*Progress In Electromagnetics Research M, Vol. 6, 139–153, 2009*

# MATHEMATICAL MODEL FOR THE PREDICTION OF MICROWAVE SIGNAL ATTENUATION DUE TO DUSTSTORM

**Z. Elabdin, M. R. Islam, O. O. Khalifa, and H. E. A. Raouf**

Wireless Communication and Signal Processing Research Group
Kulliyyah of Engineering
International Islamic University Malaysia
Malaysia

**Abstract**—The microwave signal attenuation caused by dust is one of the major problems in utilizing microwave bands for terrestrial and space communication especially at desert and semi desert area. This paper presents a mathematical model developed to characterize the microwave signal attenuation due to dust. This model enables a convenient calculation of the microwave signal path attenuation which relates attenuation to visibility, frequency, particle size and complex permittivity. The predicted values from the mathematical model, which are compared with the measured values observed by the author in Sudan show relatively optimistic agreement.

## 1. INTRODUCTION

Sand and dust-storms occur in many parts of the world, especially in the Middle East and arid parts of Asia, as well as in the southwest of the USA, in the dry states, such as Texas and Arizona.

Duststorm occurs not only in desert region, it can extend far into the atmosphere reaching up to 5 km or even higher in the mid-troposphere. Much of this dust is advected out of the region by the upper-level winds. The African easterly jet - a summer wind maximum in the midtroposphere, is imbedded in the Saharan dust layer. Due to its strength and stability, it exports dust as far as the Caribbean and South America [1].

Signal attenuation is an important parameter in telecommunications applications because of its importance in determining signal

---

Corresponding author: Z. Elabdin (zainomer@yahoo.com).

strength as a function of distance. A major cause of this phenomenon is atmospheric particles which can seriously limit the performance of telecommunication system especially at microwave level [12].

Wind speed, atmospheric stability, and source region surface characteristics are the three main environmental factors that affect the probability of occurrence, intensity, and height of duststorms. Indicators of environmental change have been developed to reflect the anthropogenic pressure, current condition and the human response to such threatening processes as accelerated erosion and disturbance of nutrient cycling through loss of surface soil. The phenomenon has increased in Khartoum in recent years as shown in Figure 1.

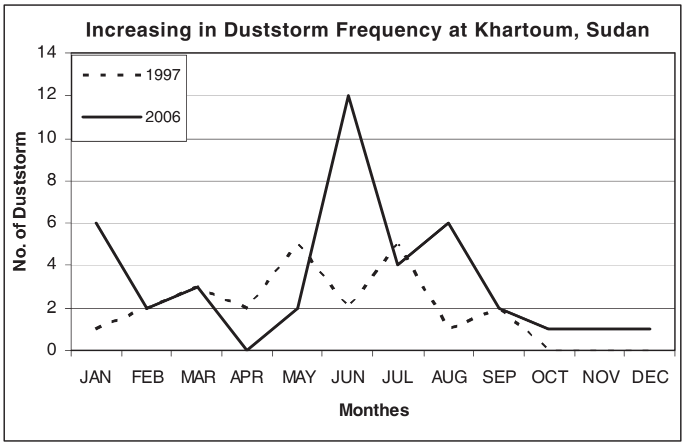

**Figure 1.** Increasing in duststorm frequency at Khartoum (1997, 2006).

## 2. DUSTSTORM EFFECTS

The effect of precipitating particles on signal attenuation has received considerable attention especially at high frequencies [2]. As most of the work done in this area was carried out in Europe and USA, a significant amount of research has done in developing models to quantify the impact of rain and snow attenuation on communication systems operating in the microwave region [3–7].

In contrast of that, little work has been done to investigate the impact of duststorm on the same propagation paths [8–10]. Rapid development in telecommunication technology and increasing competition in the sector have extended service to new locations and environments especially in Africa and Asia.

## 3. THEORY OF SINGLE-PARTICLE SCATTERING

When microwaves pass through the medium containing precipitations like rain, snow or dust particles, the microwave signals get attenuated through two phenomena [20]:

1) Absorption of energy by these particles.
2) Scattering of energy out of the beam by these particles.

Microwaves suffer absorption and scattering by the atmosphere especially at higher frequencies where the scattering effects become more severe [21].

The basic theory under mathematical model for attenuation is the theory for single particle scattering [22]. The propagation effects may be modeled by volumetric integration of scattering by individual particles. When an object is illuminated by a wave, part of the incident power is scattered out and another part is absorbed by the object. The characteristics of these two phenomena, scattering and absorption, can be expressed most conveniently by assuming an incident plane wave.

### 3.1. Signal Attenuation Due to Duststorm

The methods to predict signal attenuation due to rain effects are also applicable to duststorm, as the general model for scattering in sand and dust particle populations is essentially the same as that for a population of hydrometeors; both of them are discrete random medium [14].

The signal attenuation due to duststorm is estimated generally by solving the forward scattering amplitude function of a single particle [15]. The solution may be carried out using the Rayleigh approximation or Mie solutions. The method depends largely on the wave number and particle radius [16].

The attenuation of electromagnetic radiation ($A_T$) over a path of extent $L$ through precipitating particles may be written as [5]:

$$A_T\,(\mathrm{dB}) = \int_0^L A_p dx \tag{1}$$

Where $A_p$ (dB/km) is the specific attenuation characterizing the precipitating particles.

Several authors used the following expression to calculate the attenuation due to rain [3, 5, 13]:

$$A_p\ (\mathrm{dB/km}) = 4.343 \times 10^3 \int_{a_{\min}}^{a_{\max}} \sigma_t\,(a) \cdot N\,(a)\,da \tag{2}$$

where $N(a)da$ is the number of particles per unit volume of air with particles radius between $a$ and $a + da$; $\sigma_t$ is the total attenuation cross section efficiency factors of particle of radius $a$.

The investigation methods to predicted the signal attenuation due to rain effects can be applied to duststorm. Both of them are discrete random medium. Starting from the above we can express the attenuation of electromagnetic radiation ($A_T$) over a path of extent $L$ through duststorm as:

$$A_T\,(\mathrm{dB}) = \int_0^L A_d dx \tag{3}$$

where $A_d$ (dB/km) is the specific attenuation characterizing the duststorm which can be expressed as:

$$A_d\ (\mathrm{dB/km}) = 4.343 \times 10^3 \int_{a_{\min}}^{a_{\max}} \sigma_t\,(a) \cdot N\,(a)\,da \tag{4}$$

Where $N(a)da$ is the number of particles per unit volume of air with dust particles radius between $a$ and $a + da$; $\sigma_t$ is the total attenuation cross section efficiency factors of dust particle of radius $a$.

### 3.2. Dependence on Visibility

To calculate the attenuation by the above equations, data are required for the number of particles of dust $N$, which is difficult to measure accurately.

On the other hand, statistical information on duststorm visibility is available. Goldhirsh [15] expresses the visibility in term of the particle density as:

$$V\,(\mathrm{km}) = \frac{5.5 \times 10^{-4}}{N a_e^2} \tag{5}$$

where the unit of $N$ is particles/$\mathrm{m}^3$ and $a_e$ is the equivalent particle radius in meters.

By solving $N$ in the above formula we can express the particle density in term of the visibility and the radius as:

$$N = \frac{5.5 \times 10^{-4}}{V a_e^2} \tag{6}$$

## 4. ANALYTICAL MODELS FOR SCATTERING

Two models give an analytical solution for the scattering of a plane wave by a spherical particle, Rayleigh approximation and Mie solution.

Rayleigh approximation loses its reliability as the size of the dust particles approaches the operating wavelength or vice-versa, because Rayleigh formula is based on the assumption that $a \ll \lambda$, where $a$ is the dust particle radius and $\lambda$ is the operating wavelength in meters. This is the reasons that it is difficult to use it for frequencies higher than 37 GHz [17].

In contrast to Rayleigh scattering Mie solutions embrace all possible ratios of diameter to wavelength and do not depend upon any such limitation and can be utilized to predict attenuation in microwave wave band with high reliability especially at higher frequencies.

Chu [14] developed a formula to predict signal attenuation caused by dust particles using Rayleigh approximation, so a new formula that can predict signal attenuation due to dust particles at higher frequencies is highly recommended for new telecommunication application.

Collin [11] presented an expression of the total cross-section efficiency factors ($\sigma_t$) using Mie solutions as:

$$\sigma_t = \frac{\lambda^2}{2\pi}(ka)^3\left(c_1 + c_2(ka)^2 + c_3(ka)^3\right) \tag{7}$$

Where $a$ is the particle radius; $k$ is the wave number ($k = 2\pi/\lambda$), $\lambda$ is the wavelength and $c_1$, $c_2$ and $c_3$ are constants whose values depend on real ($\varepsilon'$) and imaginary ($\varepsilon''$) parts of the dielectric constant of the particles as:

$$c_1 = \frac{6\varepsilon''}{(\varepsilon'+2)^2 + \varepsilon''^2} \tag{8}$$

$$c_2 = \varepsilon''\left\{\frac{6}{5}\frac{7\varepsilon'^2 + 7\varepsilon''^2 + 4\varepsilon' - 20}{\left[(\varepsilon'+2)^2 + \varepsilon''^2\right]^2} + \frac{1}{15} + \frac{5}{3\left[(2\varepsilon'+3)^2 + 4\varepsilon''^2\right]}\right\} \tag{9}$$

$$c_3 = \frac{4}{3}\left\{\frac{(\varepsilon'-1)^2(\varepsilon'+2) + [2(\varepsilon'-1)(\varepsilon'+2) - 9] + \varepsilon''^4}{\left[(\varepsilon'+2)^2 + \varepsilon''^2\right]^2}\right\} \tag{10}$$

## 5. THE PREDICTED MODEL

By substituting Collin expression (7) for the total crosssection efficiency factors ($\sigma_t$) and the particle density expression in (6), $A_d$

(dB/km) may alternately be expressed as:

$$A_d = 4.343 \times 10^3 \left[\frac{\lambda^2}{2\pi}(ka)^3 \left(c_1 + c_2 (ka)^2 + c_3 (ka)^3\right) \cdot \frac{5.5 \times 10^{-4}}{V a_e^2}\right] \quad [\text{dB/km}]. \tag{11}$$

A further approximation can be made in these calculations, assuming that every dust particle in a real storm may be replaced by an equivalent particle ($a_e$) whose radius is the mean radius for all dust particles. By this assumption, the value of equivalent particle radius ($a_e$) is considered as constant value and Eq. (11) may alternately be expressed as algebraic expression:

$$A_d = 4.343 \times 10^3 \left[\frac{\lambda^2}{2\pi}\left(\frac{2\pi a}{\lambda}\right)^3 \left(c_1 + c_2 \left(\frac{2\pi a}{\lambda}\right)^2 + c_3 \left(\frac{2\pi a}{\lambda}\right)^3\right) \frac{5.5 \times 10^{-4}}{V a_e^2}\right] \quad [\text{dB/km}]. \tag{12}$$

In the following equations there are consecutive algebraic calculation and approximation for Eq. (12):

$$A_d = \frac{4.343 \times 10^3 \times 5.5 \times 10^{-4}}{2\pi}\left[\lambda^2 (ka_e)^3 \left(c_1 + c_2 (ka_e)^2 + c_3 (ka_e)^3\right) \frac{1}{V a_e^2}\right] \quad [\text{dB/km}]. \tag{13a}$$

Then

$$A_d = 0.38 \left[\lambda^2 (ka_e)^3 \left(c_1 + c_2 (ka_e)^2 + c_3 (ka_e)^3\right) \frac{1}{V a_e^2}\right] \quad [\text{dB/km}]. \tag{13b}$$

Then

$$A_d = 0.38 \frac{\lambda^2}{V}\left[k^3 a_e \left(c_1 + c_2 (ka_e)^2 + c_3 (ka_e)^3\right)\right] \quad [\text{dB/km}]. \tag{13c}$$

Then

$$A_d = \frac{0.38 \times \lambda^2}{V}\left(c_1 k^3 a_e + c_2 k^5 a_e^3 + c_3 k^6 a_e^4\right) \quad [\text{dB/km}]. \tag{13d}$$

By substituting $k = 2\pi/\lambda$ in the Eq. (13d):

$$A_d = \frac{0.38}{V}\left(c_1 \frac{8\pi^3}{\lambda} a_e + c_2 \frac{32\pi^5}{\lambda^3} a_e^3 + c_3 \frac{64\pi^6}{\lambda^4} a_e^4\right) \quad [\text{dB/km}]. \tag{14}$$

This can be simplified to:

$$A_d = 94.3 \times c_1 \frac{a_e}{V\lambda} + 3721.2 \times c_2 \frac{a_e^3}{V\lambda^3} + 23381 \times c_3 \frac{a_e^4}{V\lambda^4} \quad [\text{dB/km}]. \tag{15}$$

By introducing new parameters $\alpha, \beta$ and $\theta$ where:

$$\alpha = 94.3 \times c_1 \tag{16}$$

$$\beta = 3721.2 \times c_2 \tag{17}$$

$$\theta = 23381 \times c_3 \tag{18}$$

So by substituting equations (16), (17) and (18) in Eq. (15) we can express the specific attenuation due to duststorm $A_d$ (dB/km) as:

$$A_d = \frac{\alpha a_e}{V\lambda} + \frac{\beta a_e^3}{V\lambda^3} + \frac{\theta a_e^4}{V\lambda^4} \qquad [\text{dB/km}]. \tag{19}$$

Where

$a_e$: the equivalent particle radius in meters,

$V$: the visibility in kilometer,

$\lambda$: the wavelength in meter and;

$\alpha, \beta$ and $\theta$: constants whose values depend on real ($\varepsilon'$) and imaginary ($\varepsilon''$) parts of the dielectric constant of the dust particles as:

$$\alpha = \frac{565.8\varepsilon''}{(\varepsilon' + 2)^2 + \varepsilon''^2} \tag{20}$$

$$\beta = 3.7 \times 10^3 \cdot \varepsilon'' \left\{ \frac{6}{5} \frac{7\varepsilon'^2 + 7\varepsilon''^2 + 4\varepsilon' - 20}{\left[(\varepsilon' + 2)^2 + \varepsilon''^2\right]^2} + \frac{1}{15} + \frac{5}{3\left[(2\varepsilon' + 3)^2 + 4\varepsilon''^2\right]} \right\} \tag{21}$$

$$\theta = 3.12 \times 10^4 \left\{ \frac{(\varepsilon' - 1)^2 (\varepsilon' + 2) + [2(\varepsilon' - 1)(\varepsilon' + 2) - 9] + \varepsilon''^4}{\left[(\varepsilon' + 2)^2 + \varepsilon''^2\right]^2} \right\} \tag{22}$$

For more simplification of the Eq. (19) it is better to express the wavelength ($\lambda$) in term of frequencies ($f$) in GHz which is easier to use by microwave network engineers. So the specific attenuation of duststorm $A_d$ (dB/km) can be expressed as;

$$A_d = \frac{\alpha a_e f}{(0.3)V} + \frac{\beta a_e^3 f^3}{(0.3)^3 V} + \frac{\theta a_e^4 f^4}{(0.3)^4 V} \qquad [\text{dB/km}]. \tag{23}$$

By introducing new parameters $X, Y$ and $Z$ where:

$$X = \frac{\alpha}{0.3} \tag{24}$$

$$Y = \frac{\beta}{0.3} \tag{25}$$

$$Z = \frac{\theta}{0.3} \tag{26}$$

So by substituting equations (24), (25) and (26) in Eq. (23) we can express the specific attenuation due to duststorm $A_d$ (dB/km) as:

$$A_d = \frac{a_e f}{V}\left(X + Y a_e^2 f^2 + Z a_e^3 f^3\right) \qquad [\mathrm{dB/km}] \tag{27}$$

Where

$a_e$: the equivalent particle radius in meters,

$V$: the visibility in kilometer,

$f$: the frequency in GHz and;

$X, Y$ and $Z$: constants whose values depend on real ($\varepsilon'$) and imaginary ($\varepsilon''$) parts of the dielectric constant of the dust particles as:

$$X = \frac{1886 \cdot \varepsilon''}{(\varepsilon' + 2)^2 + \varepsilon''^2} \tag{28}$$

$$Y = 137 \times 10^3 \cdot \varepsilon'' \left\{ \frac{6}{5} \frac{7\varepsilon'^2 + 7\varepsilon''^2 + 4\varepsilon' - 20}{\left[(\varepsilon' + 2)^2 + \varepsilon''^2\right]^2} + \frac{1}{15} + \frac{5}{3\left[(2\varepsilon' + 3)^2 + 4\varepsilon''^2\right]} \right\} \tag{29}$$

$$Z = 379 \times 10^4 \left\{ \frac{(\varepsilon' - 1)^2 (\varepsilon' + 2) + [2(\varepsilon' - 1)(\varepsilon' + 2) - 9] + \varepsilon''^4}{\left[(\varepsilon' + 2)^2 + \varepsilon''^2\right]^2} \right\} \tag{30}$$

The important assumptions in this model are:

- The particles with a radius up to 1 mm have spherical shapes.
- The medium surrounding the particles (the air) is non-conducting; that means there is no power loss in this medium.
- All particles are axially symmetrical.

Equation (13) may be modified to various frequencies band (up to W band) by substituting appropriate dielectric permittivities (e.g., given in Table 1). The signal attenuation (dB/km) versus frequency for four different values of visibility at particle radius equal to 50 μm has been plotted in Figures 2, 3, 4, 5, 6 and 7 at S, X, Ku, K, Ka and W-bands respectively.

## 6. COMPARISON WITH MEASURED DATA

Measurement in Khartoum-Sudan on September 1, 2007 shows attenuation 0.67 dB per kilometre observed by the author on 15 km link at 13 GHz (Ku band). The duststorm produced a visibility smaller than 50 m. The predicted value found by the Ku-band specific attenuation formula is 0.55 dB per kilometre for the same visibility assuming dust particle radius equal to 50 μm.

In the course of measurements, Alhaider and Ali [18] recorded several duststorms during 1987 in the city of Riyadh, Saudi Arabia. The duststorm observed by visibility reduction was measured by using

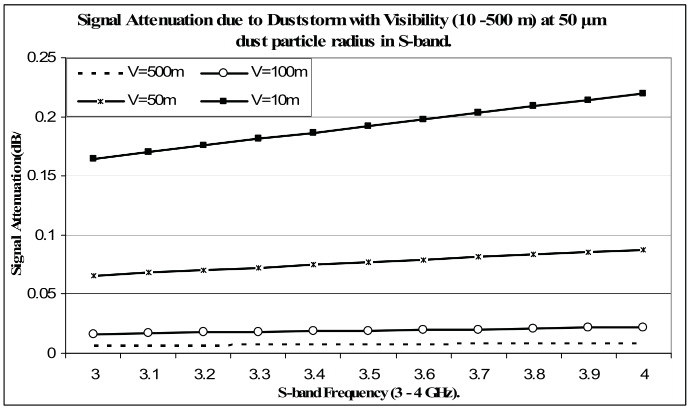

**Figure 2.** Signal attenuation (dB/km) vs frequency at S-band.

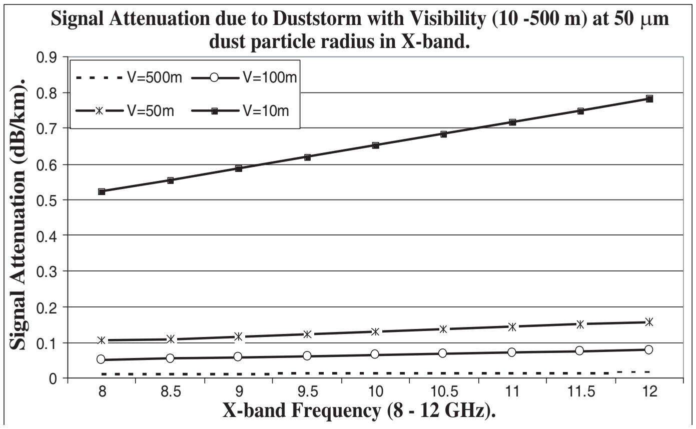

**Figure 3.** Signal attenuation (dB/km) vs frequency at X-band.

**Table 1.** Listing of dielectric constants at various frequencies measured by the indicated investigators.

| Frequency Band | $\varepsilon'$ | $\varepsilon''$ | Reference |
|---|---|---|---|
| S-band | 4.56 | 0.25 | Ghobrial [22] |
| X-band | 5.73 | 0.42 | Ghobrial and Sharief [23] |
| Ku-band | 5.5 | 1.3 | Ruike [24] |
| K-band | 5.1 | 1.4 | Ruike [24] |
| Ka-band | 4 | 1.33 | Ruike [24] |
| W-band | 3.5 | 1.64 | Ruike [24] |

**Table 2.** Comparison between measurements and calculations of attenuation values using Goldhirsh model and proposed model at 40 GHz.

| Obs. No. | Visibility (km) | Measured Value (dB/km) | Predicted Value by Goldhirsh Model (dB/km) | Predicted Value by Proposed Model (dB/km) |
|---|---|---|---|---|
| 1 | 0.625 | 0.14 | 0.02 | 0.13 |
| 2 | 1.25 | 0.1 | 0.01 | 0.064 |
| 3 | 1.42 | 0.071 | 0.007 | 0.06 |
| 4 | 3.75 | 0.05 | 0.003 | 0.021 |
| 5 | 5.56 | 0.036 | 0.002 | 0.014 |

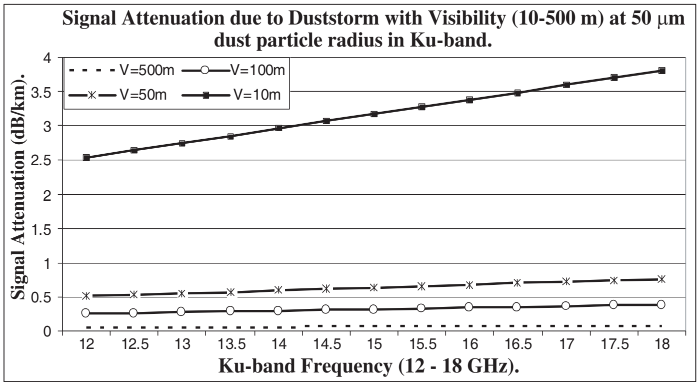

**Figure 4.** Signal attenuation (dB/km) vs frequency at Ku-band.

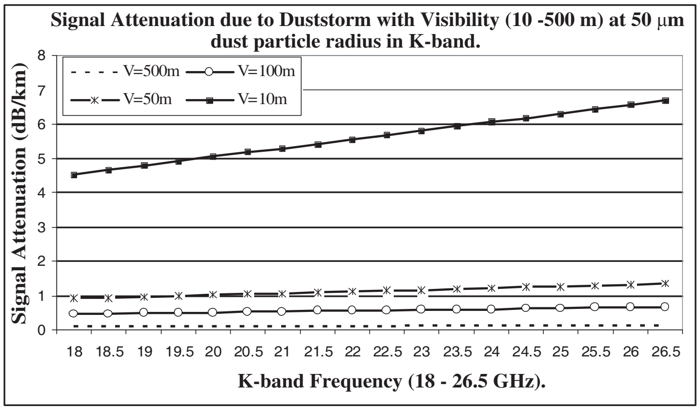

**Figure 5.** Signal attenuation (dB/km) vs frequency at K-band.

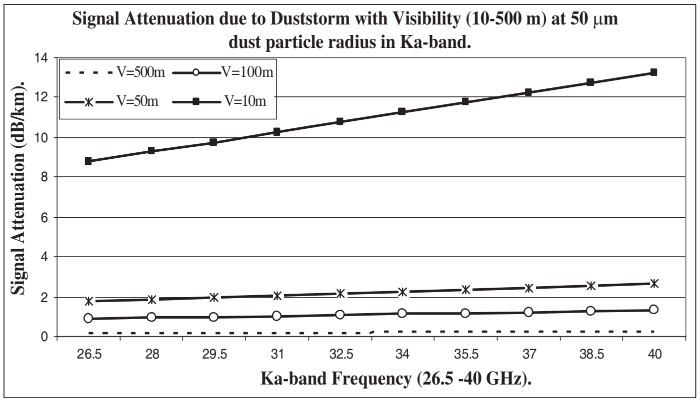

**Figure 6.** Signal attenuation (dB/km) vs frequency at Ka-band.

the known marked distance method. The measurements run over 14 km microwave link at 40 GHz. The millimeter wave transmitters and receivers are placed at 100 and 25 m above ground, respectively.

Calculated attenuation values for different values of visibility at 40 GHz are given in Table 2 together with attenuation measured values observed in Saudi Arabia. The predicted values are calculated by the proposed mathematical model and Goldhirsh model. Comparison between measured and calculated values at 40 GHz that appears in Figure 8 shows optimistic agreement unlike the predicted values from Goldhirsh model.

Table 2 gives the result of measurements and calculations for

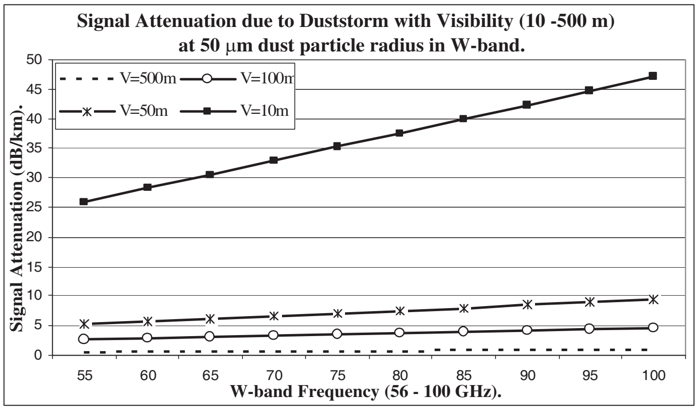

**Figure 7.** Signal attenuation (dB/km) vs frequency at W-band.

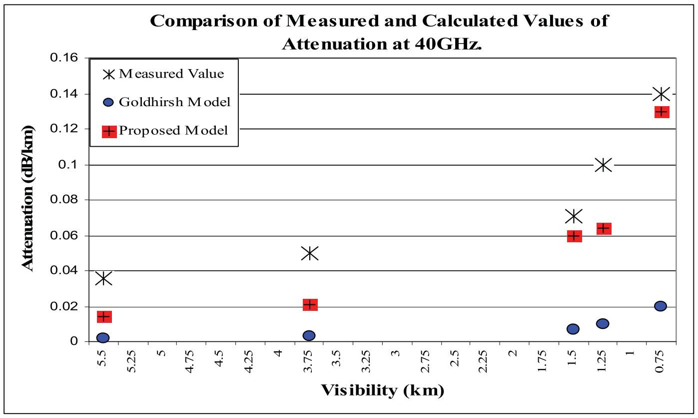

**Figure 8.** Comparison between measured and calculated attenuation.

different values of visibility at 40 GHz. Dust particle radius equal to 50 µm is considered in the calculation according to measurements in Riyadh area [19].

Several duststorms were measured by Alhaider and Ali during 1987 in Saudi Arabia on 14 km microwave link at 40 GHz (Ka-band) [18]. Table 1 gives the result of measurements and calculations for different values of visibility at 40 GHz. The predicted values are found by the mathematical attenuation model using the Ka-band specific attenuation formula. Comparison between measured ($A_m$) and calculated ($A_c$) values appeared in Figure 8 shows close agreement. Dust particle radius equal to 50 µm is considered in the calculation according to measurements in Riyadh area [19].

Data measured in Sudan and Saudi Arabia at different microwave links with different frequencies for several duststorms show close agreement with the predicted values found by the mathematical attenuation model.

## 7. CONCLUSIONS

The work presented in this paper represents a considerable advance in our understanding of the role of duststorms in the microwave signal attenuation. The approach used to investigate the above objective is by introducing mathematical models to predict the microwave signal attenuation due to duststorms and validating the model by direct measurement of the received signal level on the operating microwave links.

A mathematical model has been developed to deal with all possible ratios of dust particle diameter to wavelength and predict attenuation in microwave band with high reliability using Mie solution of Maxwell's equations for the scattering of electromagnetic wave by dielectric spherical particles. In this proposed model the term visibility is applied to denote the degree of duststorm density instate of total number of dust particles.

The particle radius and dielectric constant of dust vary according to local rock sources and conditions. The proposed mathematical model shows that the microwave signal attenuation due to duststorm depends on visibility, frequency, dust particle radius and dielectric constant. There are directly proportional relationship between the attenuation values and the frequency, dust particle radius and dielectric constant, while it has inversely proportional relationship to visibility values. The predicted values from the mathematical model, which are compared with the measured values observed in Saudi Arabia and Sudan show relatively optimistic agreement.

## REFERENCES

1. N'tchayi Mbourou, G., J. J. Bertrand, and S. E. Nicholson, "The diurnal and seasonal cycles of wind-borne dust over Africa north of the equator," *Journal of Applied Meteorology*, Vol. 36, 868–882, 1997.
2. Williams, K. and R. Greeley, "Radar attenuation by sand: Laboratory measurements of radar transmission," *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 39, No. 11, Nov. 2001.

3. Olsen, R. L., et al., "The $aR^b$ relation in the calculation of rain attenuation," *IEEE Transactions on Antennas and Propagation*, Vol. 26, No. 2, Mar. 1978.
4. Li, L., P. Kooi, M. Leong, T. Yeo, and M. Gao, "Microwave attenuation by realistically distorted raindrops: Part I — Theory," *IEEE Transactions on Antennas and Propagation*, Vol. 43, No. 8, Aug. 1995.
5. Rogers, R. R., "Statistical rainstorm models: Their theoretical and physical foundations," *IEEE Transactions on Antennas and Propagation*, July 1976.
6. Crane, R. K., "Prediction of attenuation by rain," *IEEE Trans. Commun.*, Vol. 29, 1717–33, 1980.
7. Jain, Y. M. and P. A. Watson, "Attenuation in melting snow on microwave and millimeter wave terrestrial radio link," *Electron. Lett.*, Vol. 21, No. 2, 68–69, 1985.
8. Srivastava, S. K. and B. R. Vishwakarma, "Cross-polarization and attenuation of microwave/millimeter wave propagation in storm layer containing sand, silt and clay as dust constituents," *IE(I) Journal-ET*, Vol. 84, Jul. 2003.
9. Ruike, Y., W. Zhensen, and Y. Jinguang, "The study of MMW and MW attenuation considering multiple scattering effect in sand and dust storms at slant paths," *International Journal of Infrared and Millimeter Waves*, Vol. 24, No. 8, Aug. 2003.
10. Yu, Z., Z. Peng, P. Liu, and X. Wu, "The influence of charged sand particles on the external insulation performance of composite insulators in sandstorm condition," *IEEE 8th International Conference on Properties and Applications of Dielectric Materials*, Jun. 2006.
11. Collin, R. E., *Antenna & Radiowave Propagation*, McGraw-hill, International Edition, Singapore, 1985.
12. Crane, R. K., "Propagation phenomena affecting satellite communication systems operating in the centimeter and millimeter wavelength bands," *Proc. IEEE*, Vol. 59, No. 2, 173–88, 1971.
13. Oguchi, T., "Electromagnetic wave propagation and scattering in hydrometeors," *Proceedings of the IEEE*, Vol. 71, No. 9, Sep. 1983.
14. Chu, T. S., "Effects of sandstorms on microwave propagation," *Bell System Technical Journal*, Vol. 58, No. 2, Feb. 1979.
15. Goldhirsh, J., "Attenuation and backscatter from a derived two-dimensional duststorm model," *IEEE Trans. Antennas Propagation*, Vol. 49, No. 12, 1703–1711, 2001.
16. Ishimaru, A., *Wave Propagation and Scattering in Random Media*,

IEEE, N.Y., 1997.

17. Vishvakarma, B. R. and C. S. Rai, “Limitations of rayleigh scattering in the prediction of millimeter wave attenuation in sand and dust storms,” *Geoscience and Remote Sensing Symposium, IEEE Inter.*, 1993.
18. Alhaider, M. A. and A. A. Ali, “Experimental studies on millimeterwave and infrared propagation in arid land: The effect of sand storms,” *Sixth International Conference on Antennas and Propagation ICAP*, 1989.
19. Ahmed, et al., “Airborne dust size analysis for tropospheric propagation of millimetricwaves into duststorms,” *IEEE Transactions on Geoscience and Remote Sensing*, Vol. GE-25, No. 5, Sep. 1987.
20. Crane, R. K., “Propagation phenomena affecting satellite communication systems operating in the centimeter and millimeter wavelength bands,” *Proceedings of IEEE*, Vol. 59, No. 2, 173–188, 1971.
21. Williams, K. and R. Greeley, “Radar attenuation by sand: Laboratory measurements of radar transmission,” *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 29, No. 11, Nov. 2001.
22. Ghobrial, S. I., “The effect of sand storms on microwave propagation,” *Proc. Nat. Telecommun. Conf.*, Vol. 2, Proc. No. CH1539-6/80/0000-0216, 43.5.1–43.5.4, Houston, TX, 1980.
23. Ghobrial, S. I. and S. M. Sharief, “Microwave attenuation and cross polarization in dust storms,” *IEEE Trans. Antennas Propagat.*, Vol. AP-35, 418–425, Apr. 1987.
24. Ruike, Y., W. Zhensen, and Y. Jinguang, “The study of MMW and MW attenuation considering multiple scattering effect in sand and dust storms at slant paths,” *International Journal of Infrared and Millimeter Waves*, Vol. 24, No. 8, Aug. 2003.