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Non-Rainy Attenuation Over Earth-Space Paths at Tropical and Temperate Sites Using Meteorological Data and NWP Products

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ABSTRACT A long-term investigation of the attenuation in non-rainy conditions has been carried out, for a tropical and a temperate location, using meteorological data and NWP (Numerical Weather Prediction) products during the period 2011-2015. The results show that ERA-5 full profiles are appropriate to estimate non-rainy attenuation in lieu of radiometric or radiosonde observations. Simpler regression-based methods are established. A new formulation for oxygen attenuation is introduced, which only requires surface temperature and pressure. Mass absorption coefficients are used for water vapour and cloud attenuation. Simpler regression-based approaches are then validated. The non-rainy attenuation at K, Ka and Q bands has been found noticeably higher in the tropics than in the temperate region. This study would facilitate the planning of global mobile satellite communication systems.

INDEX TERMS Cloud, non-rainy attenuation, oxygen, radiometers, radio wave propagation, satellite communication, water vapour.

I. INTRODUCTION

The ever-increasing demand for higher data rates to support satellite services has led to a migration of communications to higher bands, namely from 11 to 50 GHz. In the higher frequency bands, the signal is significantly impaired by atmospheric constituents like gases, clouds, rain, and tropospheric turbulence, affecting the link reliability and system performance [1]–[3].

In the current state of affairs, diurnal as well as seasonal variations of the attenuation due to rain have been studied over different locations of the world to assess its temporal and spatial variability [4], [5]. Studies on rain attenuation in tropical and temperate regions at various frequency bands facilitated the selection of suitable Fade Mitigation Technique to increase data rates and link availabilities [3], [6]–[8]. However, though many propagation campaigns were undertaken in Europe and the USA (Olympus, Italsat, ACTS), actual signal measurements in tropical regions are still limited [3]. In addition, there were comparatively fewer studies focusing on the attenuation in non-rainy conditions, even though the degradation due to gases and clouds increases in Q/V band at lower elevation angle.

The processing of satellite beacon signals enables the retrieval of the excess attenuation due to rain. The total attenuation necessitates an evaluation of the attenuation due to gases and clouds, called non-rainy attenuation [9], [10]. The latter can be obtained from a co-located radiometer

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with the same elevation and azimuth as the beacon receiver antenna. A radiometer measures the brightness temperature of the atmosphere, and, as a result, enables the estimation of the total attenuation along the path in the absence of scattering [11]. However, a radiometer is not always available concurrently with beacon receivers, due to its high cost. In the absence of a radiometer, the estimation of non-rainy attenuation needs to be calculated from meteorological data, with some known results for oxygen, water vapour and clouds [10], [12]–[16]. Important candidates for the estimation are Numerical Weather Prediction (NWP) products like ERA-5 and ERA-Interim.

The present paper deals with non-rainy attenuation estimates at a tropical and a temperate location. The tropical station is located at (22.57° N, 88.36° E), Institute of Radio Physics and Electronics, University of Calcutta, Kolkata, India, where the statistical characterization of rain impairments over an Earth-space link was carried out with NSS-6 at Ku band [5]. The Indian satellite GSAT-14 facilitates propagation measurements by providing beacon transmission at Ka-band. The temperate station is located at (50.67° N, 4.61° E), UCLouvain, Louvain-la-Neuve (LLN), Belgium, where measurements have been conducted with Alphasat TDP5 signals at 19.7 GHz and 39.4 GHz [15].

The major contributions of this paper are twofold: i) Non-rainy attenuation estimates are made in the 20-40 GHz range over five years (2011-2015) using atmospheric profiles from radiosonde observations (RAOBS) and from NWP products over a tropical and a temperate location. ii) The second aspect of this study is to derive simple yet reliable estimation techniques based on ERA-5 data that require only surface pressure and temperature, integrated water vapour (IWV), and the integrated cloud liquid water content (ICLWC). For Kolkata, IWV and ICLWC obtained from a microwave radiometer are also available for comparison.

This paper is organized as follows: Section II gives the data and methodology used in the study. Section III and IV present respectively the attenuations due to gases and cloud by establishing the simple estimation techniques. Section V compares the non-rainy attenuation values in the two climatic regions. Section VI provides further discussions and Section VII concludes the study.

II. DATA AND METHODOLOGY

In order to estimate non-rainy attenuation, at the locations of interest, this study principally relies on vertical profiles of pressure, temperature and humidity extracted from:

- ERA-Interim data on 37 pressure levels, available with a temporal resolution of 6 h and a horizontal resolution of 0.75° × 0.75° (~80 km). The data are obtained from ECMWF during 2011-2015 for both Kolkata and LLN.
- ERA-5 data on 137 model levels, available at the higher resolutions of 1 h and 0.28° × 0.28° (~30 km). The data are taken for both Kolkata and LLN during 2011-2015 available from ECMWF data archive.
- Radiosonde observations (RAOBS) data obtained from the University of Wyoming archive for both Kolkata (every 12 h) and Beauvechain (daily) during the time period 2011-2015. It may be noted that the distance between Beauvechain and LLN is ~21 km. The RAOBS data are available from the website: http://weather.uwyo.edu/upperair/sounding.html.

Making use of the vertical profiles, the following reference methods are used to estimate the specific attenuation in non-rainy conditions at different heights:

- the specific attenuation due to gases (oxygen and water vapour) is estimated from the line-by-line methods given in the Annex I of the recommendation ITU-R P.676-11 [17].
- the specific attenuation due to clouds is obtained from the ITU-R P.840-7 model [18], after deriving the cloud liquid water profile using the Salonen model [16].

The specific attenuation profiles are then integrated vertically and scaled with the cosecant of the link elevation. The links for Kolkata and LLN are simulated at the frequencies of 19.7, 30.5 and 39.4 GHz (frequencies from Alphasat and GSAT-14), with an elevation angle of 29.8° (between LLN and Alphasat) i.e. corresponding to roughly twice as much as the zenith attenuation. The period of investigation is from 2011 to 2015.

As mentioned earlier, the first goal of the present study is to validate the NWP derived attenuation against the RAOBS-derived attenuation. The next aim is to evaluate efficient yet simple methods to obtain the attenuation from the NWP data. In this regard, meteorological variables are considered namely, surface temperature and surface pressure, integrated water vapour (IWV), and integrated cloud liquid water content (ICLWC).

Importantly, measurements with a multi-frequency microwave radiometer (RPG HATPRO [19]) in Kolkata are also available during 2011-2015 [13]. Humidity profiles are derived from measurements in the 22–31.4 GHz band, and temperature profiles from measurements in the 51.26–58 GHz band. The agreement between the radiometric profiles with local radiosonde observations has been assessed satisfactorily [13]. The IWV and ICLWC obtained from the radiometer are also used for the water vapour and cloud attenuation estimation respectively over Kolkata.

III. ATTENUATION DUE TO GASES

A. ATTENUATION DUE TO OXYGEN

Oxygen attenuation values obtained from different datasets, over Kolkata are shown in Fig. 1(a), (b), and (c) for the frequencies 19.7, 30.5, and 39.4 GHz, respectively, at 29.8° elevation angle during the time period 2011-2015. Correlations of NWP with RAOBS exceed 0.77. Fig. 1 (d) shows the oxygen attenuation variation during one year (January-December, 2015) at 29.8° over Kolkata. It indicates that the attenuation is high during the winter months (December-February) and low during summer months (June-August).

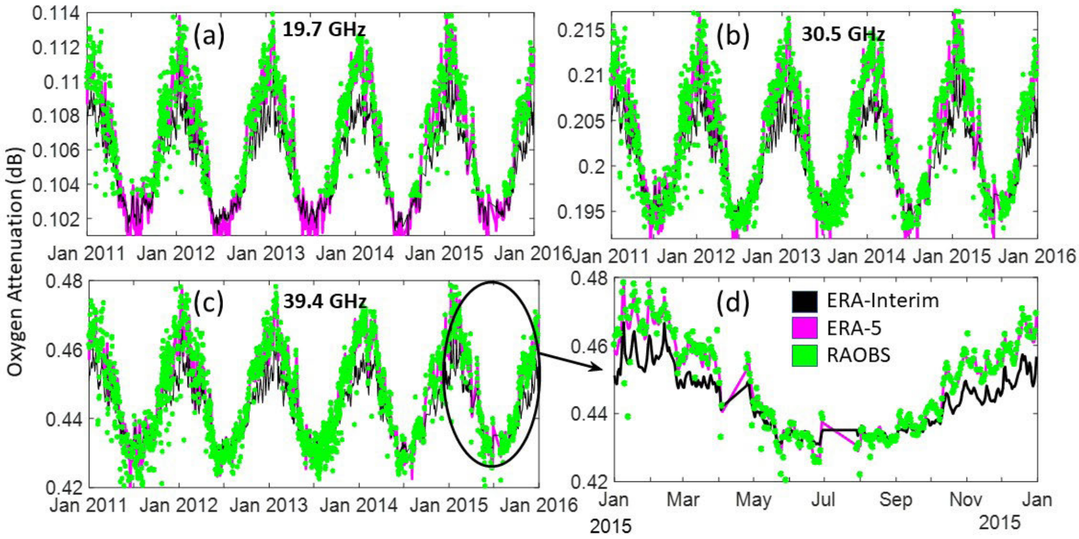

FIGURE 1. Time series of oxygen attenuation over Kolkata at 29.8° elevation angle at frequencies: (a) 19.7 GHz, (b) 30.5 GHz and (c) 39.4 GHz, and (d) Variation of oxygen attenuation over Kolkata during January 2015 to December 2015 at Q band (39.4 GHz).

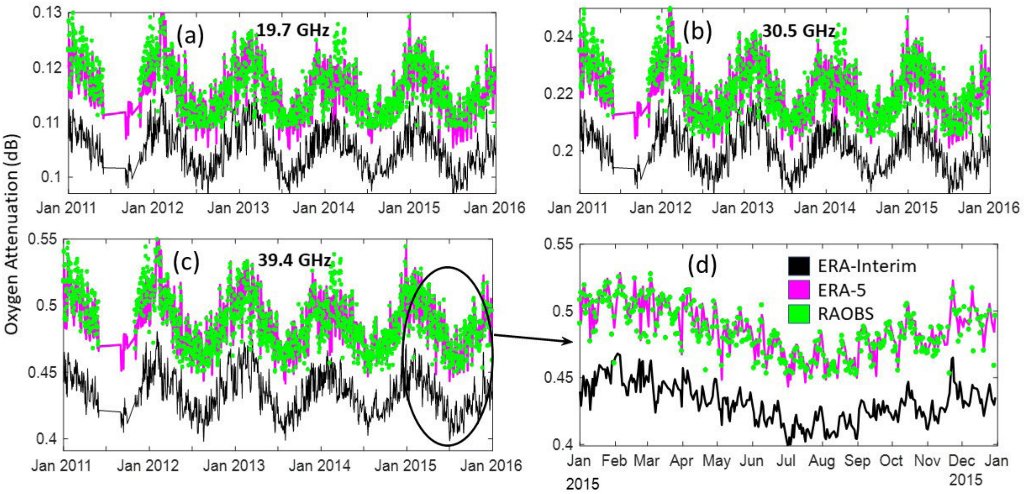

FIGURE 2. Time series of oxygen attenuation over LLN at 29.8° elevation angle at frequencies: (a) 19.7 GHz, (b) 30.5 GHz and (c) 39.4 GHz, and (d) Variation of oxygen attenuation over LLN during January 2015 to December 2015 at Q band (39.4 GHz).

The attenuation due to oxygen over the temperate location LLN is shown in Fig. 2(a), (b) and (c), for three different frequencies, at 29.8° elevation angle. It is seen that the ERA-Interim pressure level data (indicated by the black line) underestimates oxygen attenuation compared to the RAOBS and ERA-5 data. Still, correlations of NWP with RAOBS exceed 0.91. The one-year (January-December 2015) data of oxygen attenuation over LLN is shown in Fig. 2(d), revealing that oxygen attenuation is high during January-March and low during July-September over LLN. Also, oxygen attenuation is higher at LLN than at Kolkata.

It may be noted that radiosonde data are not available everywhere, whereas ERA-Interim pressure levels, ERA-5 data are globally available. In this context, it is worth pointing out that the ERA-5 data have better correlation and smaller errors with the radiosonde observations than the ERA-Interim pressure level data, as revealed from Fig. 1 and 2. This seems reasonable due to the higher spatial (both horizontal and vertical) resolution of ERA-5 dataset, as well as the improved forecast prediction accuracy.

Hence, ERA-5 data are used to regress a frequency dependent relationship of oxygen attenuation with the surface temperature T_s (°C) and surface pressure P_s (hPa), which can be used in the absence of profile data, that is (1)

$$A_{dry}(f) = a(f) + c(f)P_s + c(f)T_s \tag{1}$$

where a, b, and c are coefficients depending on the frequency f (GHz) for zenith attenuation and A_{dry} (dB) is the simple oxygen attenuation estimate.

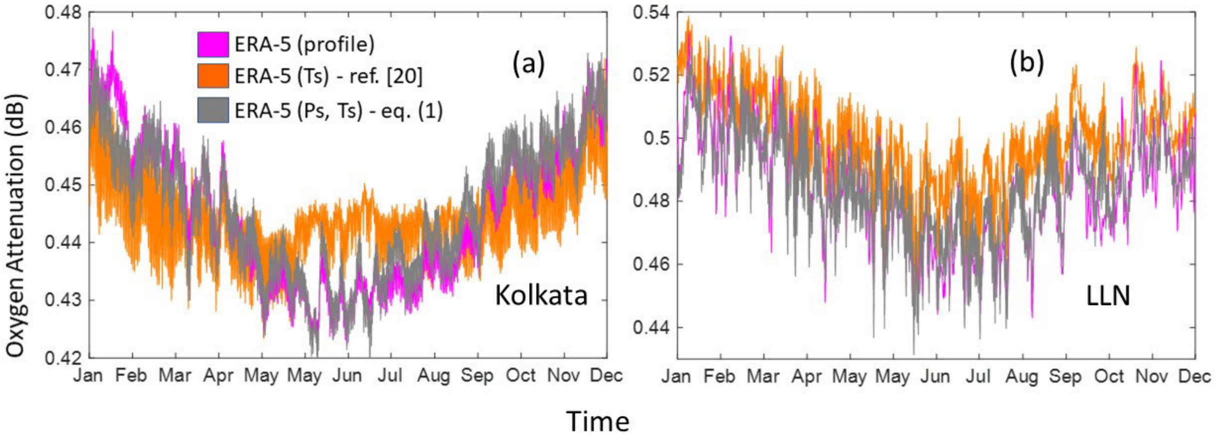

FIGURE 3. Oxygen attenuation during January 2015 to December 2015 at Q band (39.4 GHz) at 29.8° elevation angle obtained from the method proposed in [20], ITU-R P.676-11, and from (1): (a) Kolkata and (b) LLN.

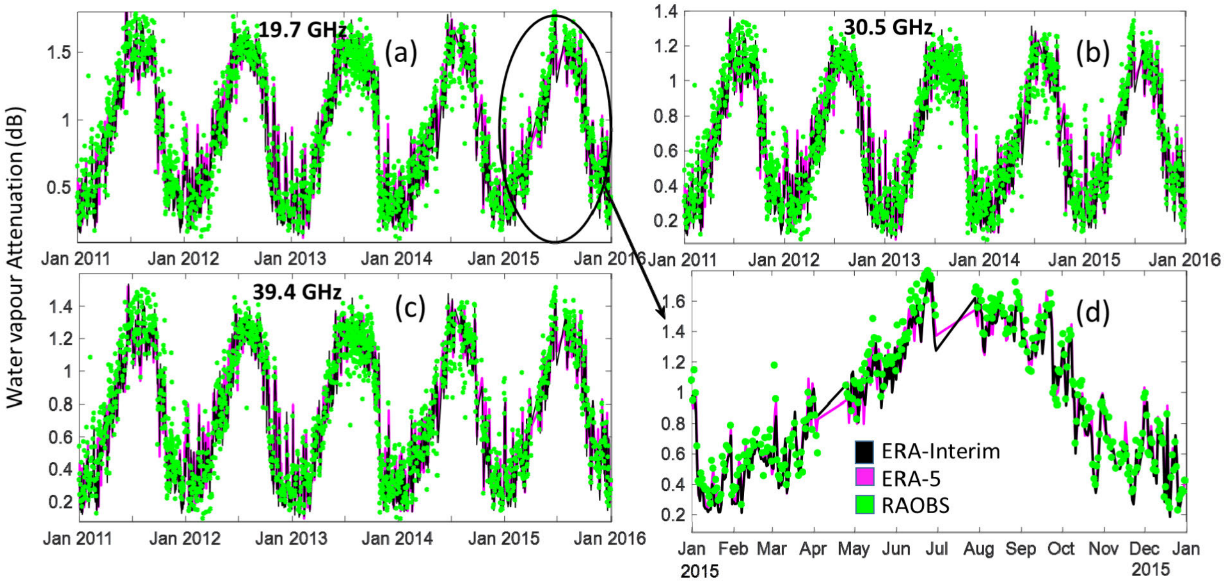

FIGURE 4. Time series of water vapour attenuation over Kolkata at 29.8° elevation angle at frequencies: (a) 19.7 GHz, (b) 30.5 GHz and (c) 39.4 GHz, and (d) Variation of water vapour attenuation over Kolkata during January 2015 to December 2015 at K band (19.7 GHz).

The values of a, b and c for zenith attenuation over Kolkata and LLN from five years ERA-5 data are given in Table 1.

TABLE 1. Coefficients in relation (1) for Zenith Oxygen Attenuation over Kolkata and LLN.

f (GHz)	19.7		30.5		39.4	
	Kol	LLN	Kol	LLN	Kol	LLN
a (dB)	-0.162	0.064	-0.287	0.126	-0.586	0.286
$b\times10^3$ (dB/hPa)	0.229	0.074	0.415	0.137	0.866	0.296
$c\times10^3$ (dB/°C)	-0.533	-0.284	-0.100	-0.544	-0.218	-1.200

Fig. 3 compares the oxygen attenuation estimated over Kolkata and LLN in 2015 using the full ITU-R line by line calculation, the method in [12] and [20] based on a five-year regression for T_s only, and the method in (1) based on a five-year regression for both P_s and T_s. It is seen the latter method closely agrees with the ITU-R derived results, while the former method based only on T_s shows a lower agreement. This improvement, though small in magnitude, emphasizes the physical basis that atmospheric pressure has a role in determining oxygen attenuation which was not considered in the previous model.

B. ATTENUATION DUE TO WATER VAPOUR

Atmospheric water vapour can impose significant limitations on Earth-space propagation, especially at low elevation angles. The time series of water vapour attenuation over Kolkata at 29.8° elevation angle for the frequencies at K, Ka and Q band have been estimated from the ERA-Interim pressure level data, ERA-5 data and RAOBS during 2011-2015, as shown in Fig. 4(a), (b) and (c). Water vapour

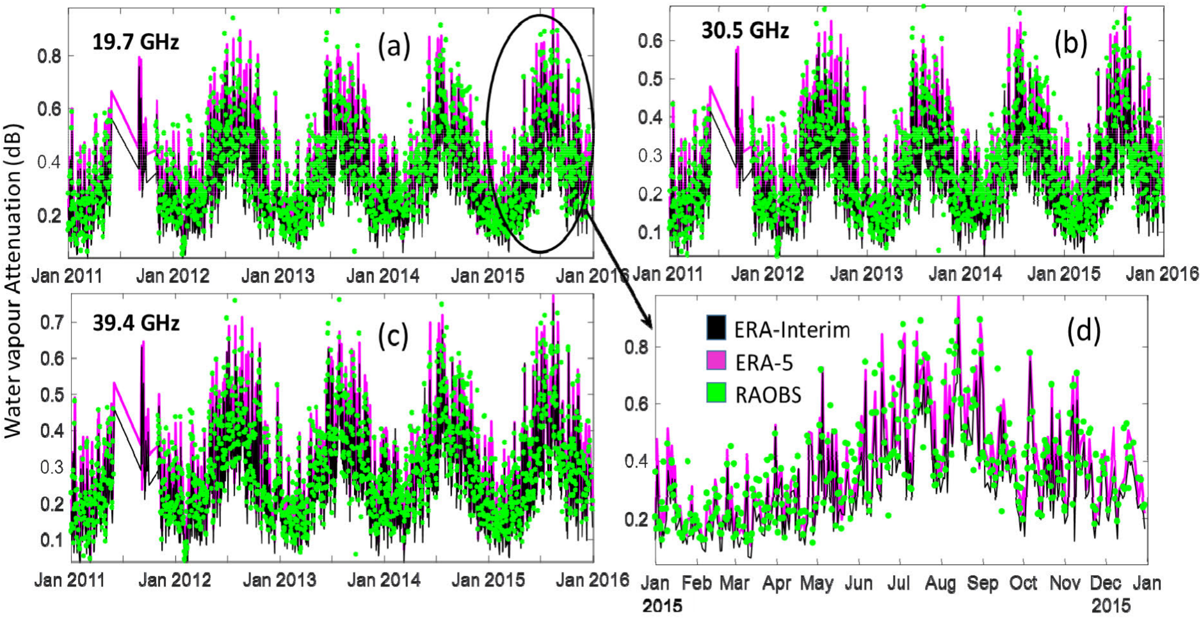

FIGURE 5. Time series of water vapour attenuation over LLN at 29.8 ° elevation angle at frequencies: (a) 19.7 GHz, (b) 30.5 GHz and (c) 39.4 GHz, and (d) Variation of water vapour attenuation over LLN during January 2015 to December 2015 at K band (19.7 GHz).

attenuation during one year (2015) is shown in Fig. 4(d) which reveals that water vapour attenuation is high during monsoon months (June-September) reaching values up to 1.8 dB for 19.7 GHz at an elevation of 29.8° over Kolkata.

Fig. 5(a), (b) and (c) show the water vapour attenuation over LLN for K, Ka and Q band frequencies at an elevation angle of 29.8° during the time period 2011-2015. Water vapour over a period one year (2015) for LLN is shown as well in Fig. 5 (d). It is observed that water vapour attenuation is high during the summer months of July to September and low from January to March. This is of course related to the yearly variation of the humidity at both the sites.

Also, for water vapour attenuation, it is found that the ERA-5 data show better agreement with RAOBS than the ERA-Interim data at both the tropical and the temperate site. Therefore, ERA-5 data are used to regress a frequency dependent linear relation between the water vapour attenuation and the integrated water vapour IWV (mm) as in (2)

$$A_{wv}(f) = a_{wv}(f) IWV \tag{2}$$

where a_{wv} (dBmm^{-1}) is the water vapour mass absorption coefficient depending on the frequency f (GHz) and A_{wv} (dB) is the zenith water vapour attenuation estimate.

The values of a_{wv} for zenith attenuation over Kolkata and LLN from five years of ERA-5 data are in Table 2. It is noted that the values of a_{wv} over Kolkata and LLN are almost equal for the same frequency. The value remains same for Kolkata and LLN and appears to be independent of the site, which is in agreement with previous findings [10].

To test (2), the a_{wv} values from Table 2 for Kolkata have been used to estimate back the water vapour attenuation from all available sources of IWV data considered for this work. Fig. 6 shows the exceedance probability of water vapour attenuation at an elevation of 29.8° and at different frequencies from IWV data and (2), including the previously used datasets as well as radiometric data. A reasonably good agreement is obtained between the different datasets.

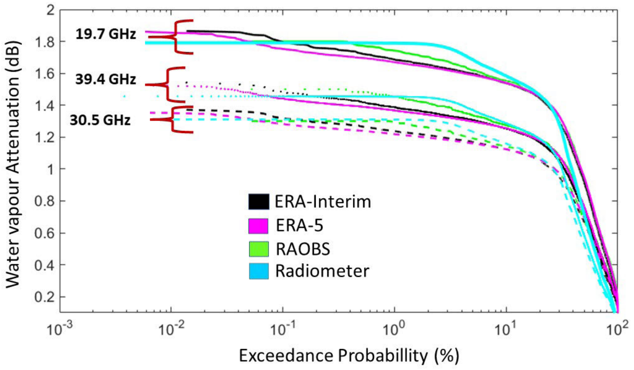

FIGURE 6. Exceedance probability of water vapour attenuation from various meteorological data sources over Kolkata at 29.8°.

TABLE 2. Water vapour mass absorption coefficients in relation (2) and liquid water mass absorption coefficient in relation (3) for attenuation over Kolkata and LLN.

Symbol	19.7		30.5		39.4	
	Kol	LLN	Kol	LLN	Kol	LLN
a_{wv} (dB/mm)	0.011	0.011	0.008	0.008	0.009	0.009
a_{clwc} (dB/mm)	0.306	0.375	0.705	0.847	1.125	1.329

IV. ATTENUATION DUE TO CLOUDS

Clouds occur much more frequently than rain, on a yearly basis [14]. Therefore, the cloud attenuation on radio wave propagation at higher frequency bands is important.

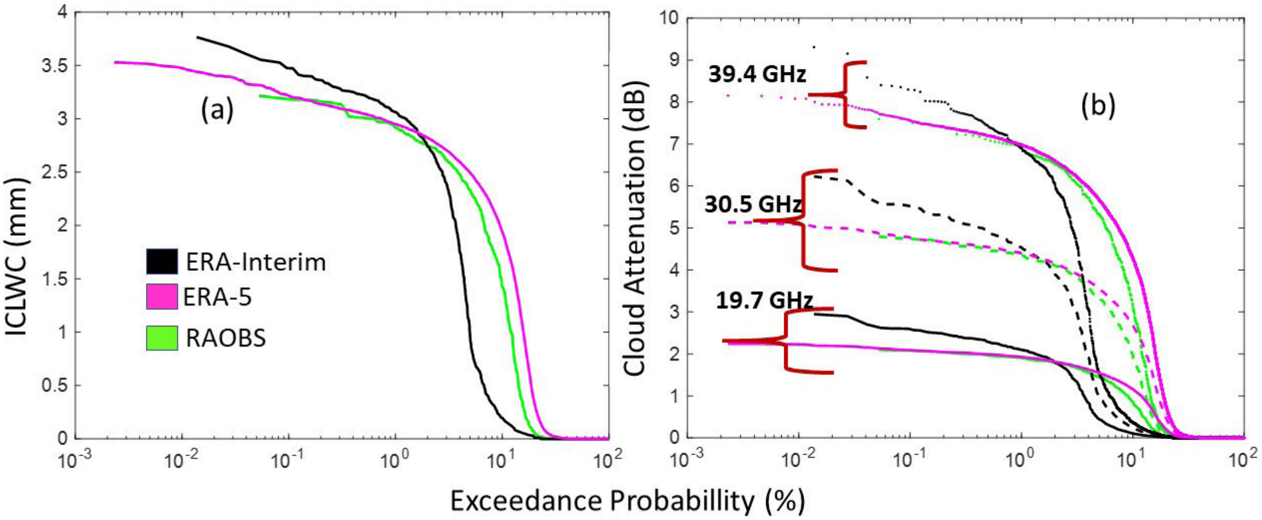

FIGURE 7. Exceedance probability of (a) ICLWC and (b) cloud attenuation, obtained from RAOBS, ERA-5 and ERA-Interim data over Kolkata at an elevation 29.8° during 2011-2015.

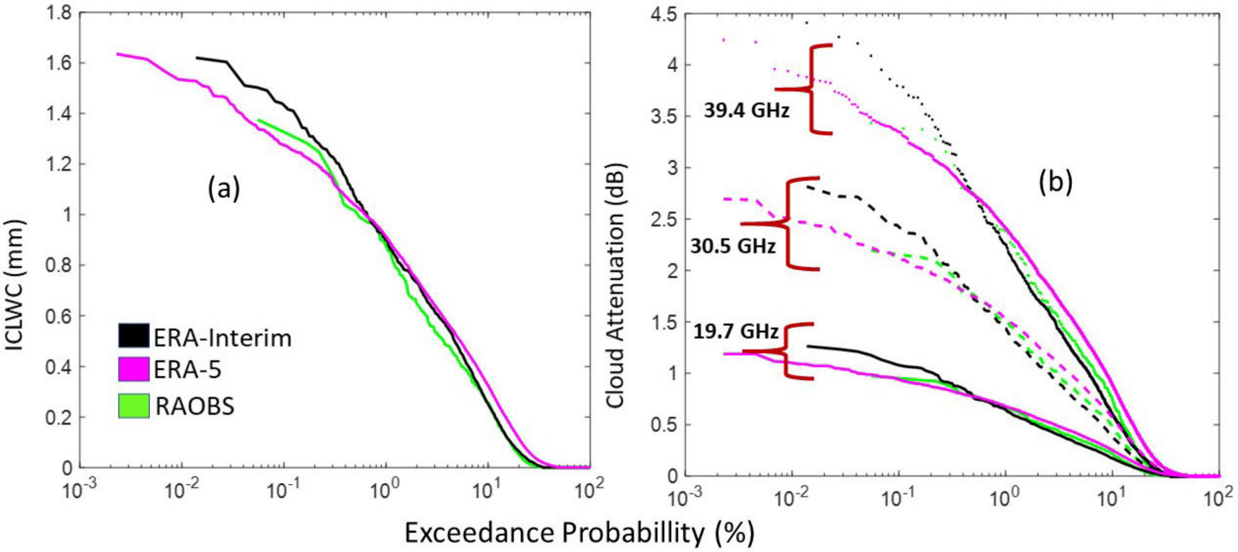

FIGURE 8. Exceedance probability of (a) ICLWC and (b) cloud attenuation, obtained from RAOBS, ERA-5 and ERA-Interim data over LLN at an elevation 29.8° during 2011-2015.

The exceedance probability of integrated cloud liquid water content (ICLWC) (mm) and cloud attenuation (dB) over Kolkata obtained from RAOBS, ERA-5 and ERA-Interim pressure levels data are shown in Fig. 7. Fig. 7(a) shows that ERA-5 data (indicated by the magenta curve) agree with RAOBS data (indicated in green), much more closely compared to ERA-Interim pressure level data (shown in black). The same behavior is also reflected in the attenuation exceedance probability plots (see Fig. 7(b)). The reasons ERA-5 outperforms ERA-Interim are associated to the higher spatial and temporal resolutions of the former dataset, as well as to the modifications introduced by the ECMWF to the forecast model.

For LLN, Fig. 8(a) and (b) give the exceedance probability plots of ICLWC and cloud attenuation, which shows that ERA-5 data have close agreement with RAOBS compared to ERA-Interim data. This shows that ERA-Interim pressure level data with coarse resolution are less reliable than ERA-5 model level data for cloud detection and attenuation estimation, particularly for tropical locations where cloud occurrence is higher compared to temperate locations.

In a similar fashion to oxygen and water vapour attenuations, ERA-5 data are used to regress a frequency dependent linear relation between the cloud attenuation and the integrated cloud liquid water content ICLWC (mm) such that

$$A_{cl}(f) = a_{clwc}(f)ICLWC \tag{3}$$

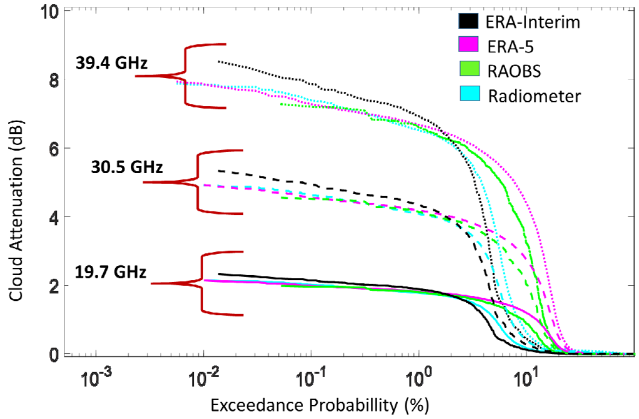

FIGURE 9. Exceedance probability of cloud attenuation from various meteorological data sources over Kolkata at an elevation 29.8°.

where a_{clwc} (dBmm^{-1}) is the cloud liquid water mass absorption coefficient [14], [21] depending on the frequency f (GHz) and A_{cl} (dB) is the zenith cloud attenuation estimate. The values of a_{clwc} for zenith attenuation over Kolkata and LLN from five years ERA-5 data are given in Table 2.

To test (3), a_{clwc} values from Table 2 for Kolkata are used to estimate back the cloud attenuation from all available sources of ICLWC data, as seen in Fig. 9. Radiometric measurements with high time resolution (~4 s) show rapid fluctuations for lower values of ICLWC that ERA-5 or RAOBS data with much coarser time resolution do not capture. When compared to RAOBS and ERA-5, radiometric cloud attenuation measurements give a higher percentage occurrence of lower cloud attenuation [9]. In this regard it may be mentioned that current radiometric measurements yield low ICLWC values (less than 0.5 mm) for 91 % of time compared to 85% for RAOBS and 80% for ERA-5. This pattern of radiometric measurements of ICLWC yields lower cloud attenuation values compared to ERA-5 and RAOBS results for exceedance probabilities greater than 2%, but, at lower exceedance probabilities, radiometric attenuation occurrences match well with RAOBS and ERA-5 data (Fig. 9). It should be remembered that the occurrence probabilities for high attenuation values are rather crucial when evaluating link reliability under adverse propagation conditions. The results show that Radiometer, RAOBS, and ERA-5 data, in combination, have produced useful statistics of cloud attenuation occurrences that validate the regression model (3), and are also useful for evaluating satellite link budget at the three frequency bands considered.

V. COMPARISON OF TOTAL NON-RAINY ATTENUATION BETWEEN KOLKATA AND LLN

To have a further comparison of total gaseous attenuation over tropical and temperate locations, Fig. 10 shows hourly variation of gaseous attenuation over Kolkata and LLN in 2015 at K, Ka and Q bands, as obtained from ERA-5 data. The maximum gaseous attenuation over Kolkata at 19.7, 30.5 and 39.4 GHz is respectively around 1.8, 1.5, 1.8 dB for the elevation angle 29.8°, whereas LLN experiences a maximum gaseous attenuation of approximately 1.1, 0.9, 1.23 dB for the frequencies 19.7, 30.5 and 39.4 GHz respectively at 29.8°. It is important to note that Kolkata experiences more gaseous attenuation than LLN due to large water vapor content of the tropical atmosphere whereas oxygen attenuation is comparable for both locations. The average IWV during 2011-2015 as observed from ERA-5 data over Kolkata is 42.36 mm and that over LLN is 16.82 mm. The location of Kolkata, situated near the land-ocean boundary of the Bay of Bengal, experiences Indian summer monsoon (ISM) during the months of June to September, which is characterized by high moisture laden air [13]. Both locations experience maximum gaseous attenuation from June to September.

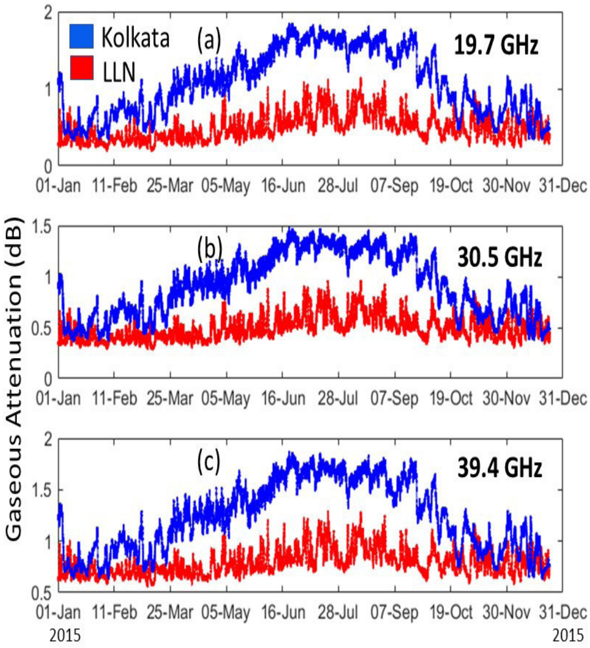

FIGURE 10. Gaseous attenuation over Kolkata and LLN during the time period January 2015 to December 2015 for: (a) 19.7 GHz, (b) 30.5 GHz and (c) 39.4 GHz at an elevation of 29.8°.

Fig. 11 shows a comparative picture of total non-rainy attenuation (gaseous and cloud) over the two locations, Kolkata and LLN, estimated from ERA-5 using ITU-R recommendations [16]–[18] during January-December 2015. Kolkata experienced maximum non-rainy attenuation of roughly 3.9, 6.3, 9.5 dB at frequencies 19.7, 30.5 and 39.4 GHz respectively, for 29.8° elevation angle. Non-rainy attenuation reaches maximum value of approximately 2.2, 3.5, 5.4 dB over LLN at 19.7, 30.5 and 39.4 GHz frequencies for the same elevation. The total non-rainy attenuation increases with the frequency (Fig. 11(b)-(d)) and becomes seriously detrimental for Q/V band, where it reaches a maximum of about 9.5 dB for the link at 39.4 GHz for Kolkata. Figure 11(a) shows the exceedance probability of total non-rainy attenuation over Kolkata and LLN during 2015, using ERA-5 data. For exceedance probability of 20%, total attenuation at K, Ka and Q band in Kolkata, is around 1.5-2 dB, whereas it is around 0.7-1 dB in LLN. As the exceedance probability decreases, the differences in

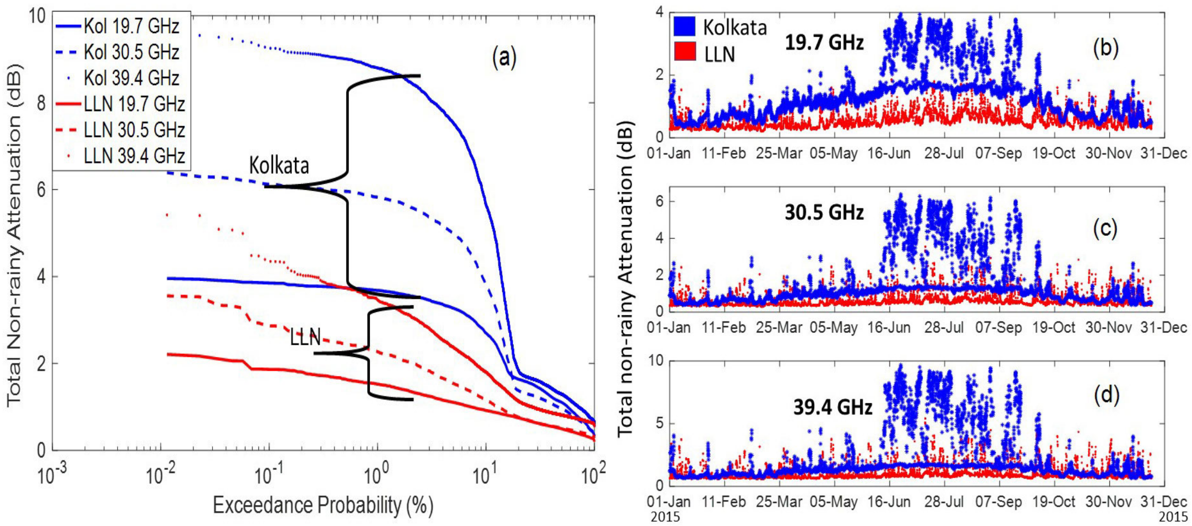

FIGURE 11. (a) Exceedance probability of total non-rainy attenuation (at 29.8°) from ERA-5 data sources over Kolkata and LLN during 2015 and, total non-rainy attenuation (dB) over Kolkata and LLN during the time period January 2015 to December 2015 for: (b) 19.7 GHz, (c) 30.5 GHz, (d) 39.4 GHz at an elevation of 29.8°.

the non-rainy attenuation at different frequencies increase for the two locations. As it is evident from Fig. 11, a significant higher attenuation values at the three frequencies are obtained at elevation angle 29.8° at Kolkata compared to LLN. It should be noted that an abrupt increase in the attenuation value is observed at Kolkata for exceedance probability less than 20%, which is due to a significant increase in the cloud attenuation during Indian Summer Monsoon (ISM), as evident from the time series plot of Fig. 11(b)-(d) caused by high cloud cover, while LLN does not experience such high cloud attenuation during a particular season [21].

VI. DISCUSSION

The study presents the total non-rainy (gaseous and cloud) attenuation over a temperate and a tropical location estimated using ITU-R for the two beacon frequencies of Alphasat satellite (19.7, 39.4 GHz) and the frequency of GSAT-14 (30.5 GHz). It is found that the water vapour attenuation is higher at 19.7 GHz than at 30.5 and 39.4 GHz, as the water vapour absorption peaks at 22.235 GHz. The attenuation due to water vapour is found to be much higher over the tropical location than the temperate location. The maximum value of attenuation reaches about 1.8 dB over Kolkata, whereas it is about 0.89 dB over LLN at 19.7 GHz for 29.8° during 2011-2015. Oxygen attenuation is slightly higher over LLN (maximum value of 0.53 dB) than over Kolkata (0.47 dB) at 39.4 GHz for 29.8° elevation angle which is due to temperature difference at the two locations.

The cloud attenuation shows much higher values over Kolkata than LLN due to the higher cloud liquid water content. The exceedance probability plot for cloud attenuation obtained from ERA-5 and RAOBS data over Kolkata shows a maximum value of around 7.5 dB whereas it is around 3.5 dB over LLN at 39.4 GHz (for 29.8° elevation) during 2011-2015 for 0.1% of time (Fig. 7 (b), 8(b)). As the frequency increases, the cloud attenuation dominates the non-rainy attenuation which is a concern for an Earth-space link at Ka and higher frequency bands, especially at low elevation angles. The fact that non-rainy attenuation is significantly higher in the tropical region than in the temperate region as evident from the present investigation is important for future satellite link design at Ka/Q band.

ERA-5 data with an hourly temporal resolution and 137 levels show better agreement with the RAOBS compared to ERA-Interim pressure level data. This shows that the ERA-5 data are appropriate to estimate non-rainy attenuation at both tropical and temperate locations as an alternative to radiosonde or radiometric measurements. Mass absorption coefficients for water vapour (a_{wv}) and liquid water content (a_{clwc}) over the two locations have been estimated from the ERA-5 data. The values of a_{wv} at different frequencies do not vary with locations. However, the liquid water mass absorption coefficients are different for tropical and temperate locations. As shown in Table 1, the frequency dependent coefficients a, b and c for estimating oxygen attenuation are also found to be different for tropical and temperate locations due to the difference in temperature profiles. Our proposed method of oxygen attenuation estimation using both surface temperature and pressure shows better accuracy and understanding of the physical basis compared to the previous method based on the surface temperature alone [20].

Finally, the usefulness of derivation of the mass absorption coefficients a_{wv} and a_{clwc} for water vapour and cloud (Table 2) and frequency dependent coefficients a, b and c for oxygen attenuation (Table 1) lies in the fact that in our case this non-rainy attenuation can be estimated from surface temperature, pressure, integrated water vapor, liquid water without involving the profile data and this has been done in such a comprehensive manner using data from tropical and temperate locations.

VII. CONCLUSION

The design of satellite links at K, Ka and Q bands requires a reliable knowledge of attenuation due to non-rainy atmosphere as well as rain attenuation in order to specify the physical layer of the communication links. The present study shows that propagation effects at K, Ka and Q bands in non-rainy conditions can be considerably higher in the tropical region than in the temperate region. This highlights the importance of adequate propagation measurements in non-rainy atmosphere at tropical locations given the complex climatology of this region.

This paper reveals that ERA-5 data is appropriate to estimate non-rainy attenuation, which is otherwise classically performed by radiometers or RAOBS measurements.

A simplistic approach is adopted to estimate non-rainy attenuation due to water vapour and cloud from IWV and ICLWC respectively using the appropriate mass absorption coefficients.

For oxygen attenuation estimation, a relation has been proposed between oxygen attenuation and surface temperature and pressure that provides a better performance and physical basis of the estimation.

ERA-5 data give a full 3D picture of the meteorological parameters around the receiving station; this can facilitate an accurate evaluation of the degradation on non-geostationary satellites that is not available otherwise. The accuracy of estimation will however depend on the precision of NWP products, which will improve with higher spatial and time resolutions in the future.

The present work offers an effective means for characterizing the non-rainy attenuation in the link budget for satellite communications in the K, Ka, and Q bands.

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