Comparative analysis of precipitable liquid water content from micro rain radar and era-interim data: implication on radio wave propagation in a tropical location

J S Ojo¹, A A Kayode¹ and O. L. Ojo²
¹Department of Physics, Federal University of Technology Akure, Nigeria
²Department of Physics, University of Lagos, Akoka, Lagos Nigeria

Corresponding e-mail: kayodeahmed97@gmail.com, josnno@yahoo.com

Abstract. The characteristics of the vertical profile of precipitable liquid water content (PLWC) obtained from Micro Rain Radar (MRR) and ERA-Interim data at a tropical site (Akure, Nigeria) is reported in this work. One (1) year (2014) data of PLWC was obtained from a vertically-looking MRR sited at the Department of Physics, FUTA (7°15’N, 5°15’E) and data set of PLWC obtained from the European Centre for Medium-Range Weather Forecast (ECMWF) re-analysis ERA-Interim with a resolution of 0.25 × 0.25. Comparative studies based on the vertical profile of the PLWC diurnally, seasonally, and monthly were carried out to deduce the significant trend. The profile assessment over the two sources of data shows low PLWC which is less than 0.1 gm⁻³ with a maximum value of about 1.5 gm⁻³. The specific attenuation due to cloud obtained using the two data sets at a frequency range of 15 - 75 GHz (Ku – V band) shows that attenuation values are more pronounced using data obtained from the ground-based radar. The ERA-Interim data tends to underestimate the cloud-based attenuation in this region.

Keywords: MRR, Era-Interim, PLWC, Cloud-based Attenuation

1. Introduction
The components of the atmosphere have an impact on radio wave propagation. Several atmospheric elements can reflect, refract, scatter, and absorb radio waves. The frequency, power, and state of the troposphere through which the radio wave propagates all play a role in the magnitude of atmospheric impacts. The depiction of tropospheric variability has significant implications for radio communications, aerospace, environmental monitoring, disaster forecasting, and other applications. Worse propagation conditions, for example, produce increased fading of communication, resulting in lower power levels at the receiver.

The Precipitable Liquid Water Content (PLWC) of a cloud is discovered to be the primary factor affecting cloud attenuation. Precipitation occurs when cloud particles expand to a size where their falling velocity exceeds the upward wind speed in the air due to complex processes such as condensation and aggregation. The Precipitable Liquid Water Content (PLWC) is the measure of the mass of the water in a cloud in a specified amount of dry air. It is commonly measured per volume of air or mass of air [1]. The PLWC has a strong relationship with cloud drop effective radius, cloud drop number concentration, and cloud drop size distribution in determining which types of clouds are likely to form [2].

Because cumulonimbus clouds are associated with thunderstorms and heavy rain, and cirrus clouds are linked to precipitation indirectly, the ability to predict cloud formation is useful for weather forecasting. With a diameter of around 100 μm, there is a considerable difference between PLWC and cloud droplet water content. [3].
The study of PLWC profiles will help to improve the representation of clouds in numerical models by increasing knowledge and understanding of the processes that act to build and sustain cloud systems. The subject received some interest in the tropical region as well [4, 5], particularly in the Indian subcontinent. The majority of these researches, on the other hand, established the use of radiosonde data. This research employed the use of both MRR and ERA-Interim data which has given comprehensive results and the characteristics of the vertical profiles of PLWC in Akure over one year.

2. Research Methodology

For this study, two datasets were used. The first is a one-year (2014) PLWC data set gathered from the Communication Research Group (CRG) of the Federal University of Technology Akure (FUTA), Nigeria, utilizing a vertically-pointing Micro Rain Radar (MRR) at the Department of Physics. At six (6) distinct heights, the variations were taken: 160 m, 320 m, 960 m, 1600 m, 4160 m, and 4800 m. To determine the vertical profile of PLWC, the spatial heights were selected from the lower, middle, and upper bins of the heights recorded by the MRR.

The second set is PLWC data from the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-analysis ERA-Interim for one year (2014). At pressure levels of 1000 hPa, 975 hPa, 900 hPa, 825 hPa, 600 hPa, and 550 hPa, the PLWC data was acquired. These pressure levels have been adjusted to correspond to the MRR heights as follows: 1000 hPa to 160 m, 975 hPa to 320 m, 900 hPa to 960 m, 825 hPa to 1600 m, 600 hPa to 4160 m, and 550 hPa to 4800 m.

The study was conducted at the Federal University of Technology Akure in Ondo State, Nigeria, which is located at (7°15'N, 5°15'E). Ondo State is made up of plains and rough hills, some of which have granitic outcrops. The topography rises in general from the southern beach area (less than 15 m above sea level) to the steep hills of the north-eastern region. Ondo State has a lowland tropical rainforest climate with different wet and dry seasons. The average monthly temperature in the south is around 27°C, with a monthly range of 2°C, and relative humidity of around 75%. The mean monthly temperature and its ranges, on the other hand, are around 30°C and 6°C in the northern region of the state. The relative humidity is less than 70% every month on average.

The PLWC was acquired using MRR, a ground-based radar. The MRR uses electromagnetic waves with a frequency of 24.1 GHz as its measuring principle. The signals are transmitted vertically into the atmosphere, unlike traditional rain-radar equipment. A portion of the transmitted signal is dispersed by raindrops, which return to the parabolic antenna. The output signal is transmitted continuously (continuous wave, CW mode in contrast to pulsed radars). The MRR is a Doppler radar, which means that as raindrops hit the ground, they shift relative to the ground antenna, which serves as both transmitter and receiver. Quantitative rain rates, liquid water content, drop size distributions, and other rain variables are all retrieved simultaneously by the MRR on vertical profiles up to several kilometres above the radar [6]. The MRR was adjusted at a 60-second temporal resolution and a spatial resolution of 160 m up to 4800 m. The MRR has an outdoor unit outside the Physics Department building and an indoor unit inside the Communication Research Laboratory, FUTA.

The parameters of rainfall as recorded by the MRR and applicable to the study are related by the following expressions:

Precipitable Liquid Water Content (PLWC) is given by:

\[
\text{PLWC} = \rho_w \int_0^\infty N(D)D^3 dD
\]

where \(D\) = diameter (mm), \(N(D)\) = drop size distribution \((m^3 mm^{-1})\) and \(\rho_w\) = density of water \((kg/m^3)\).

ERA-Interim is a global reanalysis of climate data collected over the last three decades. It’s offered as a gridded data collection with 37 atmospheric levels and a spatial resolution of about 0.7 degrees.
The specific attenuation was calculated using a model that predicts cloud and fog attenuation along a satellite path [7]. This model is a good predictor of cloud attenuation. Radio signals at the Ku and Ka frequencies are predicted to suffer losses due to cloud at any time of day, depending on the season and climate of the location. Although rain has a greater effect on radio waves than clouds, cloud occurrence is always greater than rain. Cloud attenuation is caused by the PLWC of clouds.

Three processes are required to obtain cloud attenuation: cloud detection, liquid water content calculation, and specific attenuation calculation. The specific attenuation can be determined using:

$$\gamma_c = k_c M \text{ dB/km}$$

(2)

where $\gamma_c$ is the specific attenuation of the cloud, in dB/km; $k_c$ is the specific attenuation coefficient, in (dB/km)/(g/m$^3$); and $M$ is the liquid water content in the cloud or fog, in g/m$^3$.

The Rayleigh approximation can be used to estimate specific attenuation since cloud droplets are so small. For radio wave frequencies up to about 100 GHz, this approximation is valid. The value of $k_c$ for Ka, Ku, and V band frequencies was calculated using a mathematical model based on Rayleigh scattering, which employs a double-Debye model for water’s dielectric permittivity ($f$):

$$k_c = \frac{0.819 f}{\varepsilon' - (1 + \eta^2)} \text{ (dB/km) / (g/m}^3\text{)}$$

(3)

$$\eta = \frac{2 + \varepsilon}{\varepsilon}$$

(4)

where $f$ is the frequency in GHz, $\varepsilon'(f) + i \varepsilon^* (f)$ is the complex dielectric permittivity of water and

$$\varepsilon'^*(f) = \frac{f^2 \varepsilon_0 - f^2 \varepsilon_1}{f^2 + (f/f_p)^2} + \frac{f^2 \varepsilon_1 - f^2 \varepsilon_2}{f^2 + (f/f_s)^2}$$

(5)

$$\varepsilon'(f) = \frac{(\varepsilon_0 - \varepsilon_1)}{[1+(f/f_p)^2]} + \frac{(\varepsilon_1 - \varepsilon_2)}{[1+(f/f_s)^2]} + \varepsilon_2$$

(6)

where:

$$\varepsilon_0 = 77.6 + 103.3 (\theta - 1)$$

$\varepsilon_1 = 5.48$

$\varepsilon_2 = 3.51$

$$\theta = 300 / T$$

(7)

with $T$, the temperature = 293 K

The principal and secondary relaxation frequencies are:

$$f_p = 20.09 - 142 (\theta - 1) + 294 (\theta - 1)^2 \text{ (GHz)}$$

(8)

$$f_s = 590 - 1500 (\theta - 1) \text{ (GHz)}$$

(9)

3. Results and Discussion

3.1 Diurnal variation of PLWC based on MRR and ERA-Interim Data

Figures 1 to 5 depict the diurnal and monthly variations of the PLWC (MRR and ERA-Interim data) at the selected heights in 2014. The days from the indicated months were chosen because they contain more PLWC values required to analyse the PLWC trend. The dry season begins and ends in November to March, whereas the wet season begins and ends in April to October.

In general, there is a seasonal variation in PLWC, with notably higher PLWC in the wet season, from April to October, compared to other months. PLWC changes from one height to another and at different periods of the day. Theoretically, PLWC rises with altitude, a distinct function of height above the cloud base. Because of the high level of PLWC during the wet season, radio signal transmission may be hampered.

For example, Figures 1 and 2 show the plots for some typical days in the early months and the end of the dry season respectively. As observed from the MRR data (Fig. 1a), the peak value of PLWC was attained
at 320 m and a value of about 1.5 $gm^{-3}$. Based on the ERA-Interim data (Fig. 1b), the PLWC attains a peak value of about 0.3 $gm^{-3}$ at 320 m. This shows that the peak value for both MRR and ERA-Interim was attained at the 320 m heights. Figures 3 and 4 present the variation of the vertical profile of PLWC for some specific days during the peak and the end of the wet season respectively. Generally, PLWC values are higher; this is a result of the high amount of water associated with the wet season. For the MRR (Fig. 3a), the peak value of 1.8 $gm^{-3}$ was attained at 160 m in July, while for the ERA-Interim (Fig. 4b), the peak value was attained at 4800 m in October. This also confirms that during the wet season, PLWC values are higher than during the dry season.

Figure 5 depicts the monthly variation of PLWC based on MRR and ERA-Interim at the indicated heights. In Figure 5 (a) for example, the result based on the MRR data reveals that August recorded the highest value of about 0.12 gm$^{-3}$ followed by November with a value of 0.09 gm$^{-3}$. It was also confirmed that the PLWC recorded its peak value at 4160 m. As a result of the enhancement due to high reflectivity from melting ice at this height, as previously described in the work of [8], this corresponds to the freezing height level (rain height 4250 m based on the ITU rain height relation) for the research location [9]. The result shows the likelihood of correlations between the melting layer height and the PLWC. Based on the ERA-Interim data, Figure 5 (b) shows a strong seasonal pattern of PLWC in the monthly variation result, as higher values are obtained at the rainy season and lower values in the dry season which is a key characteristic of the tropical region. It recorded the highest value of PLWC of over 0.05 $gm^{-3}$ at 960 m in August. Regardless of the year, the dry months continue to have the lowest PLWC values.
3.2 Specific attenuation based on MRR and ERA-Interim data at different frequencies (Ku – V band frequencies)

The specific attenuation based on the liquid water content has been analyzed using equations (2) – (9). The analysis determined the level to which either of the data set can contribute to attenuation due to cloud. The specific attenuation for each month and season were estimated for three frequency bands – Ka, Ku, and V bands.

The variation of the specific attenuation due to cloud at a frequency range between 15 and 75 GHz is shown in Figures 6–11 for the specified heights and seasons. As expected, the specific attenuation due to cloud increases as the PLWC increases; nevertheless, the specific attenuation decreases with height. The
The highest specific cloud attenuation values were obtained at 160 m, while the lowest was recorded at 4800 m. This could be due to downward drift, in which the lower height accumulated more precipitation as a result of raindrop breakup than the upper height. However, it was observed that attenuation with the cloud increases as the frequency of operation increases.

Figures 6 and 7 represent the plots for November and February for the year and it typified the commencement and the peak of the dry season respectively. Low values of specific attenuation are recorded for these months with the highest value of about 0.25 dB/km as shown in Figure 6 (a). Figures 8 and 9 present the specific attenuation due to cloud for the wet season. High values were recorded for these months with the highest value of about 0.7 dB/km in May.

Figure 10 presents the monthly variation of specific attenuation due to cloud for the year. The highest value of specific attenuation was attained in May with a value of 0.16 dB/km.

Generally and based on the ERA-Interim data, it was observed that the upper heights have more attenuation value than the lower heights except in few cases where the middle heights recorded some higher values of specific attenuation due to cloud. The 4800 m height recorded the highest values of about 0.09 dB/km while the height 160 m recorded the lowest value of about 0.00013 dB/km, summarily; it is evident that specific attenuation due to cloud is higher during the wet season than in the dry season.

Figure 11 shows that specific attenuation due to cloud recorded higher values based on the ground-based radar when compared with the satellite data. This is because the attenuation values are more pronounced using ground-based radar. The MRR recorded a higher value of 0.07 dB/km for specific attenuation due to cloud than the ERA-Interim generated cloud-based attenuation.

![Figure 6](image1.png)  
**Figure 6.** Specific attenuation at Ku - V bands frequency for commencement dry seasons- November 2014 for (a), MRR and (b) ERA Interim

![Figure 7](image2.png)  
**Figure 7.** Specific attenuation at Ku - V bands frequency for the peak of the dry season-February 2014 for (a), MRR, and (b) ERA Interim
Figure 8. Specific attenuation at Ku - V bands frequency for the commencement of wet season - May 2014, for (a) MRR, and (b) ERA Interim

Figure 9. Specific attenuation at Ku - V bands frequency for the peak of the wet season - September 2014 for (a), MRR and (b) ERA Interim

Figure 10. Monthly variation of specific attenuation due to cloud in the year 2014 over some selected frequencies based on (a) MRR (b) ERA-Interim
4. Conclusion
The study of precipitable liquid water content over the year 2014 in a tropical location has been presented. The study demonstrates that PLWC has a strong variance, with a significant increase in the wet season. In general, PLWC values are higher during the wet season. In contrast to the results from the ERA-Interim data, which reveal that the values are dominant at the upper heights, the MRR data shows that the PLWC values are prominent in the lower heights (160 m and 320 m). Furthermore, the results show that the presence of clouds increases the specific attenuation due to cloud values to about 0.0702 dB/km in Akure. The attenuation values are more pronounced using data retrieved from the ground-based radar, while the ERA-Interim data tends to underestimate cloud-based attenuation in this region.

References
[1] Bohren, C.F., and D.R Huffman, (1998). Absorption and scattering of light by small particles. Wiley – Interscience, pp 544
[2] Wallace, J.M., and Hobbs, P.V. (2006). An Introduction Survey. Atmospheric Science, 2nd ed. London (UK)
[3] Tattelmann, P., and Willis, P. (1989). Drop-Size Distribution Associated with Intense Rainfall. Journal of Applied Meteorology, 28, 3-15. https://doi.org/10.1175/1520-0450(1989)028<0003:DSDAWI>2.0.CO;2
[4] Maitra, A., and Chakraborty, S. (2009). Cloud Liquid Content and Cloud Attenuation Studies with Radiosonde Data at a Tropical Location. Journal of Infrared, Millimeter and Terahertz Waves, 30, 367-373. https://doi.org/10.1007/s10762-008-9452-8
[5] Chakraborty, S., and Maitra, A. (2012). A Comparative Study of Cloud Liquid Water Content from Radiosonde Data at a Tropical Location. International Journal of Geosciences, 3, 44-49. https://doi.org/10.4236/ijg.2012.31006
[6] Recommendation ITU-R P.840-3 (1999), Attenuation due to clouds and fog: International Telecommunication Union, Geneva (Switzerland)
[7] Ojo, J. S., Falodun, S. E., and Odiba, O. (2014). 0°C Isotherm Height Distribution for Earth-Space Communication Satellite Links in Nigeria. Indian Journal of Radio and Space Physics, 43, 225-234.
[8] Atlas, D. (1954). The Estimation of Cloud Content by Radar. J. Meteor, 11, 309-317. https://doi.org/10.1175/1520-0469(1954)011<0309:TEOCPB>2.0.CO;2
[9] Crewell, S., & Lohmert, U. (2003). Accuracy of Cloud Liquid Water Path from Ground-Based Microwave Radiometry. Part II. Sensor Accuracy and Synergy. Radio Science, 38. https://doi.org/10.1029/2002RS00263
[10] J. S. Mandeep, and K. Tanaka (2008), Cloud attenuation in millimeter wave and microwave frequencies for satellite applications over equatorial climate. Int. J. Infrared Milli. Waves 29, 201–206.
[12] Donaldson, R. J. (1955). Measurement of Cloud Liquid Water Content by Radar. *Journal of Meteorology, 12, 238-244*. https://doi.org/10.1175/15200469(1955)012<0238:TMOCLW>2.0.CO;2

[13] Green, D. R., & Clark, R. A. (1972). Vertically Integrated Liquid Water—A New Analysis Tool. *Monthly Weather Review, 100, 548-552*. https://doi.org/10.1175/1520-0493(1972)100<0548:VILWNA>2.3.CO;2