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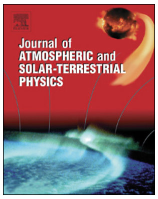

Radiometric measurements of cloud attenuation at a tropical location in India

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ABSTRACT

The effect of the earth's atmosphere on radio waves propagating over an earth-space path is a major concern in the design and performance of satellite communications systems. Some characteristics of cloud and its effect on signal propagation has been studied using multi-wavelength radiometer at a tropical location of Kolkata, India. The liquid water content profile shows high values at higher altitude during pre-monsoon season indicating the presence of cloud above zero degree isotherm. Significant change in attenuation value is observed for same liquid water content due to change in temperature and accordingly a suitable relationship is obtained for the present location. The measurements indicate that ~4 dB and ~12 dB attenuation is caused due to cloud at 0.01% outage probability at the Ka and *V* band, respectively. ITU-R model is found to be overestimating the cloud attenuation over this location and indicate the need for more experimental measurement from tropical region.

1. Introduction

Cloud attenuation is one of the important factors that can limit the possibility of extensive use of V/Q or higher frequency bands in satellite communication (Allnutt and Rogers, 1989). It is, however, relatively smaller compared to the rain attenuation at Ku/Ka band. Cloud consists of particles of water in the liquid or ice phase. The proportion of liquid water and ice particles depends on the type of cloud. The attenuation due to ice particles can be neglected in the microwave frequency range. However, ice particles have significant contribution to signal depolarisation. The water present in the cloud can lead to significant attenuation throughout the year (Altshuler and Marr, 1989; Mandeep and Hassan, 2008). The attenuation will be more severe in tropical regions like India due to frequent occurrence of cumulus cloud (Sarkar et al., 2005; Maitra and Chakraborty, 2009; Dissanayake et al., 2001). Cloud attenuation, therefore, is an important parameter to be considered for optimal designing of low fade margin satellite communication links operating at Ka band and higher frequencies, particularly in the tropical region.

Measurement and quantification of cloud attenuation are very limited in comparison to the rain attenuation, especially for tropical region (Dissanayake et al., 2001). The limited experimental facilities are the primary reason behind it. Separation of cloud attenuation from the rain attenuation suffered by satellite signals is another difficult aspect. Some study has already been done to estimate the cloud attenuation from noise temperature at some locations in United States (Slobin, 1982). However, experimental observations of cloud attenuation from tropical regions are very sparse.

Use of cloud radar and other instruments like GPS, radiometer or satellite observation for measurement of cloud liquid water can thus provide useful theoretical basis of cloud attenuation (Sridevi and Vijayan, 2008; Salonen and Uppala, 1991; Slobin, 1982; Davies and Watson, 1999). The relation between liquid water content and attenuation is well established (Salonen and Uppala, 1991). However, the real problem in using this relation for cloud attenuation estimation is due to the fact that cloud exists at different heights corresponds to different temperatures. Without knowing the exact temperature of the cloud liquid water content, the attenuation value can be significantly erroneous.

At Kolkata (22°34′N, 88°29′E), a tropical location in the Indian region, a multi-channel humidity and temperature profiler radiometer (RPG-Hatpro) is operating since 2009. The cloud attenuation is estimated from the profile of liquid water and temperature measured by the radiometer. The empirical relation between total cloud liquid water and cloud attenuation over this location is also compared with that proposed by ITU-R model.

2. Experimental details

2.1. Instrument and data processing

The radiometer, RPG HATPRO, measures the brightness temperature (BT) at 14 channels, 7 channels each in band 23.8–31.4 GHz and

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51–59 GHz. In the zenith pointing mode, the lower 7 channels are used to derive the humidity profile whereas the upper 7 channels give the temperature profile. An infrared radiometer mounted on the device gives the information about cloud base height. The cloud liquid water content (LWC) is then obtained from the humidity profile under assumption of single layer cloud with quadratic regression technique. The radiometric measurement accuracy of the system is within 0.5 K. The details of the parameters of this radiometer are given by Rose et al. (2005). Also, the detailed methodology for estimation of temperature and LWC profile can be found in the works of Peter and Kämpfer (1992) and Jongen et al. (1998).

The present study is based on one-year radiometric observations during the year of 2011 at Kolkata (22°34′N, 88°29′E). The temperature and liquid water profile is obtained with time resolution of 3 s. Since the retrieval of cloud profile in microwave radiometer is not very accurate in case of high rain, data has been discarded when rain is above 10 mm/h.

2.2. Cloud attenuation calculation

The typical radius of water droplets within non-rainy clouds varies from about 1 μm to 30 μm with maximum droplet density around 3–6 μm (Ippolito, 2008). Hence the extinction process is reduced to absorption process with negligible amount of scattering (Salonen and Uppala, 1991; Ippolito, 2008) in microwave frequency range under Rayleigh approximation. Therefore, liquid water density (M) can be treated as sole parameter controlling the cloud attenuation. The value of attenuation (α_c) depends only on the liquid water density in the cloud and the specific attenuation coefficient (γ_c) can be expressed as per ITU-R Rec.P.840 (ITU-R, 2009)

$$\alpha_c = \gamma_c M \ (\mathrm{dB/km}) \tag{1}$$

The specific attenuation (γ_c) of cloud liquid water is given by the following equation:

$$\gamma_c(h) = \frac{0.819f}{\varepsilon''(1+\eta^2)} \ (\mathrm{dB/km})/(\mathrm{gm}/m^3) \tag{2}$$

where,

$$\varepsilon = \varepsilon' + j\varepsilon'' \tag{3a}$$

$$\eta = \frac{2+\varepsilon'}{\varepsilon''} \tag{3b}$$

The complex permittivity (ε) can be obtained using double-Debye model which is also a function of frequency and temperature.

As the specific attenuation is a function of temperature and liquid water density, it varies within the cloud and from cloud to cloud. Therefore, the total cloud attenuation can be obtained considering height profiles of temperature and LWC values along the earth-space path as follows:

$$A = \frac{1}{\sin(\omega)} \int_{h_B}^{h_T} LWC * \gamma_c(h) dh \ (\mathrm{dB}) \tag{4}$$

where, h_B and h_T represent the heights of the base and top of the cloud layer, respectively and ω is the elevation angle of the satellite.

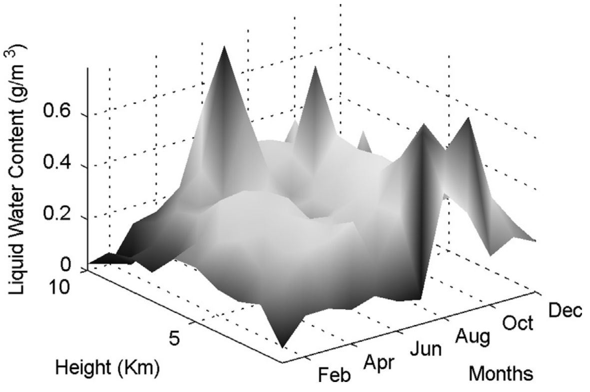

Fig. 1. Seasonal distribution of LWC at different altitudes.

3. Results

The seasonal variation of liquid water content at different height obtained at Kolkata is shown in Fig. 1. It can be seen that the LWC values are high at higher altitudes in months Apr–Jun whereas higher LWC values are obtained at lower altitudes during July–Oct. This is due to the fact that in Apr–Jun, thunderstorm activities are more prevalent whereas in July–Oct, monsoon clouds mostly occur at the present location. The high LWC values at higher altitudes in pre-monsoon season are associated with the convective phenomena. The monthly average value of LWC varies from 0.2–0.7 g/m^3, although, a single cloud can have very high LWC. This result indicates the relative distribution of cloud over different heights.

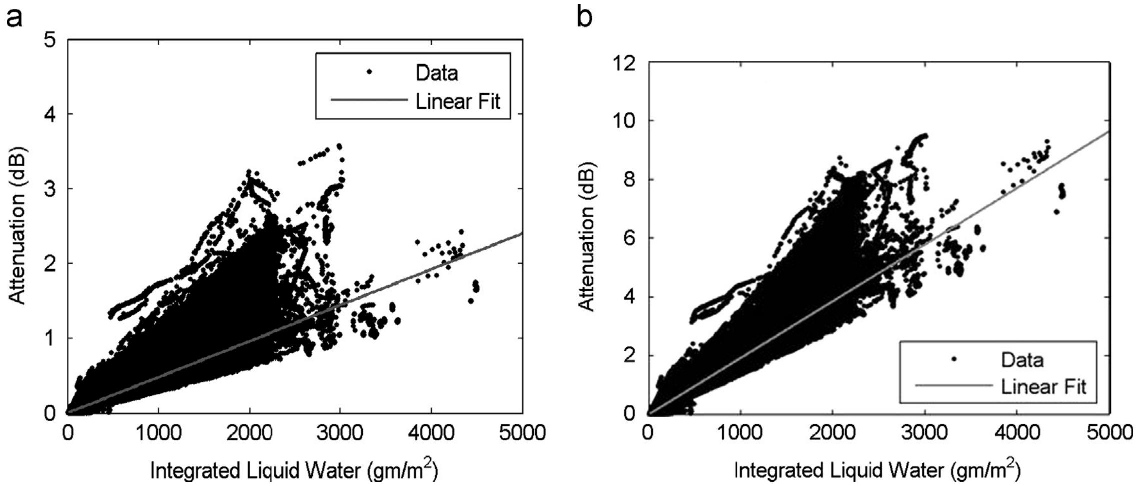

Fig. 2. Variation of attenuation with integrated liquid water for (a) 23.04 GHz and (b) 51.26 GHz.

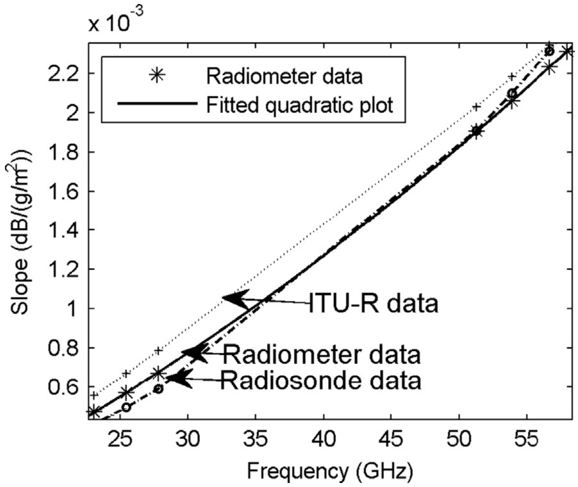

Fig. 3. Slope of linear relation between attenuation and ILWC for different frequencies.

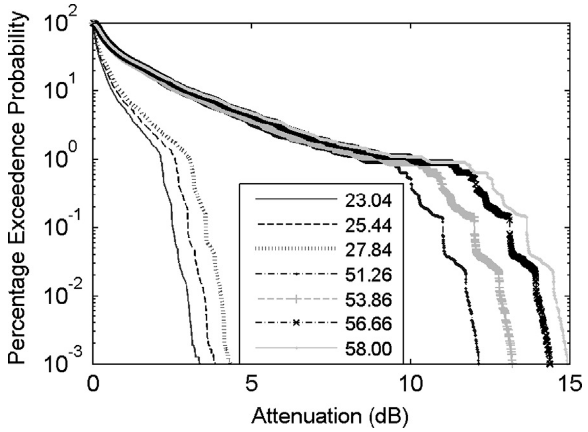

Fig. 4. Cloud attenuation exceedence probability.

As the integrated liquid water content (ILWC) is more abundantly available parameter than LWC, it is useful to relate the cloud attenuation to LWC. As an example, in Fig. 2(a)–(b), the scattered plot between integrated liquid water content and cloud attenuation is shown for frequency 23.04 GHz and 51.26 GHz. They are modelled and shown by the solid line of the following form:

$$A = m * \mathrm{ILWC}\ (\mathrm{dB}) \tag{5}$$

It can be noted that the same ILWC can correspond to different attenuation values spread over 2–4 dB depending upon frequency and ILWC. This is mainly due to the fact the temperature profiles within cloud can have significant variation. This indicates the fact that cloud attenuation modelling simply based on ILWC will not be adequate at higher frequencies and for thick clouds that are particularly observed in tropical locations.

The m value gives the slope of this linear relation and is dependent upon the frequency (f) and is shown in Fig. 3. The slope of the fitted curve is therefore modelled with the frequency as second order polynomial and the following relation is obtained,

$$m_{\exp} = 3.1 \times 10^{-7} f^2 + 2.9 \times 10^{-5} f - 3.5 \times 10^{-4} \tag{6}$$

The ITU-R model (ITU, 1999) and previously reported model for Kolkata from radiosonde observations (Maitra and Chakraborty, 2009) are respectively as follows:

$$m_{ITU} = 1.8 \times 10^{-7} f^2 + 3.9 \times 10^{-5} f - 4.4 \times 10^{-4} \tag{7}$$

$$m_{kol} = 6.6 \times 10^{-7} f^2 + 4.2 \times 10^{-6} f - 3.9 \times 10^{-4} \tag{8}$$

In Fig. 4, the exceedance probability of different attenuation values obtained at the present location is shown. It can be seen that the cloud attenuation can be very severe for link availability of 99.99% time or 0.01% exceedence probability level which turns out to be over 12 dB at V band (50–75 GHz) frequency. For Ka band frequency the same link availability requires additional fade margin of 4 dB due to cloud attenuation, which is quite substantial for low-fade margin systems.

4. Discussion and conclusions

The experimental observations of cloud attenuation at tropical regions are very limited due to complexity of separation of rain attenuation and cloud attenuation. The estimation of cloud attenuation requires experimental measurements of liquid water and temperature within the cloud region. The profiler radiometer operating at Kolkata provides an excellent opportunity to study and quantify the cloud attenuation. The radiometer provides the liquid water and temperature data at 39 height steps up to 10 km. This includes most of the cloud data occurring at this place except a few very high cumulus clouds which can be go beyond 10 km.

The results indicate that the cloud attenuation can be severe at V band frequency. The attenuation is also significant at Ka band with a value ~4 dB for 99.99% link availability. Since the profiles of water vapour and temperature data are not easily available, the relation between total liquid water and attenuation is obtained. The relation showing frequency dependence of the cloud attenuation is also investigated. There is a discrepancy between ITU-R model and the model obtained at the present location indicating the importance of such studies at tropical locations.

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