Microwave Attenuation along Earth-Satellite Link During Dust Storms

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Abstract

Microwave propagation during sand and dust storms has received appreciable attention of researchers in the recent past due to the increase in the number of terrestrial and satellite links being deployed in the regions where dust storms are predominant. Dust storms cause signal attenuation on an earth-satellite link for a substantial percentage of time which may affect quality and reliability of telecommunication services. This paper investigates the attenuation due to dust storms along the earth-satellite link. A mathematical model, expressed as a function of visibility, wavelength, elevation angle and storms' reference height, is developed to predict dust storms' attenuation along propagation path. Variation of the dust storm's visibility with height for different reference visibility conditions is also given. The mathematical model for attenuation in earth-satellite link was developed by applying visibility variation to the expression of attenuation constant in terrestrial link. This was then integrated with respect to dust storms' height. The results obtained are depicted in graphs and discussed. It is found that attenuation increases when visibility during dust storms gets severe. Lastly, the results obtained show that attenuation in earth-satellite link operating at X band, especially, during dust storms may be said to be insignificant except when visibility is extremely bad.

Keywords
Attenuation; earth-satellite link; dust storms; microwave propagation; visibility.

1. Introduction

Dust storm may be referred to as a severe weather condition characterized by very strong wind and air filled with dust and sand over a large area. It is observed in many areas around the world, including Africa, arid parts of Asia, the Middle East and the North America. The effects of dust storms are enormous in aviation and telecommunications operations as they accumulate and transport dust in the atmosphere (Zhong, 2006). Dust storms pose dangers to communication systems' reliability in the affected regions. The particles from dust storms may rise high enough above the earth's surface to lie within the radio path, thereby causing signal loss and resulting in system outage or service interruptions. The suspended particles cause attenuation in microwave propagation. Thus, dust particles are very important consideration in the attenuation calculations from a radar point of view, even though particles with a diameter of more than 50 μm cannot be elevated beyond 2m to 5 m (NRL, 2013).

Microwave propagation during dust storms has received considerable attention due to an increase in the number of terrestrial and satellite links established in world regions that encounter dust storms as well as many other radar applications especially at high frequencies (Goldhirsh, 2001; Bashir & McEwan, 1985; Ghobrial & Sharif, 1987; Ruike et al., 2003; Ansari & Evans, 2008; and Sharif, 2011). Investigators (Goldhirsh, 2001; Bashir & McEwan, 1985; Ghobrial & Sharif, 1987) and (Sharif, 2011; Musa & Bashir, 2013 and Elsheikh et al., 2010) have proposed different models focusing on dust storms and its effects on signal propagation especially on terrestrial links. However, the effects of dust storms on earth-satellite links or slant paths have received little attention even though it is becoming very difficult to efficiently manage earth-satellite dependent systems that suffer attenuation due to dust storms. The objective of this paper, therefore, is to investigate the attenuation along earth–satellite links (also known as earth-space or slant paths) during dust storms by developing a model in terms of visibility, elevation angle and reference height to estimate the magnitude of the attenuation. The variation of visibility with height is also considered. The attenuation model is based

on the principle of radio wave propagation models at X band and the properties of dusty medium i.e. air with suspended dust or sand particles.

The remaining sections of this paper are presented such that some important dust particle's properties are briefly reviewed in section 2. In section 3, the attenuation model for earth-satellite links is developed. The results are presented in section 4 and they are also discussed. Finally, a conclusion is presented in section 5.

2. Dust and Particle's Properties

This section describes dust storms, a common phenomenon observed in the arid and semi-arid parts of the world, already defined in section 1. It also describes some important dust storm particle's properties such as shape, size, relative volume and visibility which are usually required to compute propagation constants of dusty media. Dust storms occur over arable land and areas that possibly have experienced prolonged drought. Dust particles are blown from the ground and get suspended in the air by wind. When the diameter of dust particles is greater than 80 µm and the particles rarely rise beyond few meters, they are often classified as sand storms (Musa et al., 2015a). However, when the diameters vary between 10 µm and 80 µm, and the particles are raised higher up to few kilometers above the ground, they are usually referred to as dust storms. The visibility in dust storms is usually expected to be less than a kilometer.

2.1 Dust Relative Volume and Visibility

Dust density, which depends on the number of suspended dust particles in the air, is an important factor required to compute propagation constants of a dusty medium. However, the density or relative volume is a parameter that is difficult to obtain or measure in dust storms. Although the relative volume of dust dispersed in air during dust storms is much less than unity even for very low visibilities, the dust relative volume is not used as a measure of dust storms' severity in practice. Instead, visibility during dust storm is used. In other words, dust storms are meteorologically and empirically observed using visibility. Subsequently, authors such as (Musa et al., 2015a) have found a relation between the relative volume and visibility. This has necessitated treating the prediction of electromagnetic wave attenuation during dust storms in terms of visibility.

The relative volume of particles in dust storms, v, is related to visibility, V, by Goldhirsh (2001) and Musa et al. (2015a):

$$v = \frac{9.4 \times 10^{-9}}{V^{\gamma}} \tag{1}$$

where γ is a constant whose value depend on the land origin of the dust storm and the climatic condition and V is the visibility.

The visibility is directly related to how severe a dust storm is and as such, it represents a measure of severity of the dust storm. This means that visibility can be applied to denote the degree of dust storm density and concentration instead of the total number of dust particles or relative volume (Elabdin et al., 2009). This relation is usually applied in the model development of propagation constants in dust storms as it provides convenient way of application to different dust storms' scenarios. It also allows for a method of evaluating dust concentrations from information on the visibility associated with a given dust storm.

2.2 Dust Height and Visibility

An important difference between the effect of dust storms on the performance of terrestrial links and earth-satellite links is the variation of the visibility with height. The effect of height on visibility is thus one of the very important factors that are usually considered when computing propagation parameters in a dusty medium. During a dust storm phenomenon, visibility decreases as the height increases. A variation of dust mass concentration with height in a form of empirical relationship between the dust mass concentration and the height was given (Chepil & Woodruff, 1957):

$$M = \frac{a}{h^{b}} \tag{2}$$

where M is the dust mass concentration (kg/m^3), h is the height (m), and a and b are constants. It was noted that the constants depend on the dust particle size distribution, climatic conditions and some meteorological factors. They may therefore be said to vary very slightly from one year to another.

Similarly, the mass of suspended dust particles per unit volume of air, i.e. the dust mass concentration was related to visibility during dust storms as:

$$M = \frac{C}{V^{\gamma}} \tag{3}$$

where V is visibility (km), while C and γ are constants that depend on the land origin of the dust storm and the climatic conditions.

In relating the visibility during dust storms and the mass concentration, different values of C is usually applied depending on factors such as local erosion (Gillett, 1979) or the distance from the source of the aerosol. It is observed that Chepil & Woodruff (1957) reported 5.6×10^{-5} and 1.25, respectively, as the values of C and γ, but Ghobrial & Sharif (1987) had $C = 2.3 \times 10^{-5}$ and γ = 1.07. The later is widely applied in studies that are dust storms related in Africa region and is also adopted in this work.

Equating (2) and (3) and rewriting the output in terms of visibility gives the expression in (4):

$$V^{1.07} = C\frac{h^b}{a} \tag{4}$$

where C is a constant which depends on the land origin of the dust storm and the climatic conditions, h is the height (m), and a and b are constants.

Equation (4) can be rewritten if V_0 is the visibility at some reference height h_0.

$$V_0^{1.07} = C\frac{h_0^b}{a} \tag{5}$$

Equation (5) may as well be expressed as (6).

$$\frac{C}{a} = \frac{V_0^{1.07}}{h_0^b} \tag{6}$$

Given that the constant, b, is 0.28 as reported by Chepil & Woodruff (1957), (6) can be substituted into (4) to obtain (7).

$$V = V_0\left[\frac{h}{h_0}\right]^{0.26} \tag{7}$$

Visibility, V, in (7) at any height, h, is related to the reference visibility, V_0, at a reference height, h_0,. From (7), it is clear that the visibility along the propagation path is not constant.

Some meteorological agencies, according to reports, measure visibility at 15 m height (Sharif, 2011). Thus, (7) is applied using the highlighted values to obtain the variation of visibility with height as:

$$V = 2.98V_0h^{0.26} \tag{8}$$

where V and h are both in km.

3.3 Particle Shape and Sizes

Dust particle shapes and sizes are other important properties when investigating dust storms and signal transmission parameters. Although dust particle shape is a very complex issue, the nearest geometry that approximates a dust particle is the ellipsoid with axis ratio varying over wide range which is from 0 to 1 (Musa et al., 2015a). The attenuation and the phase constants of a medium with suspending ellipsoids can be computed if the ratios of the ellipsoid axes are known. Particle size varies over a wide range and depends on whether it is dust storm or sand storms as explained earlier.

3.4 Dielectric

Knowledge of the dielectric permittivity of materials in the microwave frequency range is very essential because it enables evaluation of scattering properties in electromagnetic computation. The dielectric constant of a dry dust depends on its physical and electrical properties. The moisture contents of dust particles also affect the dielectric constant of the sample. The moisture content depends on the air relative humidity. For instance, the average dielectric constant value of dust samples collected in Sudan was 5.23 – j0.26, while the average dielectric constant value of dust samples with 4% moisture content was 6.23 – j0.57 (Sharif, 2011). A comparison between the two results of both dry and moistened dust samples suggests a critical dependence of both the real and the imaginary permittivity parts on the moisture contents.

4. Attenuation Along Earth-Satellite Link

The attenuation of microwave signals in dusty media may occur from two physical mechanisms – scattering and absorption of energy by suspended dust particles (Ghobrial & Sharif, 1987; Ruike et al., 2003; Ansari & Evans, 2008). Attenuation in earth-satellite links, which are also referred to as earth–space links, are attributed mainly to suspended particles from rain, snow or dust, even as earth-satellite links are usually free from multipath fading. In such links, it is important to consider the variation of the visibility with height and the inclination angle of the beam, depending on the location of the earth station and the satellite, when being compared with terrestrial links. The variation has been discussed in section 2.

In terrestrial links, the visibility (with height) may be said to be constant over the entire signal path and the inclination angle is zero relative to the horizontal. Along the earth–satellite paths, however, attenuation constant depends on height because the visibility and particle equivalent radius are also dependent on height. In earth-satellite links, attenuation is introduced to both uplink and downlink signals by dust storms.

Drawing inference from the concept of terrestrial link, the attenuation constant at any given height was derived by Musa and Bashir (2013) as a function of visibility and given as:

$$\alpha = \frac{1.061\times10^{-2}}{\lambda V^{\gamma}}.[I_m(G)]\ [dB/km] \qquad (9)$$

where V is the visibility during dust storms, $I_m(G)$ is the imaginary part of relative complex permittivity, λ is the wavelength and γ is a constant.

In treating an earth–satellite link, however, recall that the visibility is a function of height as expressed in (7). Also, if the same dielectric constant is assumed for the measured values at 10 GHz, the attenuation constant at a given height, h, can be expressed as (10) when (7) is substituted into (9):

$$\alpha = \frac{1.061\times10^{-2}}{\lambda {V_0}^{1.07} h^{0.28}}.{h_0}^{0.28} \qquad (10)$$

It is to be noted that the value of γ is taken to be 1.07 (Ghobrial & Sharif, 1987) and as mentioned, the reference height is reported to be 15 m. This suggests that (10) can be further reduced to:

$$\alpha = \frac{3.27\times10^{-3}}{\lambda {V_0}^{1.07} h^{0.28}} \qquad (11)$$

where h is the height in km, V is the visibility in km and λ is the wavelength.

If an earth-satellite path with an elevation angle θ is considered and because of the distribution density of dust storms varying with height, the total attenuation, α_θ, along the earth–satellite path can be given by integrating (11).

$$\alpha_\theta = \int_0^h \alpha(h)\frac{dh}{\sin\theta} \qquad (12)$$

where h is the height of dust storm (km) and θ is the elevation angle (in degree).

Equation (11) is substituted into (12) and integration is performed to obtain:

$$\alpha_\theta = \frac{3.27\times10^{-3}}{\lambda {V_0}^{1.07}} . \frac{h^{0.72}}{\sin\theta} \tag{13}$$

where h is the height in km, V_0 is the reference visibility, λ is the wavelength and θ is the elevation angle (in degree).

Equation (13) is the expression for estimating the microwave attenuation along the earth-satellite link during dust storms. It is important to note that in the attenuation expression, one of the considerations was that the density of the dust storms along the wave propagation path in the link is no identical and another consideration is that the value of the dielectric constant is the same as the measured values at 10 GHz. Furthermore, it is observed from the expression that as θ approaches zero, the attenuation approaches infinity. This is true because the path length becomes zero under such condition. In terrestrial link, however, the path length is definite.

4. Results and Discussions

Using (13), the attenuation introduced by dust storms in earth-satellite link is estimated. Figure 1, Figure 2 and Figure 3 give the attenuation for different path elevation angles versus reference visibility. Figure 1 is the plot when height is 4 km, while Figure 2 and Figure 3 are the plots when height is 2 km and 0.5 km respectively.

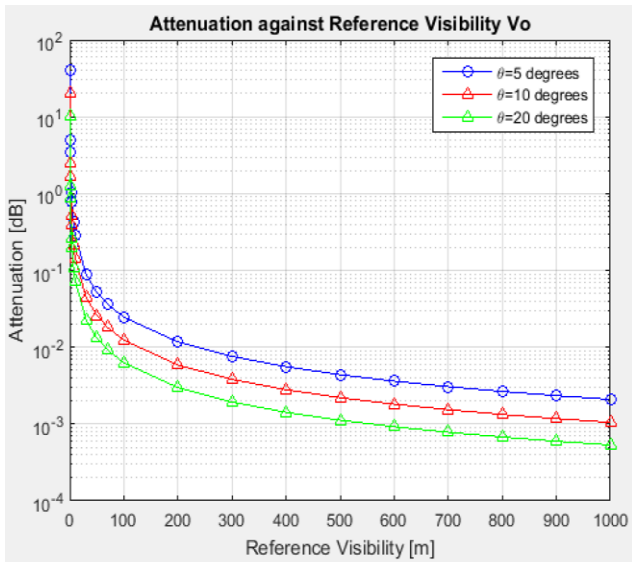

Figure 1. Attenuation Variation with Reference Visibility (h = 4 km)

The maximum dust storm's height observed by Chepil & Woodruff (1957) is 4 km and is used in this work to obtain the attenuation against reference visibility for different elevation angles. At elevation angles 5^0, 10^0 and 20^0, 39 dB, 20 dB and 10 dB are respectively obtained at 1 m reference visibility. The general trend observed is the severity of attenuation (i.e. increase in attenuation value) as the elevation angle is reduced. This is true because it is observed in (13) that as θ approaches zero, the attenuation approaches infinity. This means that, under such condition, the path length becomes zero.

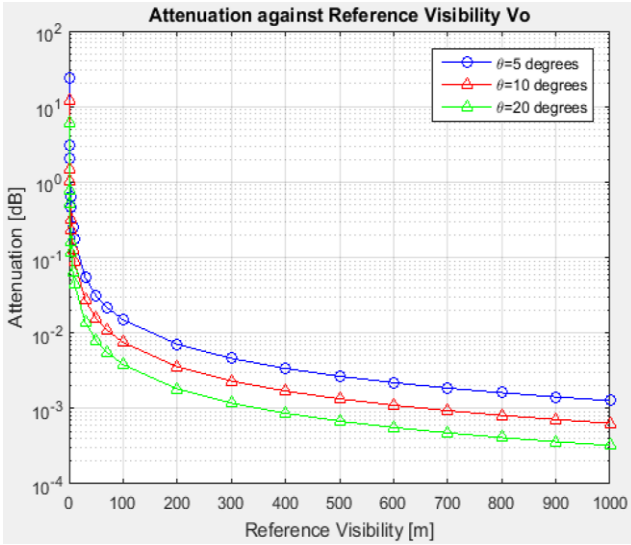

Figure 2. Attenuation Variation with Reference Visibility (h = 2 km)

The results (from Figure 1 to Figure 3) generally show that the signal propagation on an earth-satellite link (i.e. earth-space link or slant paths) gets better as the visibility improves. In other words, attenuation reduces when visibility increases.

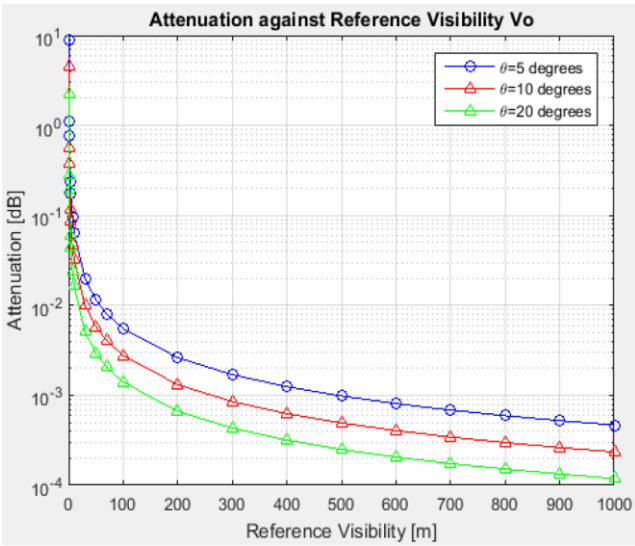

Figure 3. Attenuation Variation with Reference Visibility (h = 0.5km)

Figure 4, obtained when (8) is applied, shows the variation of the visibility with height for different reference visibilities. From these plots, it is noticed that as the reference visibility is incrementally varied (from 1 m, 10 m, 100 m to 500 m), the visibility also increases. For reference visibility greater than 100 m, the storm's visibility may be said to be negligible. Similarly, as the height increases, the visibility also increases, albeit very slightly.

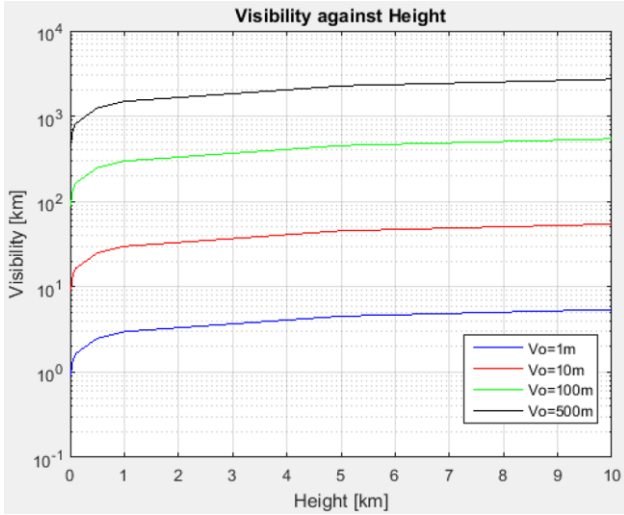

Figure 4. Visibility Variation with Height

5. Conclusion

A method, using mathematical model, for estimating microwave attenuation during dust storm in earth-satellite link has been developed. The model was premised on 10 GHz dielectric constant values and that density of dust storm along the wave propagation path in earth-satellite link is not the same. It is observed that the performance of satellite systems operating at the X band is not very sensitive to the propagation characteristics of the transmission medium. However, at a frequency above the X band such as the Ku and the Ka bands, dust storms could be very sensitive and cause degradation on earth-satellite paths. This may be experienced for a substantial percentage of time especially with severe and prolonged storms. In such scenario, reduction in both the quality and the availability of communication services is not unexpected.

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Babu Sena Paul received his B.Tech and M.Tech degree in Radio physics and Electronics from the University of Calcutta, India. He received his Ph.D. degree from the Department of Electronics and Communication Engineering, Indian Institute of Technology, Guwahati, India. He has published over sixty research papers in international and national conferences and peer reviewed journals. He joined the University of Johannesburg in 2010 and has served as the Head of the Department of Electrical and Electronic Engineering Technology from 2015 to March 2018. He is the currently serving as the Director to the Institute for Intelligent Systems, University of Johannesburg.