

## Rain Attenuation Studies in the Microwave Band over a Southern Latitude.

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### ABSTRACT

Brightness temperatures at 22.234, 23.834 and 30 GHz and corresponding rain rates were measured using a ground based radiometer and a fast response optical rain gauge co-located with the radiometer during the year 2009 at Cauchuria, Paulista (22.57° S, 89° W), Brazil. A statistical analysis reveals that the number of occurrences goes beyond 200 times for rain rate up to 15 mm/hr. It was observed also that the number of events suddenly falls to 75 for rain rates 15-25 mm/hr. Hence it suggests that at the place of experiment the most abundant rain rate was up to 25 mm/hr. The brightness temperature as measured by the radiometer sharply increases up to rain rate 10-12 mm/hr. But above this rain rate, radiometer brightness temperature slowly increases and has a tendency of saturation at all frequencies.

A slight departure is observed in variation pattern of attenuation at 22.234 GHz during 21:35:00 to 23:43:25 hrs (local time), when rain rate is very low. Below 5 mm/hr, the measured attenuation is found to be higher than the calculated attenuation. This might be due to the fact that the heated earth surface evaporates water vapor and subsequently is filling up the antenna beam by a more amount of vapor when rain drop falls on the surface. This becomes prominent only at 22.234 GHz since the frequency of the radiometer lies just at the water vapor resonance line, although weak. This kind of anomaly is not recognized at the pressure independent frequency 23.834 GHz. So it appears that rain attenuation measurements at 22.234 GHz are contaminated by the unwanted

presence of water vapor. This effect is minimized at the window frequency region (around 30 GHz) where attenuation due to water vapor is very less. It was also noticed that rain attenuation increases monotonically with rain rate with an exception at 23.834 GHz.

During our study it was also observed at 23.834 GHz the attenuation always provides a minimum irrespective of any rain rate within the water vapor band. Hence, 23.834 may be considered as a good choice of radiometric measurement in the water vapor band. It is interesting to point out that effective rain height measured at 23.834 matches well with the physical rain height which was found to be 3.62 km.

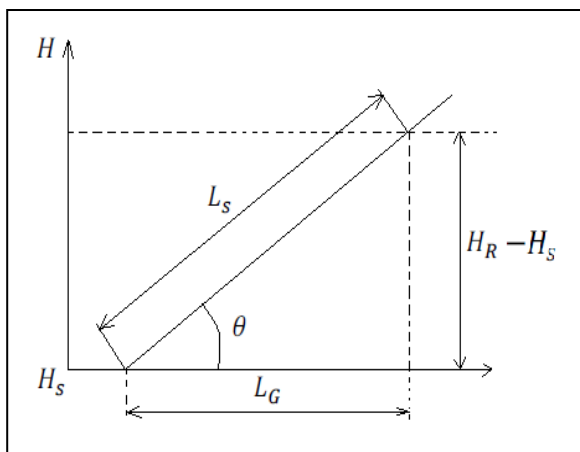
(Keywords: radiometer, rain attenuation, rain height, water vapor, microwave propagation)

### INTRODUCTION

Rain attenuation in the microwave band is currently considered to be a major concern in the design of satellite communication systems at frequencies above 10 GHz. The prediction of rain attenuation generally starts from known point rainfall rate statistics, considering the vertical and horizontal structures of rain cell using climatological parameters (Karmakar et al., 1991). These data can be used to estimate rain attenuations with the help of physical and statistical modeling procedures. Attenuations can be estimated experimentally from radiometric measurements of sky noise temperatures with certain assumptions made regarding the

atmospheric medium. The vertical extent of rain can be estimated from meteorological measurements of the height of the zero degree isotherm or radar reflectivity measurements (Mawira et al., 1981), from which rain attenuations along the path through the atmosphere can be determined.

A number of prediction procedures have been developed for earth space paths over the last decade which are applicable to temperate climate, but have been found to overestimate rain attenuations in tropical region (Dissanayake et al., 1990). This overestimation of the predicted result is considered to be due to an incorrect estimate of the effective path length, essentially leading to an inaccurate estimation of the path attenuation. The developments of improved and more accurate rain attenuation models applicable to tropical climates thus require more experimental data from such tropical regions. It has been considered that the equivalent vertical path length through the rain is not equal to the physical rain height. The ITU-R has developed a model for the path length reduction coefficient for the horizontal projection of the path,  $L_G$  (Figure 1), with the vertical path equivalent to the height of zero degree isotherms (Ajayi et.al, 1990). An empirical vertical reduction factor for earth-space paths have been proposed to derive an effective rain height from the height of the zero degree isotherm during rainy condition (CCIR, Doc. 5/387-E, 1989).



**Figure 1:** Schematic Diagram of Earth-Space Path.

In order to study the attenuations in the microwave band, continuous measurements of sky noise temperatures at 22.234, 23.834 and 30 GHz were conducted using a ground based radiometer during the year 2009 at Cauchuria, Paulista (22.57° S, 89° W), Brazil.

The experimental measurements were supported by the results obtained from a fast response optical rain gauge co-located with the radiometer.

## INSTRUMENTATION

### Radiometer

The radiometer used for this purpose is a ground based radiometer. The details of this radiometer (MP-3000A) are available from [www.radiometrics.com](http://www.radiometrics.com). The selected frequency bands in the said Radiometer were (i) Water vapour absorption band (22-30 GHz) and (ii) Oxygen absorption band (50-60 GHz). But we have selected only the water vapour band for the sake of current studies. The radiometer is controlled by Radiometrics proprietary software and preinstalled control computer. The control computer is connected directly to the radiometer via supplied RS-422 cable. The operating code provides a single use graphical interface that allows the selection of user defined observation procedure and automated calibration procedure.

Real time observation and calibration data are displayed in graphical format. Now depending upon the choice of operating codes, it begins logging data to level '0' file (raw sensor data in volts), level '1' file (brightness temperature) and others along with calibration file. The radiometer antenna has its beam width and side lobe 4.9-6.3 deg.; -24 dB (for 22-30 GHz band) respectively. The dynamic range of the radiometer is from 0 to 400 K. It has channel bandwidth 300 MHz and depending on the integration time it possesses the resolution of 0.1 to 1.0 K. Here in our study, we have chosen the resolution as 1.0 K.

### Laser Precipitation Monitor

Rainfall intensity is measured by this monitor. It has the capability to measure particle size down to 0.16 mm diameter. The instrument has the following characteristics:

- i) Laser: 785 nm, optical: 0.5 nw (max).
- ii) Measuring area: 46 cm<sup>2</sup> (23x2 cm).
- iii) Minimum intensity: 0.005 mm/hr (drizzle)
- iv) Maximum intensity: 250 mm/hr
- v) Integration time: 10 seconds.

**THEORITICAL BACKGROUND:**

Rain attenuation is characterized by the non-uniformity of rainfall intensity, raindrop number density, size, shape or orientation and raindrop temperature in addition to its intrinsic variability in time and space. Rain attenuation on an earth space path may be expressed by the following relation:

$$A(s) = \int_0^{\infty} \lambda(s) ds \tag{1}$$

where, ds represent the incremental distance from the ground along the earth-space paths, under consideration and  $\lambda(s)$  is the specific attenuation (dB/km).

For practical application, however, the calculation of rain attenuation is approximated to a simple power law for a number of rain drop size distributions and temperatures in the form:

$$A(s) = \int_0^{L_S} aR^b ds \tag{2}$$

where, ‘a’ and ‘b’ are the coefficients which depend on frequency, temperature and rain drop size distribution; R is the rain rate in mm/hr and  $\lambda$  is substituted as  $aR^b$ , dB/km. The parameter  $L_G$  is the projection of the rainy earth-space path along the ground (Figure.1) and is given by:

$$L_G = [(H_R - H_S) / \tan(\theta)] \tag{3}$$

where,  $\theta$  is the angle of elevation,  $H_R$  the rain height and  $H_S$  the height from sea level. The parameter  $L_S$  is the slant path below the rain height and is given by:

$$L_S = [(H_R - H_S) / \sin(\theta)] \tag{4}$$

The rain attenuation (dB) may be determined from the measured rain intensity data assuming that the rain is spatially uniform. However, in

practice, rain is generally not uniform over the entire radio path. Therefore, the entire path may be divided into small incremental volumes  $\delta V$  in which the rain rate is approximately uniform. According to Semplek and Bodtman (Semplek et al., 1969; Bodtman et al., 1974), an approximate choice of  $\delta V$  was considered to be  $1m^3$  for meaningful measurement of very low rain intensity. An experimental study (Lin, 1975) indicates that heavy rain also has finite structure of the order of  $m^3$ . With this choice of  $\delta V$ , total path attenuation may also be obtained as the integral of the attenuation coefficient (dB/km) along the entire radio path.

The values of the coefficients ‘a’ and ‘b’, applicable to the chosen frequencies are taken from ITU-R (ITU-R p.618-8, 1995) data base, where the rain drop size was assumed to obey the log-normal distribution. These values are frequency and polarization dependent and are shown in Table 1.

**Table 1:** Values of Constants ‘a’ and ‘b’.

Frequency (GHz)	Value of ‘a’	Value of ‘b’
22.234	0.0766	1.1074
23.834	0.0906	1.1014
30	0.1581	1.0427

In the simplified model, the rain intensity in the rain medium is considered not to vary along the path, i.e., the rain intensity is homogeneous along the vertical path up to a height  $H_R$ . This height is assumed to be the level from which rain drops with a diameter larger than 0.1 mm fall, and may be described as the physical rain height. The rain attenuation in the zenith direction (z) is then given by:

$$A(z) = (H_R - H_S) aR^b \text{ dB} \tag{5}$$

It may also be noted that the physical rain height is not easily measureable and the simplest approximation being identified with the zero degree isotherm height.

The zero degree isotherm height, i.e., the rain height during rainy condition for latitudes less than 36 degree is given by the relation (Fedi 1981):

$$H_R = 3.0 + 0.028\Phi \text{ km} \tag{6}$$

where,  $\Phi$  is the latitude in degrees. For tropical latitudes, i.e., for  $\Phi < 36$  degree, it has been proposed that a path reduction factor deduced in this regard using ITU-R model (ITU-R, p.618-8, 1995) to be incorporated while calculating  $H_R$ . It is worthwhile to note that the path reduction factor was evaluated for 0.01 percent of time in a year. It was striking to note that out of 217 rain events occurred during 2009, the highest rain rate was 107 mm/hr but we have restricted ourselves within 20-25mm/hr rain rate.

Referring to equation (4), for a zenith-pointing radiometer ( $\theta=90$  deg.), we write:

$$L_S = H_R - H_S \quad (7)$$

The measured brightness temperature  $T_a$ , during rain, have been converted to total attenuation (dB) using the relation (Allnutt, 1976).

$$A = 10 \log_{10}((T_m - T_c)/(T_m - T_a)) \quad (8)$$

where,  $T_m$  is the mean atmospheric temperature. For tropical latitudes like Brazil (22.57 deg. S) the values of  $T_m$  will be higher than those in temperate latitudes, due to the higher temperatures and larger water vapour content (Sen et al., 1990) and is defined as (Wu, 1979).

$$T_m = \frac{\int T(z) \alpha(z) \exp -\alpha(z) dz}{\int \alpha(z) \exp -\alpha(z) dz} \quad (9)$$

The value of  $T_m$  has been calculated with the help of known vertical profile of atmospheric temperature and the corresponding vertical profile of attenuation coefficients. The value of  $T_c$  was considered as 2.75K (Ulaby 1986). The attenuation coefficients are calculated by using the Millimetre Wave Propagation model (MPM) by Liebe (1985) where the input parameters were temperature, pressure, humidity of the ambient atmosphere. These data were made available from British Atmospheric Data Centre, (BADC), over Brazil.

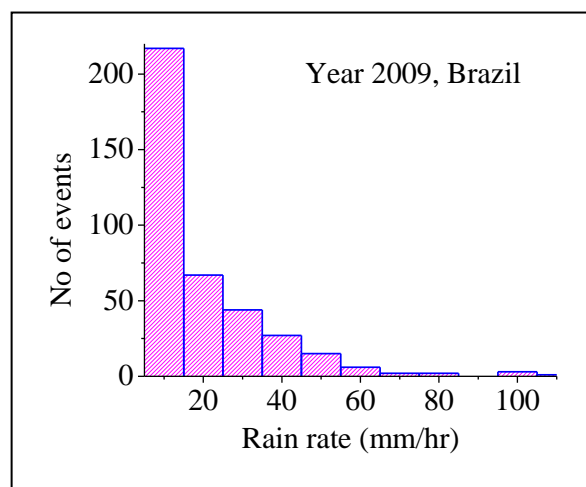
To get the relation between the surface temperature  $T_s$ , an attempt has been made, for the sake of simplicity, to correlate them with a linear relation and subsequently it was found that  $T_m = M + NT_s$  (Mitra *et al.* 2000), where M and N are the regression coefficients derivable for different frequencies.  $T_m$  is the mean atmospheric temperature dependent on frequency and is

related to surface (ground) temperature. The values of M and N for 22.234, 23.834 and 30 GHz were calculated as  $M=270.05$ , 270.03 and 270.00 K, respectively;  $N=0.778$ , 0.791 and 0.816  $K/^\circ C$ . So it is obvious that the values of  $T_m$  would be different for different frequencies. Hence, by observing the ground temperature and using the appropriate values of M and N, the mean atmospheric temperature  $T_m$  were found out. Now with the knowledge of  $T_m$  and  $T_c$  and by using equation 8, the attenuation values were found out where  $T_a$  is the measured brightness temperature at the chosen frequency

## ANALYSIS AND RESULTS:

### Rainfall Rate Measurement

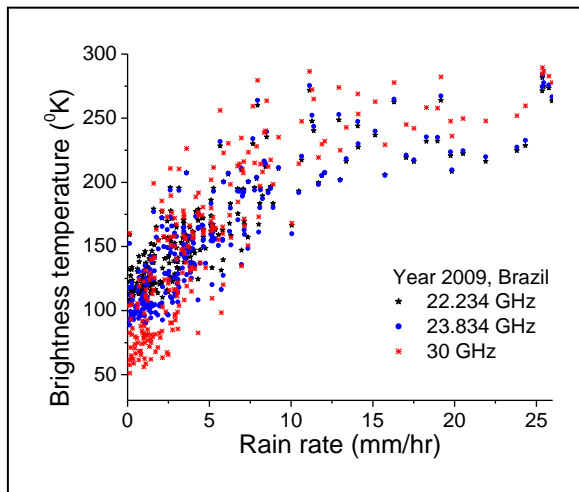
Figure 2 represents the histogram plot of rain intensity (mm/hr) measured by a fast response disdrometer. It is interesting to note that rain rate rarely goes beyond 100 mm/hr during our study. There were few events occurred when rain rate attains a maximum value of 107 mm/hr. A statistical analysis of the number of rain events over Cachoeira Paulista (CP, 22<sup>o</sup> S), Brazil during the year 2009 reveal that the number of occurrence goes beyond 200 times for rain rate up to 15 mm/hr but quite interestingly it is observed also that the number of events suddenly falls to 75 for rain rates 15-25 mm/hr. Hence it suggests that at the place of experiment the most abundant rain rate was up to 25 mm/hr.



**Figure 2:** Rain Rate Distribution over Brazil.

### Brightness Temperature

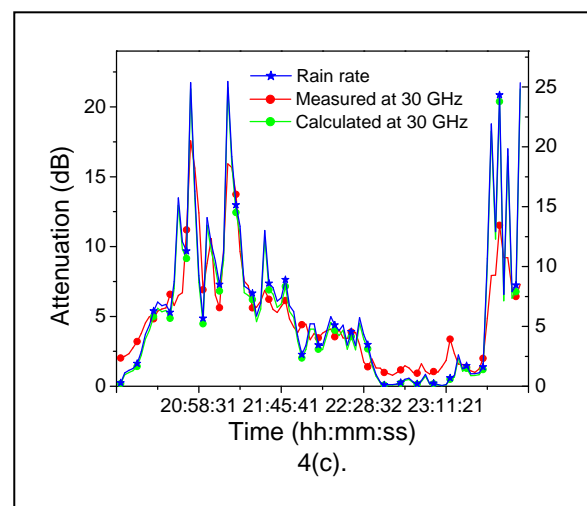
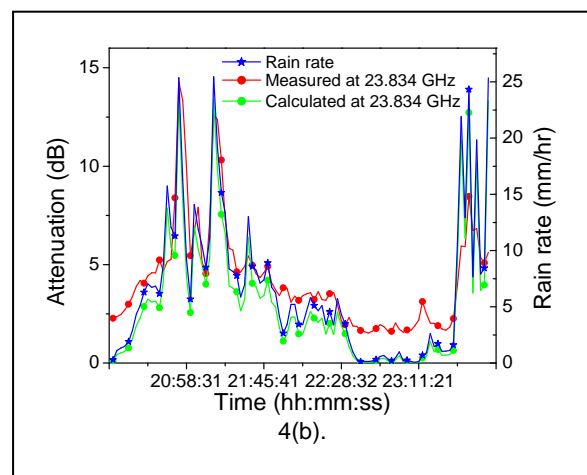
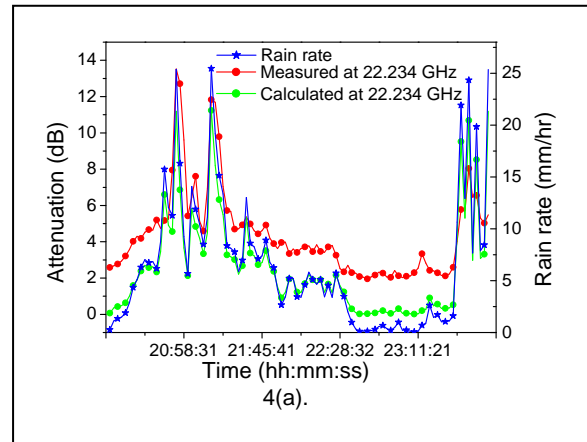
The maximum brightness temperature  $T_a$  observed by the radiometer was around 291 K for the water vapor frequency band (20 – 30 GHz). There were several events in which the sky noise temperatures exceeded 290 K. It is interesting to point out from Figure 3 that the brightness temperature sharply increases up to rain rate 10-12 mm/hr. But above this rain rate, radiometer brightness temperature slowly increases and has a tendency of saturation at all frequencies. The relationships of the radiometer brightness temperature at different frequencies with rain rate appear to follow the power law equation as is evident from Figure 3.



**Figure 3:** Variation of Brightness Temperature with Rain Intensity.

### Attenuation

From the observed values of brightness temperature at three frequencies in the water vapor band, the vertical path attenuation was calculated using Equation (8). Figure 4 presents the time variation of measured and calculated path attenuations (see Equations 5 and 6) and rainfall rate for a particular event on January 20, 2009. It is interesting to note that variation pattern of path attenuation at all the frequencies followed rain intensity (mm/hr) variation pattern measured by fast response disdrometer.



**Figure 4:** Time Series of Measured and Calculated Attenuation and Corresponding Rain Rates over Brazil on 20<sup>th</sup> January 2009.

It is to be mentioned here that disdrometer and radiometer were co-located at INPE, Brazil.

A slight departure is observed in variation pattern of attenuation at 22.234 GHz (Figure 4a) during 21:35:00 to 23:43:25 hrs (local time), when rain rate is very low.

Below 5 mm/hr, the measured attenuation is found to be higher than the calculated attenuation. This might be due to the fact that the heated earth surface evaporates water vapor and subsequently is filling up the antenna beam by a more amount of vapor when rain drop falls on the surface. This becomes prominent only at 22.234 GHz since the frequency of the radiometer lies just at the water vapor resonance line, although weak. But it is to be noted that the radiometer always maintained a threshold attenuation level. This shows the larger sensitivity of water vapor at 22.234 GHz although this frequency is pressure broadened and hence not suitable for accurate estimation of water vapor. This kind of anomaly is not recognized at 23.834 GHz (Figure 4b) which is found to be pressure independent. So it appears that rain attenuation measurements at 22.234 GHz are contaminated by the unwanted presence of water vapor. This effect is minimized at the window frequency region (around 30 GHz) where attenuation due to water vapor is very less (Figure 4c).

Another interesting result is noticed here that at the peak rain rates (Figure 4), the calculated attenuations at all the frequencies are much higher than those of the measured attenuations. It is very prominent at 30 GHz as this is the highest frequency in our study.

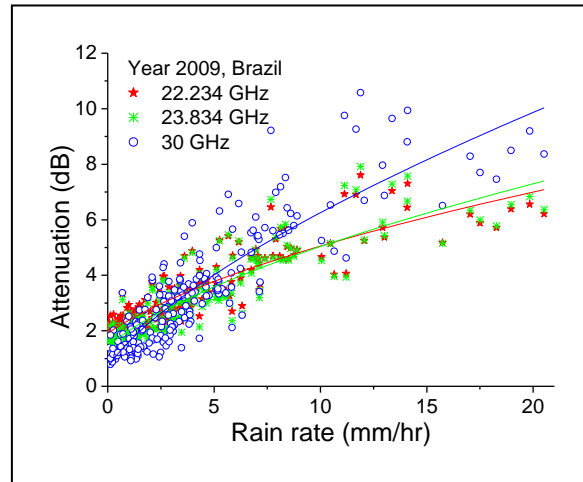
Another attempt has been made to work out regression analyses to a power law yields the following best-fit relations, at the said frequencies (Figure 5).

The equation was found to be in the form  $A$  (dB) =  $H_R a(R-R_c)^b$

$$A_{22.234}(\text{dB}) = 3.63 \times 0.367 (R+1.944)^{0.536} \quad (r^2=0.797)$$

$$A_{23.834}(\text{dB}) = 3.63 \times 0.332 (R+1.373)^{0.587} \quad (r^2=0.797)$$

$$A_{30}(\text{dB}) = 3.63 \times 0.353 (R+0.394)^{0.675} \quad (r^2=0.797)$$



**Figure 5.** Scatter and Best Fit Plot of Rain Attenuation at 22.234, 23.834, and 30 GHz and the Corresponding Rain Rates.

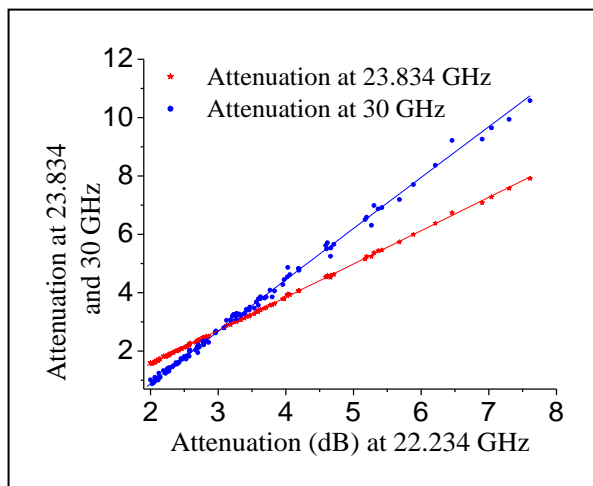
The experimental results were compared with those obtained theoretically for different frequencies, using the values of 'a' and 'b' listed in table1. It was found that the calculated rain attenuations deviated significantly from the measured values, at higher rain rates. For this reason best fit curves have been drawn up to 20 mm/hr rain rates and corresponding 'a' and 'b' coefficient matched very well up to this rain rate.

It is to be noted here that attenuation at all frequencies maintained a minimum threshold level. At 30 GHz it is nearly 0.685 dB and at 22.234 GHz it is around 1.906 dB, even when rain rate is zero. This is because of the fact that the frequencies around 22.234 GHz are water vapor sensitive but 30 GHz is not that much sensitive to water vapor. So it is suggested that as we move on to the higher frequencies from 22.234 up to 30 GHz, the water vapor sensitivity becomes lesser. Keeping this in mind we were prompted to see the variation pattern of rain attenuation at 23.834 and 30 GHz with respect to 22.234 GHz (Figure 6).

Regression analyses of attenuation taking 22.234 GHz as reference frequency, we get:

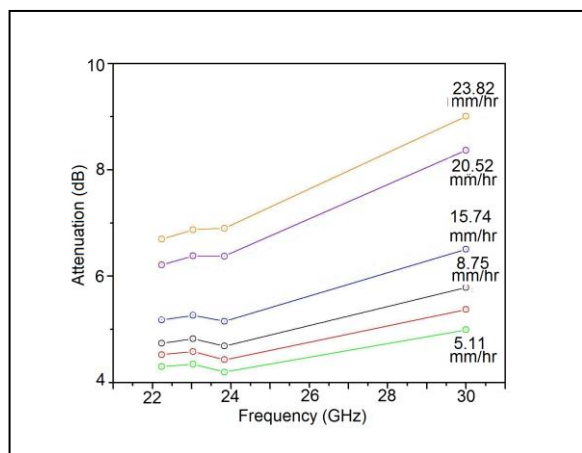
$$A_{23.834}(\text{dB}) = 1.133 (A_{22.234} - 0.6204)^{1.003} \quad (r^2=0.999)$$

$$A_{30}(\text{dB}) = 1.823 (A_{22.234} - 1.528)^{0.982} \quad (r^2=0.997)$$



**Figure 6:** Scatter Plot and Best-Fit Result of Attenuation at 22.834 GHz and 30 GHz against 22.234 GHz during the year 2009.

So using these equations, one can have the idea of getting an approximate value of rain attenuation at the said two frequencies by measuring rain attenuation at 22.234 GHz, at the corresponding rain rate. An attempt has also been made to present the variation of rain attenuation with frequency taking rain as a parameter (Figure 7). Here we have restricted ourselves within the rain rate 5–25 mm/hr. It is surprisingly noticed that rain attenuation increases monotonically with rain rate with an exception at 23.834 GHz. During our study it is also observed that at 23.834 GHz the attenuation is always minimum irrespective of any rain rate within the water vapor band.



**Figure 7:** Variation of Rain Attenuation at Different Frequency Taking Rain as Parameter.

In this connection it is to be mentioned that this 23.834 GHz is such a frequency which is found to be pressure independent and considered as a good choice of radiometric measurement in the water vapor band.

### Rain Height

The non-uniform horizontal rain structure is accounted for the use of a rain rate reduction factor to convert the physical path length to an effective path length. The simple vertical structure assumes that rainfall is uniform from the ground to rain height. The physical rain height is the level up to which the water drops with diameter larger than 0.1 mm present. However, the effective rain height may be obtained by analyzing the measured attenuation and point rainfall intensity data. Any non-uniformity of the vertical profile of rain is, in fact, integrated with time provided that all the water falling inside an ideal column ultimately reaches the ground. But it may so happen that a few raindrops remain aloft and then the radio wave propagation may not be affected. Moreover wind may also drive away the floating rain drops from the radio path. But, in practice, the vertical non-uniformity is very unlikely to occur and it causes the effective rain height to seem higher than the physical rain height.

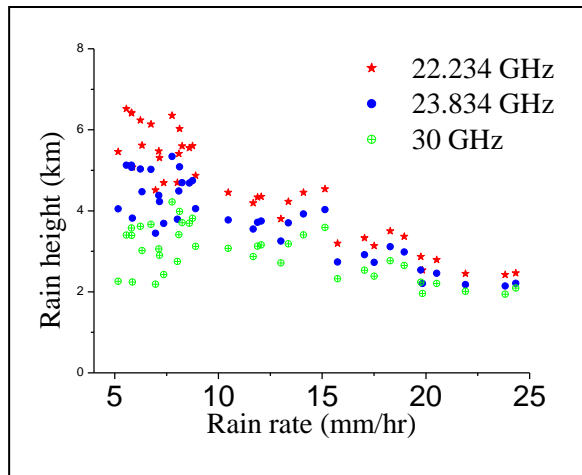
The situation becomes more complex when horizontal non-uniformity occurs and is relevant in considering the global rain attenuation effect. At first approximation, the vertical non-uniformity may be disregarded in comparison to horizontal non-uniformity except for high elevation angle ( $\phi > 60^\circ$ ). This is the reason for which the rain height may be used instead of rain thickness for both physical and effective measurements of rain attenuation.

The physical rain height is not easily measurable and the closest approximation for rain height is to consider the  $0^\circ$  isotherm, which is readily available from radiosonde data. But during rain, there lies a big difference between the two, which, in turn, depends on the types of rain (Schumacher and Houze 2003). In warm rain, the physical rain height is lower than the  $0^\circ$  isotherm. In thunderstorm rain it is normally present well above the  $0^\circ$  isotherm and in stratiform rain, the  $0^\circ$  isotherm and the physical rain height become coincident. This happens especially in the cold season when the falling ice crystals melt below the  $0^\circ$  isotherm height (Ajayi and Barbaliscia

1990). However we have taken the liberty to calculate or to get a first hand idea of rain height from the measured rain fall intensity data corresponding to rain attenuation data at 22.234, 23.834 and 30 GHz. From Equation (5), the attenuation can be expressed in the form:

$$A = aR^b H_R \quad (20)$$

where  $H_R$  is the effective rain height. The experimental measurements of attenuations have been used to derive values for this effective rain height over Brazil. Figure 8 shows the obtained results at all frequencies. The average rain heights at different frequency are shown in Table 2.



**Figure 8:** Effective Rain Height Measured by Radiometer.

**Table 2:** Measured Rain Height by Radiometer at Different Frequency.

Frequency(GHz)	Rain Height (km)
22.234	4.572
23.834	3.80
30	2.94
Average Rain Height =3.77 (km)	

It is interesting to point out that effective rain height measured at 23.834 matches well with the physical rain height (see Equation 6) which is 3.62 km.

## DISCUSSION AND CONCLUSIONS

The studies presented here give an idea of rain attenuation measurement by radiometer applicable to tropical climate. From the measured result it has found that extra attenuation caused by evaporation of water vapor from heated earth surface at the time of the start of rain, particularly at low rain rates below about  $5 \text{ mm hr}^{-1}$ , dominating the measured attenuation which is an extra error in the measurement. The several experimental results over the different parts of the world including temperate and tropical regions reveal that the  $0^\circ\text{C}$  isotherm varies with several factors. In this context, Ajayi and Barbaliscia (Ajayi et al., 1990) made a comprehensive study. There, the quantities  $h_{FM}$ ,  $h_{FY}$ ,  $h_{FS}$  and  $h_{FR}$  the mean values of the  $0^\circ\text{C}$  isotherm height in an average month, year, summer and half-year respectively, the mean values for rainy conditions for various rain thresholds were taken into consideration. In the northern hemisphere the summer half-year includes the months from May to October but in the southern hemisphere it is from November to April. In the northern hemisphere the results were obtained from  $3.4^\circ$  to  $46^\circ$  N, and those in the southern hemisphere the latitude varied from  $6.88^\circ$  to  $45.47^\circ$  S.

It is observed also that there lies a negligible difference between noon and midnight values of  $h_{FY}$  and  $h_{FS}$ . The diurnal variations over the temperate and tropical locations were found to be insignificant in comparison to monthly or seasonal variation. This suggests that one year data is adequate for studying the year-to-year variability of  $0^\circ\text{C}$  isotherm height over a particular place of choice. Similarly, in the tropical location like Minna, the monthly variation over a year is less than 5%. These confirm the negligible dependence of rain rate on the  $0^\circ\text{C}$  isotherm height. But the determination of  $h_{FR}$  during rainy conditions is difficult. Here, it has been assumed that the significant rain occurs in the summer half-year. It has been observed that for the temperate location when summer rains are considered alone, the  $0^\circ\text{C}$  isotherm height appears to be almost independent of rain intensity at least up to  $15 \text{ mm/hr}$  (Ajayi et al., 1990). But beyond this there might be little dependence on rain intensity. So it is suggested to perform the rain height determination experiment within the limit of  $10\text{--}15 \text{ mm/hr}$ .

The mean value for the effective rain height measured at three frequencies, 22.234, 23.834, and 30 GHz was deduced 4.572, 3.80, and 2.94 km, respectively. Only the 30 GHz measurement is underestimated from predicted rain height 3.62 km. From this phenomenon it can be concluded that while measuring the rain induced attenuations one has to eliminate completely water vapor contribution, and at the same time the drop size distribution has to be properly chosen. However, more data are required on rain attenuations in tropical location in order to give a better insight into the dependence of rain height on rain type before any firm conclusion can be drawn.

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