84	39.07	41.74	41.74	42.86	40.81	38.49
	40.02	38.93	40.91	40.91	41.65	39.77	37.45
	39.96	38.60	40.05	40.05	40.86	39.30	37.31
	39.63	38.39	39.75	39.75	40.47	38.71	37.14
	39.44	38.36	38.99	38.99	39.38	38.31	37.13
	39.11	38.05	38.05	38.05	39.30	38.31	37.11
	39.07	38.02	37.55	37.55	39.28	37.89	36.85
	38.62	37.95	37.55	37.55	38.74	37.77	36.78
	38.36	37.79	37.37	37.37	38.59	37.71	36.77
	38.24	37.79	37.35	37.35	38.48	37.45	36.73
	37.97	37.64	37.16	37.16	37.77	37.42	36.71
	37.65	37.56	37.14	37.14	37.74	37.37	36.70
	37.54	37.50	37.11	37.11	37.48	37.34	36.49
	37.45	37.45	36.66	36.66	37.37	36.92	36.06
	37.39	37.44	36.57	36.57	37.32	36.85	36.02
	37.33	37.42	36.57	36.57	37.32	36.62	35.95
	37.30	37.20	36.51	36.51	37.22	36.33	35.78
	37.29	37.17	36.41	36.41	36.82	36.26	35.71
	36.84	37.16	36.38	36.38	36.80	36.19	35.66
	36.76	37.07	36.29	36.29	36.61	35.79	35.58
	36.45	36.44	36.74	35.74	35.90	35.53	35.43

*(dBZ) is the reflectivity factor values with attenuation correction.
+Each column represents the selected vertical range gate heights.
**Each row represents the horizontal scan width of the radar beam at 4 km (horizontal distance) each for the selected height.

Table 4: A typical raw sample of radar reflectivity factor data pixel measured from MRR(dBZgv*) at some selected heights

++Heights	160 m	480 m	960 m	1440 m	2080 m	3040 m	4000 m
	REFLECTIVITY FACTOR VALUES (dBZ)gv						
	46.5	43.7	40.4	38.4	35.2	28.8	32.0**
	44.9	43.4	36.8	36.8	33.5	28.3	32.0
	44.5	42.9	36.1	36.1	33.3	28.3	31.6
	43.7	42.5	36.0	36.0	33.3	27.4	31.5
	43.5	41.7	36.0	36.0	33.1	27.4	31.5
	42.1	38.5	33.6	33.6	30.7	26.7	31.1
	41.7	38.3	33.4	33.4	30.4	26.6	31.1
	38.3	37.4	32.7	32.7	30.3	26.1	31.1
	38.1	36.3	32.7	32.7	29.5	26.0	31.1
	37.2	35.6	32.2	32.2	29.5	25.9	31.1
	37.1	35.6	31.8	31.8	29.4	25.7	31.1
	37.1	35.4	31.1	31.1	29.4	25.7	30.6
	37.0	34.8	30.9	30.9	29.2	25.6	30.6
	37.0	34.8	30.6	30.6	29.2	25.6	30.5
	36.8	34.7	30.5	30.5	29.1	25.4	30.2
	36.7	34.5	30.3	30.3	28.9	25.4	30.1
	36.6	34.5	30.3	30.3	28.9	25.3	30.0
	36.4	34.5	30.3	30.3	28.8	25.2	30.0
	36.4	34.3	30.0	30.0	28.7	25.0	29.9
	36.2	34.3	30.0	30.0	28.6	25.0	29.9
	36.2	34.0	30.0	30.0	28.6	24.9	29.9
	36.0	33.9	30.0	30.0	28.6	24.9	29.8
	35.8	33.8	29.9	29.9	28.5	24.8	29.8
	35.8	33.7	29.8	29.8	28.2	24.8	29.7
	35.5	33.2	29.7	29.7	28.0	24.7	29.5
	35.1	32.9	29.7	29.7	28.0	24.6	29.3
	34.9	32.7	29.6	29.6	27.9	24.6	29.2
	34.7	32.6	29.6	29.6	27.8	24.5	29.2
	34.7	32.6	29.5	29.5	27.8	24.5	29.2
	34.5	32.4	29.4	29.4	27.7	24.5	29.1
	34.5	32.3	29.3	29.3	27.7	24.4	29.1
	34.3	32.1	29.3	29.3	27.5	24.4	29.1

*(dBZ) gv is the reflectivity factor ground validation values from MRR .

++Each column represents the selected vertical range gate heights.

**Each row represents the horizontal scan width of the radar beam (horizontal distance) each for the selected height.

Table 5: Mean radar reflectivity factors of the MRR (dBZgv) and TRMM PR with (dBZ) and without attenuation correction for 28 overpass cases

Height Above Sea Level: 1.5 km							
	Overpass	**MEANS**			**CORRELATION**		
Date	Time	dBZm	dBZ	dBZgv	dBZm-dBZ	dBZ-dBZgv	Points(N)
11 March 2008	23:59	32.70	28.20	23.40	0.91	0.96	538
21 March 2008	18:30	31.50	28.70	29.90	0.91	0.92	620
25 March2008	02:35	39.64	37.30	35.70	0.99	0.99	275
4 April 2008	22:49	37.70	36.00	28.90	0.92	0.92	440
5 April 2008	21:55	28.90	26.20	27.10	0.86	0.78	1026
6 April 2008	**19:28**	**35.74**	**33.50**	**28.60**	**0.98**	**0.99**	**1028***
7 April 2008	09:20	29.50	25.10	30.60	0.59	0.72	738
12 April 2008	18:40	31.90	29.10	27.30	0.92	0.94	610
24 April 2008	01:38	35.60	33.30	31.10	0.87	0.83	775
17 June 2008	22:15	35.20	33.30	27.50	0.84	0.88	826
26 June 2008	15:40	37.40	35.40	30.20	0.84	0.79	347
21 July 2008	05:21	30.70	28.60	30.40	0.82	0.83	498
24 July 2008	14:57	32.90	30.40	28.10	0.93	0.99	976
25 Aug 2010	12:36	29.80	26.40	29.20	0.79	0.95	702
26 Aug 2010	**22:29**	**28.00**	**26.40**	**22.90**	**0.99**	**0.99**	**1208***
14 Sept 2010	14.33	29.00	27.00	26.40	0.95	0.74	230
16 Sept 2010	00:26	27.90	25.30	21.80	0.98	0.98	240
19 Sept 2010	11:36	27.50	25.00	24.40	0.93	0.91	621
27Sept 2010	09:00	28.80	26.60	24.30	0.91	0.87	614
28 Sept 2010	06:33	30.50	28.50	27.90	0.83	0.83	165
07 Oct 2010	03:02	31.00	28.00	21.40	0.80	0.79	382
08 Oct 2010	14:27	30.00	26.70	22.90	0.99	0.99	934
12 Oct 2010	23:09	27.70	25.20	23.10	0.92	0.84	328
21 Oct 2010	19:37	26.20	28.50	22.60	0.71	0.71	335
27 Oct 2010	17:20	29.50	25.60	25.50	0.94	0.91	350
29 Oct 2010	01:40	26.60	28.80	27.40	0.94	0.92	232
03 Oct 2010	23:20	29.80	26.50	24.20	0.82	0.81	225
05 Nov 2010	10:44	27.50	25.30	29.80	0.98	0.98	101
Total		868.60	804.90	752.60	23.86	24.74	15364
Weighted mean		31.02	28.75	26.88	0.85	0.88	548.71

*Rows in bold means days with the most significant rain rate and reflectivity values

Table 6: Mean radar reflectivity factors of the MRR (dBZgv) and TRMM PR with (dBZ) and without attenuation correction for 28 overpass cases

Height Above Sea Level: 4 km							
	Overpass	**MEAN**			**CORRELATION**		
Date	Time	dBZm	dBZ	dBZgv	dBZm-dBZgv	dBZ-dBZgv	Points (N)
11 March 2008	23:59	32.12	29.06	26.81	0.89	0.84	612
21 March 2008	18:30	30.72	27.95	28.20	0.94	0.93	609
25 March 2008	02:35	39.52	37.06	26.05	0.86	0.82	168
4 April 2008	22:49	36.08	34.10	28.08	0.89	0.87	384
5 April 2008	21:55	27.78	25.52	28.40	0.86	0.98	312
6 April 2008	**19:28**	**35.30**	**33.15**	**27.08**	**0.98**	**0.98**	**936***
7 April 2008	09:20	30.57	28.18	32.06	0.56	0.53	324
12 April 2008	18:40	32.50	31.00	34.20	0.99	0.99	202
24 April 2008	01:38	34.00	33.90	27.35	0.93	0.87	228
17 June 2008	22:15	39.60	38.47	27.99	0.76	0.58	96
26 June 2008	15:40	34.50	34.06	29.02	0.83	0.84	240
21 July 2008	05:21	32.50	32.17	31.20	0.59	0.55	220
24 July 2008	14:57	32.80	30.70	28.05	0.79	0.73	272
25 Aug 2010	12:36	31.84	29.09	27.39	0.89	0.89	574
26 Aug 2010	**22:29**	**28.08**	**25.79**	**20.21**	**0.98**	**0.98**	**1066***
14 Sep 2010	14.33	27.44	25.37	29.26	0.93	0.98	650
16 Sep 2010	00:26	25.80	24.42	27.68	0.93	0.89	340
19 Sep 2010	11:36	28.29	26.01	28.29	0.98	0.98	934
27 Sep 2010	09:00	28.27	27.04	24.38	0.96	0.97	914
28 Sep 2010	06:33	28.66	27.11	26.65	0.92	0.99	832
07 Oct 2010	03:02	30.03	27.95	24.15	0.97	0.97	796
08 Oct 2010	14:27	26.53	24.59	24.86	0.92	0.88	1022
12 Oct 2010	23:09	32.32	28.81	25.34	0.93	0.96	950
21 Oct 2010	19:37	30.26	26.26	24.24	0.96	0.97	596
27 Oct 2010	17:20	27.73	25.35	23.03	0.97	0.95	920
29 Oct 2010	01:40	28.34	26.44	25.33	0.97	0.98	1032
03 Nov2010	23:20	27.49	29.25	29.56	0.88	0.88	982
05 Nov2010	10:44	26.02	24.27	26.02	0.93	0.94	550
Total		853.43	813.07	761.80	24.99	24.72	16761
Weighted Mean		30.48	29.04	27.21	0.89	0.88	598.61

*Rows in bold means days with the most significant rain rate and reflectivity values.

Conclusion

The variation of the observed radar reflectivity with rain rate relation had been carried out to examine the quality of the TRMM-PR data. In doing this, the comparison of the TRMM-PR-derived reflectivity, dBZ and rain rates with the same quantities derived from near-simultaneous measurements by the MRR was done. The data obtained from the 28 overpass cases suggest that after attenuation correction, the reflectivity dBZ values are on average about 2 dB larger than the

MRR reflectivity values, dBZ_{gv}, and that this difference is approximately independent of height. Also, the difference between reflectivity dBZ_{gv} and reflectivity dBZ_m (the radar reflectivity factors obtained from the TRMM-PR without attenuation compensation) and between reflectivity dBZ and reflectivity dBZ_m shows a noticeable dependence on height.

The result shows that the reflectivity dBZ derived from the TRMM- PR data after attenuation correction agrees to an extent of 2.0 dB when compared with that of MRR with a relative variation of ± 0.9dB at different heights. The correlation coefficient over the 28 overpasses is about 0.96. This analysis will provide an assessment of the performance of the PR algorithm and also a calibration factor using MRR over Akure, Nigeria

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