Estimation of cloud attenuation over some coastal cities for satellite space links in South Africa

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Abstract. One of the vital constraints on satellite space link systems operating at higher frequencies is attenuation due to clouds. This paper presents a 5-year estimation of cloud attenuation in the millimeter-wave propagation over two coastal cities in the Republic of South Africa. The results show that some salient features of clouds observed were monthly and location dependent. The observed average cloud value ranges between 16% and 55.6%, the relative humidity recorded between 65.4% and 84.2%, while the rainfall amount is between 5.43 and 79.66 mm over the study locations. The specific attenuation coefficient and cloud attenuation increases as the frequency increases over the studied locations. Furthermore, about 1 dB and above was observed at frequencies from 60 GHz and above. The study reveals the impact of liquid water content (LWC) in the clouds, which has a more significant effect on radio signals. The differences in the attenuation observed may be due to the impact of LWC and other salient features observed over the locations.

Keywords. Cloud attenuation, liquid water content, satellite communications, subtropical region.

1. Introduction
Due to the massive use of satellite communication systems, several effects are detrimental to the effective signals along the propagation path that needed to be accounted for; the major effects are the attenuation due to clouds and rain [1, 2]. At the radio-wave spectrum, at the millimeter wavelength region, the propagated signals suffer from some hydrometeors such as cloud, hail, ice, rain, among others [3-11]. Also, cloud and rain attenuations are the major degradations, contributing significantly to the loss of signals along the satellite propagation path. Although the effect of rain is more severe than clouds, however, the effect of clouds occurs in a more significant proportion of time while the effect of rain occurs in a lesser proportion of time [2, 12-15]. Some researchers also reported that the severity of rain and cloud impairments vary regionally and increases with frequency [16, 17]. These severities are more pronounced in equatorial, tropical, and subtropical regions, where rainfall intensity is significant compared to the temperate region [16-18].

Therefore, it is crucial to understand the effects of clouds on radio-wave propagation over each location where the use of satellite systems are essential. Since the information on clouds is scant in the Republic of South Africa, this work focuses on five years (2011 – 2015) estimation of cloud attenuation over two coastal cities in South Africa, a subtropical region. Durban (29° 97’ S, 30° 95’ E) and Cape Town (33° 58’ S, 18° 36’ E) are located along the Eastern boundaries and the Southwest
coast of the Republic of South Africa, respectively. These locations are selected due to their environmental uniqueness and biological diversity, making them attractive, adventurous (for both scientific researchers and tourists), and well-populated where the need for voice and video communication and data transfer has become unavoidable.

2. Cloud attenuation methods

A cloud is the composition of smaller rain droplets or ice crystals that are suspended in the air [19, 20]. Cloud is usually situated at an elevation above the surface of the Earth [21]. The cloud content of liquid water can influence the absorption and scattering of electromagnetic signals operating above 10 GHz frequencies (that is, the millimeter wavelength region) due to its lesser intensity than rain [20]. The derivation of the cloud attenuation technique is presented in this section, as recommended by International Telecommunication Union-Radiocommunication in [22]. The technique requires liquid water content (LWC) parameter, valid for frequencies up to about 200 GHz [23]. Also, to obtain a probability given value of cloud attenuation, the equivalent of the precipitable water (mm) or the total columnar content of the liquid water statistics, \( L \) (kg/m\(^2\), of a location must be known. Hence, the 5-year mean value of \( L \) obtained from the Tropical Rainfall Measuring Mission-Precipitation Radar is used in this study. The cloud attenuation, \( A \), is expressed as:

\[
A = \frac{LK_I}{\sin \theta}
\]  

(2.1)

where \( \theta \) is the angle of elevation and \( K_I \) is the specific attenuation coefficient ((dB/km)/(g/m\(^3\))). The specific attenuation within the cloud, \( \gamma_c \), is

\[
\gamma_c = K_I M
\]  

(2.2)

where \( M \) is the liquid water density in the cloud (g/m\(^3\)). The Rayleigh scattering mathematical model which makes use of a double-Debye in the estimation of dielectric permittivity of water, \( \varepsilon \), is used to calculate specific attenuation coefficient value, \( K_I \), for frequencies, \( f \) (GHz), up to 1000 GHz, the expression is given as:

\[
K_I = \frac{0.819f}{\varepsilon''(1 + \eta^2)}
\]  

(2.3)

while

\[
\eta = \frac{2 + \varepsilon'}{\varepsilon''}
\]  

(2.4)

The complex dielectric water permittivity, \( \varepsilon \), is

\[
\varepsilon'' = \frac{f(\varepsilon_0 - \varepsilon_i) + f(\varepsilon_i - \varepsilon_2)}{f_p[1 + \left(\frac{f}{f_p}\right)^2] + f_s[1 + \left(\frac{f}{f_s}\right)^2]}
\]  

(2.5)

\[
\varepsilon' = \frac{\varepsilon_0 - \varepsilon_i}{[1 + \left(\frac{f}{f_p}\right)^2]} + \frac{\varepsilon_i - \varepsilon_2}{[1 + \left(\frac{f}{f_s}\right)^2]} + \varepsilon_2
\]  

(2.6)

where

\[
\varepsilon_0 = 77.6 + 103.3(\theta - 1)
\]  

(2.7)

\[
\varepsilon_1 = 0.0671 \varepsilon_0
\]  

(2.8)

\[
\varepsilon_2 = 3.52
\]  

(2.9)
and

$$\theta = \frac{300}{T} \tag{2.10}$$

where $f_p$, $f_s$ and $T$ are principal relaxation frequency (GHz), secondary relaxation frequency (GHz) and temperature (K). The frequencies are given as:

$$f_p = 20.20 - 146(\theta - 1) + 316(\theta - 1)^2 \tag{2.11}$$

$$f_s = 39.8f_p \tag{2.12}$$

3. Results and discussion

Since the cloud comprises water droplets, it is necessary to discuss some salient features of clouds, as presented at the beginning of this section. The average monthly statistics of cloud, relative humidity, and rainfall amount observed for five years (2011 – 2015) are presented in Table 1 as some salient features. It could be generally observed from the table that these parameters vary monthly and in location. Durban recorded its lowest average cloud value in June, while Cape Town recorded its lowest value in February with about 16% and 26% respectively. The highest average cloud values were recorded in December and August with about 55.6% and 40.6% in Durban and Cape Town, respectively. The lowest relative humidity recorded in Durban is also in June with about 65.4%. In April, Cape Town is about 68.8%. The highest relative humidity values were recorded in December and August with about 84.2% and 77.2% in Durban and Cape Town, respectively. The rainfall amount observed recorded its lowest in June and February with approximately 12.24 mm and 5.43 mm. The highest values in December and August are about 61.19 mm and 79.66 mm over Durban and Cape Town.

| Months   | Average Cloud (%) | Relative Humidity (%) | Rainfall Amount (mm) |
|----------|-------------------|-----------------------|----------------------|
|          | Durban | Cape Town | Durban | Cape Town | Durban | Cape Town |
| January  | 47.8   | 26.8     | 83.4   | 70.2      | 51.37  | 10.28     |
| February | 42.0   | 26.0     | 82.4   | 70.4      | 35.85  | 5.43      |
| March    | 42.6   | 29.6     | 82.4   | 71.6      | 58.43  | 9.95      |
| April    | 32.0   | 28.8     | 78.4   | 68.8      | 28.39  | 35.47     |
| May      | 24.2   | 35.4     | 74.0   | 75.0      | 16.04  | 41.69     |
| June     | 16.0   | 38.2     | 65.4   | 76.6      | 12.24  | 73.57     |
| July     | 24.4   | 37.2     | 70.0   | 76.6      | 31.50  | 40.79     |
| August   | 23.8   | 40.6     | 67.0   | 77.2      | 15.56  | 79.66     |
| September| 37.8   | 39.2     | 73.2   | 76.8      | 32.06  | 33.09     |
| October  | 45.0   | 33.0     | 78.0   | 74.4      | 47.27  | 14.52     |
| November | 54.8   | 32.6     | 81.0   | 70.4      | 60.47  | 16.56     |
| December | 55.6   | 27.2     | 84.2   | 70.6      | 61.19  | 7.48      |

Figure 1(a and b) presents the specific attenuation coefficient, $K_t$, observed over the studied locations, which show the values of $K_t$ for frequency ranges between 10 and 200 GHz, together with the temperatures between -8°C and 20°C. It can be seen that the specific attenuation coefficient increases as the frequency increases over the studied locations, although the temperatures intercepted each other from about 90 GHz and above. The curve equivalent to 0°C is used for the prediction in this work to determine the cloud attenuation, as speculated by reference [22]. This indicates that the cloud’s liquid water along the satellite path is critical, especially in the low link applications.
Figure 1. Specific attenuation coefficient by water droplets at different temperatures as a function of frequency over (a) Durban and (b) Cape Town.

Figure 2 depicted the cloud attenuation prediction in relation with the frequency over the selected coastal locations in South Africa. It can be generally observed from Figure 2 that the cloud attenuation increases as the frequency increases. The lowest cloud attenuation is recorded in Durban, while Cape Town recorded the highest cloud attenuation value. However, cloud attenuation is almost negligible over the observed locations at a frequency between 12 GHz and 40 GHz, which shows less than 1 dB/km over the observed locations. In comparison, about 1 dB and above was observed at frequencies above 60 GHz. For example, the cloud attenuation of about 0.4059 and 0.4332 dB/km was recorded at 40 GHz, while at 60 GHz, it was about 0.8727 and 0.9233 dB/km over Durban and Cape Town, respectively. This implies that the cloud attenuation in millimeter wave band can well be predicted especially in the lower frequencies below 200 GHz.
Figure 2. Cloud attenuation prediction over selected coastal cities in South Africa.

4. Conclusions
This paper has presented cloud attenuation estimation over some coastal cities in the Republic of South Africa. The results show that some salient features of clouds observed were monthly and location dependence. The specific attenuation co-efficient increases as the frequency increases over the studied locations, which implies the importance of the liquid water in the clouds along the satellite propagation path. Also, the cloud attenuation observed increased as the frequency increases over the studied locations. Also, the observed dB from the frequencies 60 GHz and above could be detrimental to satellite signals. This study implies that the effect of clouds due to LWC on radio signals has its impact. The differences in the attenuation observed may be due to the impact of LWC and other atmospheric parameters observed over the locations.

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