Simulation of Earth-Satellite Links Performance During Dust Storms

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Abstract

The effect of dust storms on the performance of an earth-satellite link is investigated at the x-band. Mathematical models have been developed to estimate the attenuation, differential attenuation, differential phase shift and cross-polarization discrimination (XPD) introduced by dust storms. The properties of dusty media (i.e. air with suspended soil particles) are reviewed; an expression is derived to estimate the effect of height on visibility during dust storms. Attenuation and XPD are given for an earth station located at Khartoum; (altitude 13°N and longitude 33°E) operated at 10 GHz. The obtained results shown that the attenuation and signal depolarization introduced by dust storms in earth satellite links operated in the x-band are not serious even for storm with very low visibilities, and can be ignored when designing such links.

Keywords:
microwave, propagation, radio-wave, earth-satellite links

I. Introduction

Microwave signals propagation during sand and dust storms has received considerable interest in recent years. This is due to the large development of microwave links established in tropical, semi-desert and desert regions, and introduct-

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ion of frequency re-use techniques in some of these links. However, the effect of dust and/or sand storms on the performance of earth-satellite links received little attenuation in literature. Thus the aim of this work is to simulate this problem and develop a model to investigate the system behaviour.

Earth-Satellite links are usually free of multipath fading, and microwave signal attenuation and polarization will mainly be contributed by various particles such as dust, rain or snow suspended in the atmosphere. In earth-satellite links two points should be considered when comparisons with terrestrial links are made; these are (i) the variation of the visibility with height, since in terrestrial links the visibility is constant over the entire signal path, and (ii) the inclination angle of the beam, which depends on the location of the earth station and satellite; in terrestrial links the inclination angle relative to horizontal is zero.

In this paper a model has been developed to simulate the performance of earth-satellite links during dust storms. This model is based on (i) the properties of the dusty medium (i.e. air with suspended soil particles), (ii) dust particles mechanical and electrical properties, concerned the problem and (iii) radio wave propagation models. The attenuation and cross-polarization introduced by dust storms have been estimated for an earth station at Khartoum, which is located at altitude 13°N and longitude 33°E, for different visibilities.

II. Properties of Dusty Media

In this work the term "*dusty medium*" is used to classify air medium with suspended soil particles and at least 80% by weight, of the particles have an equivalent diameter less than 60 micron[1,2].

In order to simulate the propagation of radio signal in any medium, some of the electrical and mechanical properties of that medium should be known, e.g. the refractive index, particles relative volume, etc. These parameters are mainly defined by the electrical and mechanical properties of the suspended particles (soil in this case). The parameters needed to simulate the propagation of radio signals in a dusty medium are investigated by the author for central and northern Sudan and published in references 1, 2, 3, 4. However it will be useful to review these parameters here for the sake of completeness.

Generally, dusty media are characterised by the following features :

1. The *relative volume* of dust dispersed in air during dust storms is much less than unity even for very low visibilities. Dust relative volume (v) is related to visibility (V, km) during storm by [1]

$$v = 9.43\times10^{-9} / V^{1.07} \qquad m^3/m^3 \quad .....1$$

2. Dust *particles* have random irregular *shapes*, which may vary from a needel-like to almost perfect sphere or disc. However, the dust particle shape can be approximated by an ellipsoid geometry with axis ratio varying over a wide range; i.e. from 0 to 1. The probability distributions of these ratios are given in reference (1).

3. The dust *particle size* varies over a wide range. The particles may have an equivalent diameter (D) within the range of 10 to 300 micron, with an average mean diameter of 11.4 micron[2]. Thus in the centimetres wavelength (frequency < 30 GHz) the relation $(\pi D/\lambda) \ll 1$ is valid (λ is the signal wavelength).

4. In stationary air conditions, particles, which assumed *ellipsoidal shape*, fall with the shortest axis vertical and the other two axes are randomly oriented in the horizontal plane[2,5]. However, it is well known that turbulent air flow is present during dust and sand storms, this results in random orientation of particles.

5. The dry *dust dielectric constant* depends on the sample electrical and chemical properties. The average value of dielectric constant for four samples collected in central and northern Sudan was found to be 5.23 - j0.26[4]. The moisture content of the sample which is a function of the air relative humidity seriously affects the dust dielectric constant. The average value dielectric constant of four samples with 4%, by weight, moisture content was found to be 6.23 - j0.57[4].

III. Effect of Height on Visibility

The number of particles suspended per unit volume of air (relative volume) is one of the important parameters needed to compute the medium propagation constants. In practice, visibility during dust and/or sand storms is used as the measure for storm severity rather than the dust relative volume. Thus, for convince and practical reasons, in this work the visibility is used to predict the medium propagation constants. In section II above a relation between the visibility and relative volume is given.

It is well known that the visibility during dust and/or sand storms increases as the height increases. Chepil and Woodruff[6] arrived at the following empirical relation for the variation of dust mass concentration (M, kg/m^3) with height (h, m) :

$$M = a/h^b \qquad \text{..... 2}$$

where a and b are constants that vary a little from one year to another. The constants a and b depend on the climatic conditions, meteorological factors and the particle-size distribution of the dust.

Patterson and Gillete[7] relate the dust mass concentration and visibility, at a height h, during dust or sand storms by

$$MV^{\gamma} = C \qquad \text{......... 3}$$

where C is a dimensional constant (kg/m^3) and γ is a dimensionless constant. For central and northern Sudan conditions, where storms are generally, not locally generated and climatic conditions are tropical, the values $C = 2.3\times10^{-5}$ and $\gamma = 1.07$ are applicable.

By substituting for M from equation (2), equation (3) can be written in term of visibility as

$$V^{1.07} = Ch^b/a \qquad \text{....... 4}$$

Let the visibility at some reference height h_o to be V_o, then equation (4) yields

$$V^{1.07} = V_o[h/h_o]^{b/1.07} \qquad \text{.......5}$$

Chepil and Woodruff[6] gave the average value of 0.28 for the constant b, which will be used herein. The Meterology Department, Sudan, used to measure the visibility at a height of 15 meters. Using this reference height in equation (5); i.e. h_o = 15 meters, and substitute for b an expression for the variation of visibility with height is given by :

$$V = 298 V_o h^{0.26} \quad (km) \quad \ldots\ldots\ldots 6$$

(h is in km).

The plot of Fig.(1) gives the variation of the visibility with height for different reference visibilities. It can be noted from this figure that, for reference visibilities greater than 300 meters, the storm visibility became greater than 1 km just after some hundred meters height.

The visibility statistics for some towns in Sudan is given in ref (1). However, for the sake of completeness, visibility statistics for Khartoum are given here, Fig.(2). It is noted that the visibility is less than 1 km for about 0.78% of the time per annum. This statistic is based on observations during the period from 1975 to 1980, done by the Sudan Meteorology Department.

IV. The Model

A. *Attenuation*

In earth-satellite links, dust storms introduce some attenuation in both up and down link signals. In this case the attenuation constant depends on height, since the visibility is not constant over the entire path.

The attenuation constant at a given height with visibility V (i.e. for terrestrial link) is derived in ref (1) for centemetric wavelengths and it is given for dry dust by :

$$\alpha = 1.11x10^{-3}/\lambda V^{1.07} \qquad ......7$$

(λ is the wavelength in cm).

Substituting for V from equation (5), the attenuation constant at any height (h) is given by

$$\alpha(h) = [1.11x10^{-3}/\lambda V_o^{1.07}].[h_o/h]^{0.28} \quad (dB/km) \quad ...8$$

(h is in km).

Now consider an earth-salellite path with an elevation angle θ. Let δx be an element length at distance x corresponding to the height h, Fig.(3). Thus the element attenuation [$\delta\alpha(h)$] caused by dust storm over the element distance δx is given by :

$$\delta\alpha(h) = [3.42x10^{-4}/\lambda V_o^{1.07}h^{0.28}] . \delta x$$

$$= [3.42x10^{-4}/\lambda V_o^{1.07}h^{0.28}] . [\delta h/\sin\theta] \quad (dB) \quad ..9$$

Integrating equation (9) over the height h, the "total" attenuation (α) due to dust storm of height h_1 is given by

$$\alpha = [4.75x10^{-4}/\lambda V_o^{1.07}] . [h_1^{0.72}/\sin\theta] \quad (dB) \quad .. 10$$

It is noticed that in this equation where θ approaches zero the attenuation approaching infinite value, this is true since under this condition the path length become infinite. However, this is not the case for terrestrial link, where the path has certain definite length.

B. *Differential Attenuation and Phase Shift*

Under stationary air conditions dust particles align with the shortest axis vertical, (particles are assumed to have ellipsoidal geometry, as mentioned in section II above).

Dust storms with particles having such an orientation induce cross-polarization. The estimation of the cross-polarization discrimination (XPD) requires the determination of the differential attenuation (DA) and differential phase shift (DP). Again here, visibility is not constant, thus DA and DP should depend on height.

DA and DP have been derived for terrestrial links in ref. (1). The DA at any height (h), with visibility V is given by

$$\Delta\alpha(h) = |\alpha_h(h) - \alpha_v(h)|$$

$$= 8.09\times10^{-5}/\lambda V^{1.07} \quad \text{neper/km} \quad \ldots\ldots 12$$

where α_h and α_v are the attenuation in the horizontal and vertical directions respectively, in terrestrial links.

Similarly, the DP is given by

$$\Delta\phi(h) = |\phi_h(h) - \phi_v(h)|$$

$$= 8.09\times10^{-5}/\lambda V^{1.07} \quad \text{rad/km} \quad \ldots\ldots 11$$

where ϕ_h and ϕ_v are the phase shift in the horizontal and vertical directions respectively, in terrestrial links.

Using the same analysis as for the attenuation carried out in the previous section, the DA and DP can be obtained in terms of height and visibility measured at the 15 meters reference height; i.e

$$\Delta\alpha(h) = 2.50\times10^{-5}/\lambda V_o^{1.07}h^{0.28} \quad \text{neper/km} \quad \ldots 13a$$

$$\Delta\phi(h) = 4.84\times10^{-4}/\lambda V_o^{1.07}h^{0.28} \quad \text{rad/km} \quad \ldots 13b$$

(h is in km).

The above equations are valid for terrestrial links. However, the DA and DP in earth-satellite link between polarization perpendicular and parallel to the plane of incidence, i.e. the plane which contains the direction of polarization and the dust particle vertical axis of symmetry, can be approximated by :

$$\Delta \alpha_\theta(h) = \Delta\alpha(h)\ \cos^2\theta \qquad \text{....14a}$$

$$\Delta \emptyset_\theta(h) = \Delta \emptyset(h)\ \cos^2\theta \qquad \text{....14b}$$

where θ is the elevation angle of the path, $\theta = 0$ for terrestrial cases.

Hence, using equation (13) and (14), the elements of DA and DP for an element length δx along the path are given by :

$$\delta[\Delta \alpha_\theta(h)] = [2.50\text{x}10^{-5}/\lambda V_o^{1.07}h^{0.28}]\ .\ [\cos^2\theta.\delta x] \quad \text{..15a}$$

$$\delta[\Delta \emptyset_\theta(h)] = [4.85\text{x}10\text{-}4/\lambda V_o^{1.07}h^{0.28}]\ .\ [\cos^2\theta.\delta x] \quad \text{..15b}$$

The "total" DA (m_θ) and DP ($\emptyset_\theta$) can be obtained by integrating equation (15) over the path length; i.e.

$$m_\theta = \exp[\int_0^L \delta[\Delta \alpha_\theta(h)].dx \qquad \text{nepers} \quad \text{..... 16a}$$

and $$\emptyset_\theta = \int_0^L [\Delta \emptyset_\theta(h)].dx \qquad \text{radians} \quad \text{.....16b}$$

By integrating equation (15) we get

$$m_\theta = \exp\{[3.47\text{x}10^{-5}/\lambda V_o^{1.07}].[h_1^{0.72}/\sin\theta].\cos^2\theta.\} \quad \text{..17a}$$

$$\emptyset_\theta = [6.74\text{x}10^{-4}/\lambda V_o^{1.07}].[h_1^{0.72}/\sin\theta.].\cos^2\theta \quad \text{...17b}$$

It can be shown that for dust storms, the above expression for the DA; i.e. equation (17a), gives values of m_θ which are very close to unity even for very low visibilities and small elevation angles.

C. *Cross-Polarization Discrimination (XPD)*

For the worst case, consider a circular polarized wave, this wave may be resolved into two linearly polarized waves of equal magnitude but with their polarization orthogonal and 90o out of phase. Since there exists DA and DP for polarization perpendicular and parallel to the plane of incidence, under the condition discussed in the previous section, the cross-polarization is induced.

If all particles are oriented at a single cat angle, which is assumed here, the XPD in earth satellite path with elevation i is given by

$$XPD_{\theta} = 10.\log_{10}\{[1 + 2m_{\theta}\cos \varnothing_{\theta} + m_{\theta}^{2}]/[1 - 2m_{\theta}\cos \varnothing_{\theta} + m_{\theta}^{2}]\} \quad (dB) \quad .... 18$$

where m_{θ} and $\varnothing_{\theta}$ are defined by equation (17) above.

Since $m_{\theta} \simeq 1$, as mentioned in the previous section, even for very sever storms, equation (18) can be rewritten in the form :

$$XPD = 10.\log_{10}\{[1 + \cos \varnothing_{\theta}]/[1 - \cos \varnothing_{\theta}]\} \quad (dB) \quad ..19$$

V. Case Study and Results

The attenuation introduced by dust storms in an earth-satellite link is estimated by equation (10), while equation (18) is used to estimate the XPD. The visibility statistics of section II was used to determine the statistics of these quantities for an earth station located at Khartoum and operated at 10 GHz frequency. The dust storm height may vary from about 500 meters to several kilometres. In the present model the maximum storm height, generally encountered in Khartoum area is used, i.e. $h_1 = 4$ km. The attenuation and XPD predictions were carried out for dry air conditions. Fig.(4) gives the attenuation for different elevation angles. The XPD is given in Fig.(5).

VI. Conclusions

A model had been developed to simulate the performance of earth-satellite links during dust storms. Mathematical models were given to predict the attenuation and XPD. Attenuation and XPD had been estimated for an earth-station operated at 10 GHz frequency in Khartoum. It was found that, for about 99.51% of the annum time the attenuation introduced by dust storms is less than 0.007 dB in 5° elevation links. The XPD due to dust storms is better than 25 dB in 5° elevation links for about 99.96% of the annum time. Generally, the obtained results shown that, the attenuation and signal depolarization due to dust storms in earth-satellite links are not serious, even under sever storms conditions, and can be ignored in the design of such links.

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