Airborne Dust Size Analysis for Tropospheric Propagation of Millimetric Waves into Dust Storms

ABOBAKR S. AHMED, SENIOR MEMBER, IEEE, ADEL A. ALI, MEMBER, IEEE, AND MOHAMMED A. ALHAIDER, SENIOR MEMBER, IEEE

***Abstract*—This paper presents a study of five dust storms that occurred in Riyadh together with their effect on millimeter-wave propagation. Meteorological parameters are given and airborne-dust's permittivity is estimated using relative humidity data. For large particles, the size distribution and its height dependence are investigated experimentally and the findings are presented as a functional relationship. Based on actual measurements and analysis, attenuation at 37 GHz is calculated using a newly derived expression in terms of optical visibility as a storm parameter. It is found that the fitted probability distributions are best described by normal or lognormal and vary with dust-storm conditions. The average effective sizes and the 37-GHz attenuation decreases with the increase of antenna height following a power law.**

I. Introduction

The IMPORTANCE of detection and evaluation of dust storms using remote sensing stems from the fact that arid and semiarid regions comprise approximately one third of the earth's surface. The complexity of modeling the effect of a dust storm is increased due to the complicated interaction of factors affecting the mechanism of dust storms [1]. The low rainfall rate in arid regions suggests the use of millimeter-wave radar for dust storm detection since long propagation (of the order of 10–30 km) is feasible. However, unlike precipitation, there is still uncertainty in many areas of predicting the effect of millimeter-wave propagation into a dust storm, such as particle size distribution. Most size distribution data in the literature [2] are concerned with the low particle size range (10 μm), which is important for pollution [3] or optical extinction studies [1], [4], [5]. At millimeter wave, the larger particle size (10–100 μm) has a profound effect on propagation; however, such data are lacking or uncertain. For example, Chu [6] assumed an unrealistic equisized distribution and Ghobrial [7] reported an exponential distribution for only one sample.

Based on actual measurements of sand-storm parameters in Riyadh, Saudi Arabia, this paper presents dust-storm data relevant to millimeter-wave propagation. First, the functional relationship of the excess attenuation due to dust storms is summarized and used to derive a relation between optical visibility, particle size, and attenuation at millimeter-wave length. It is shown that attenuation varies as the ratio of the third to second moments of the particle size. An estimate of dust's permittivity at 37 GHz as a function of relative humidity is presented as well. Measured size distributions are analyzed and best fit functions are found. The height dependence of average and effective radii is discussed. Attenuation at 37 GHz based on visibility, size distribution, and relative humidity is addressed and its potential for remote sensing of dust storms is discussed.

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The authors are with the College of Engineering, King Saud University, Riyadh 11421, Saudi Arabia.

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II. Relation of Dust Storm Attenuation, Particles Effective Radius and Visibility

The effects of dust storms on wave propagation are estimated generally by solving the forward scattering amplitude function of a single particle. The solution may be carried out using the Rayleigh approximation or exact Mie equations or numerical methods. The method depends largely on the factor kr (where k is the wavenumber $2\pi/\lambda$ and r is the particle radius). For randomly distributed particles in air, the single scattering approximation or multiple scattering theory is applied according to the concentration of the particles in air [8]. For dust-storm airborne dust, sizes are usually less than approximately 50 μm, with a typical refractive index $m \cong 1.5-j0.005$ [9] and the number concentration N is less than $10^8/\mathrm{m}^3$ [10]. These values—at millimeter-wave frequencies—satisfy Rayleigh and single-scattering approximations ($kr << 0.3$, $k|m|r << 1$ and volume fraction of particles $v_f <<$ 1 percent, respectively [8], [11]). It can be shown [3] that the specific attenuation α (in decibels per kilometer) of millimeter waves—even in a severe dust storm—is expressed by

$$\alpha = 1.029 \times 10^6 \left(\frac{N}{\lambda}\right)(G) \sum_i P_i r_i^3 \qquad (1)$$

where

- λ is the wavelength (in meters),
- $G = \epsilon''/[(\epsilon' + 2)^2 + \epsilon''^2]$,
- $\epsilon^* = \epsilon' - j\epsilon''$, the airborne dust's relative permittivity, and
- P_i is the probability that a particle of radius r_i (in meters) lies within the range Δr_i, i.e., $P_i = \Delta n_i/N$

where Δn_i is the number of particles with radius r_i in the range Δr_i.

The above equation requires data for the number concentration N (or volume fraction), which statistically is very scarce and difficult to measure accurately. On the other hand, statistical information on dust-storm visibility is available, and it can be measured simply by an unaided person. Therefore, we express attenuation α in terms of easily measured dust parameters. Assuming that at optical wavelength the intensity decays exponentially with distance [5], the visual range V_0 is defined quantitatively by

$$\alpha_0 = 4.343 \frac{\ell_n \left| \frac{1}{C} \right|}{V_0} \tag{2}$$

where α_0 is dust-storm attenuation at optical wavelength and C is the contrast ratio between a black object and a bright background. However, the value of C is not standardized worldwide, i.e., $C = 0.02$ [4] or 0.031 [6], for which

$$\alpha_0 = 15/V_0. \tag{3}$$

At the same time, α_0 is related to N and P_i [11] by

$$\alpha_0 = (4.343 \times 10^3) 2\pi N \sum_i P_i r_i^2 \text{ dB/km}. \tag{4}$$

Eliminating α_0 and substituting in (1), we get

$$\alpha = 566.97 \left(\frac{1}{V_0}\right) \left(\frac{r_e}{\lambda}\right) (G) \tag{5}$$

where

$$r_e = \frac{\sum_i P_i r_i^3}{\sum_i P_i r_i^2} \tag{6}$$

is the ratio of third to second moments of size distribution, which can be interpreted as the effective particle size in a dust storm, and the ratio (r_e/λ) is the effective size index. The permittivity of airborne dust is estimated from available soil data, and the size distribution is measured as explained in the next paragraph.

Equation (5) is an alternative way of predicting the excess attenuation due to dust storms when the storm is gauged by optical visibility. This information is usually available in meteorological records data. Hence, the attenuation due to a dust storm can be found, provided the availability of r_e and G. It may be noted that the use of (1) for attenuation prediction requires knowledge of the particle number concentration, rather than visibility, which may not be available in standard meteorological data.

III. Estimate of Airborne-Dust's Permittivity

A survey of the published dielectric constants of moist soils has revealed the lack of such data at frequencies in excess of 37 GHz. However, direct application of soil permittivity to predict atmospheric propagation effects due to dust storms [12] is unjustified. It has been claimed [13] that the gravimetric moisture uptake $mp\%$ (where mp is the percentage weight of moisture in the airborne particle) by dust does not exceed 9 percent at relative humidity higher than 90 percent. Assuming a linear relationship between $mp\%$ and $RH\%$, the atmospheric dust permittivity ϵ^* at certain $RH\%$ can be estimated from the permittivity of sandy clay loam ϵ_s^* published by [14] for 37 GHz and different moisture contents.

IV. Measurement of Size Distribution

In the preceding section, the relation between specific attenuation and size distribution is established. To measure the size distribution during dust storms, samples of dust are collected using passive collectors [15], which has the advantage of collecting a wide range of particle sizes since no limiting filters are used. To enable automated and accurate size analysis, a sedimentation technique is employed using the Cahn electrobalance system. The system consists of a sensitive electrobalance (0.05-μg sensitivity), a sedimentation accessory, a controlling unit, and a chart recorder as shown in Fig. 1. The collected dust sample is dried and a slurry is prepared using a few drops of distilled water. About 100 ml of diluted slurry is boiled to remove air bubbles and then stirred to get a homogeneous suspension [16]. In accordance with Stokes' law, solid particles of density ρ_s settle under gravity g in water of height h and dynamic viscosity η through a time t_i related to particle radius r_i as

$$t_i = \left(\frac{0.3 h\eta \times 10^8}{(\rho_s - 0.99) g}\right) \left(\frac{1}{2r_i}\right)^2 \text{ min}. \tag{7}$$

Substituting for the constants of the system, the time of settling is related to particle radius as

$$r_i = \frac{1}{2} \sqrt{\frac{3993.6}{t_i}} \ \mu\text{m}. \tag{8}$$

The fraction weight Δw_i is calculated from a chart record of accumulated settled weight M_i viz elapsed time t_i and total sample weight M_t using Oden's equation [17]

$$w_i = \frac{1}{M_t} \left[M_i - t_i \frac{\Delta M_i}{\Delta t_i} \right]. \tag{9}$$

For mean interval $\bar{r}_i$ and fraction weight Δw_i, the number of particles (Δn_i) is

$$\Delta n_i = \frac{\Delta w_i}{\rho_s \frac{4}{3}\pi (\bar{r}_i)^3}. \tag{10}$$

The probability density function (PDF)$_i$ is the fraction of the number of particles $(\Delta n_i / \Sigma \Delta n_i)$ per unit radius interval Δr_i, so that Σ (PDF)$_i$ = 1 over the range of r_i, i.e.

$$(\text{PFD})_i = \frac{P_i}{\Delta r_i} = \left(\frac{\Delta n_i}{\sum \Delta n_i}\right) \left(\frac{1}{\Delta r_i}\right) \mu\text{m}^{-1}. \tag{11}$$

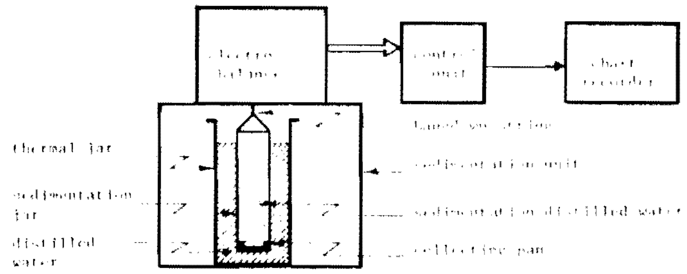


Fig. 1. Block diagram of Chan electrobalance with sedimentation unit, control unit, and chart recorder.

TABLE I
METEOROLOGICAL PARAMETERS AND ESTIMATED RELATIVE PERMITTIVITIES OF DUST STORM EVENTS IN RIYADH

Duststorm		Meteorological Parameters							Estimated Permittivities		
Event	Date (L T)	ws (m/s)	wd (°)	p (mb)	e (mb)	t (°C)	RH (%)	V_0 (km)	mp (%)	$\epsilon^*=\epsilon'-j\epsilon''$	G
I	23.3.85 (19–01)	18	270	956	4.3	29	90	1.6–2.0	9	3.2–j0.8	0.0289
II	22.4.85 (15–15.30)	16.5	270	956	4.8	28	70	1.6–2.0	7	3.0–j0.4	0.0159
III	23.4.85 (16–18)	8.2	270	956	4.8	36	80	5.0–6.0	8	3.0–j0.4	0.0159
IV	09.2.86 (17–18)	18	020	948	3.6	19	98	3.0–4.0	8.8	3.2–j0.8	0.0289
V	25.3.86 (18.50–23)	20.6	350	943	6	32	37	0.6–1.0	3.7	2.8–j0.2	0.0086

LT : local time, ws, wd : wind velocity and direction.
P, e: barometric and vapour pressure. t : temperature.
RH : relative humidity. V_0 : optical visibility.
mp : particle moisture uptake.
ϵ^* : particle relative permittivity. $G : \epsilon''/(\epsilon'+2)^2 + \epsilon''^2$

Although Stokes' law is usable for 1 μm $\leq 2r_i \leq$ 100 μm, it is most accurate for the range 10 μm $\leq 2r_i \leq$ 60 μm and the accuracy is better than 2 percent [17].

Dust samples are carefully poured into the sedimentation column to settle down against the distilled water viscosity. Larger particles reach the weighing pan faster according to (8), to be registered by the sensitive electrobalance. The accumulated settled weight M_i is automatically recorded vis t_i, and $(\mathrm{PDF})_i$ is found using (8)–(11).

V. RESULTS AND DISCUSSIONS

Table I summarizes measured meteorological parameters during five dust storms that occurred in Riyadh, Saudi Arabia. Date, local time *LT*, extreme values of wind velocity and direction (*ws* and *wd*), pressure *P*, temperature *t*, relative humidity *RH*, mean vapor pressure *e*, and range of visibility V_0 are shown. The estimated atmospheric moisture uptake of dust particles, the permittivity, and the calculated parameter *G* are also given. Generally, the parameters vary from storm to storm.

Fig. 2(a)–(e) shows the measured probability density function $(\mathrm{PDF})_i$ and the corresponding best fit function for the 16 samples. The tested functions are lognormal (*LN*), normal (*N*), exponential (*E*) and power law (*P*). Using least squares method of fitting, it is found that, out of the 16 samples, 14 are best described by normal and lognormal functions, while the remaining two samples are best described by power law. For the same event, the particle-size distributions are found to vary with height as well. Our finding of normal and lognormal distributions is in agreement with [3] and [18]. However, the exponential distribution employed by other investigators [7], [12] does not describe our samples adequately. This may be attributed to the dependence of the size distribution on the geographical location and storm conditions. In any case, it is evident that no single size distribution can be applied globally. The dependence of the fitted distribution of dust-

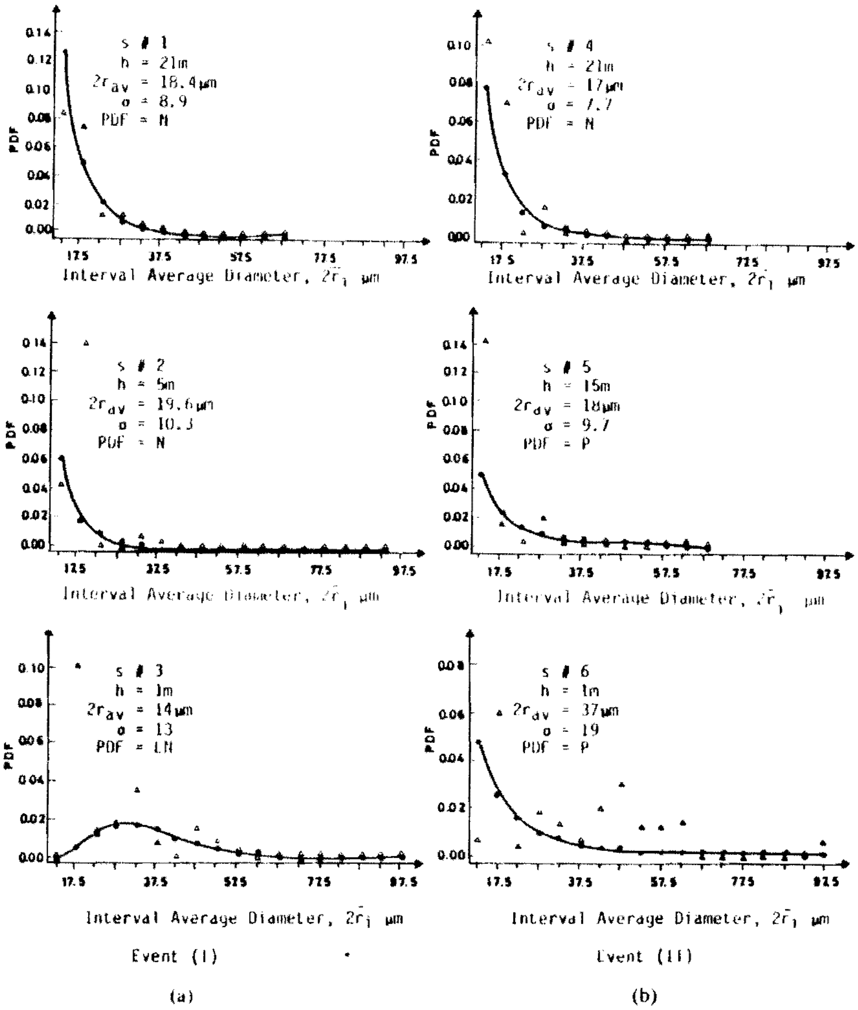


Fig. 2. Particle size distribution at different heights for five dust storms in Riyadh (Events I to V). s#: sample number; h: height; σ: standard deviation; PDF: probability density function; r_{av}: average radius; r_i: radius of index i; N: normal, LN: lognormal; P: power law; Δ: measured data; •: fitted data. (Continued on page 598.)

storm parameters is confirmed by [19]. Moreover, it has been claimed [2] that the shape of the size distributions of wind erosion aerosols ($2\ \mu m < r < 10\ \mu m$) is fairly constant with wind speed. This suggests that different particle modes behave differently during a dust storm. Particles in the saltation mode ($10\ \mu m < r < 100\ \mu m$) fall down faster than the suspension mode ($1\ \mu m < r < 10\ \mu m$), which tend to reach a constant distribution with wind speed [1], [18].

In Table II, the size distribution analysis and percentage decrease of attenuation with height are summarized. It is shown that the average and effective radii decrease with the height increase above ground. This variation can be described by a power law as shown in Fig. 3

$$r_{av} = r_{0a}\left(\frac{h}{h_0}\right)^{-\gamma_a}, \qquad \gamma_a = 0.15 \tag{12}$$

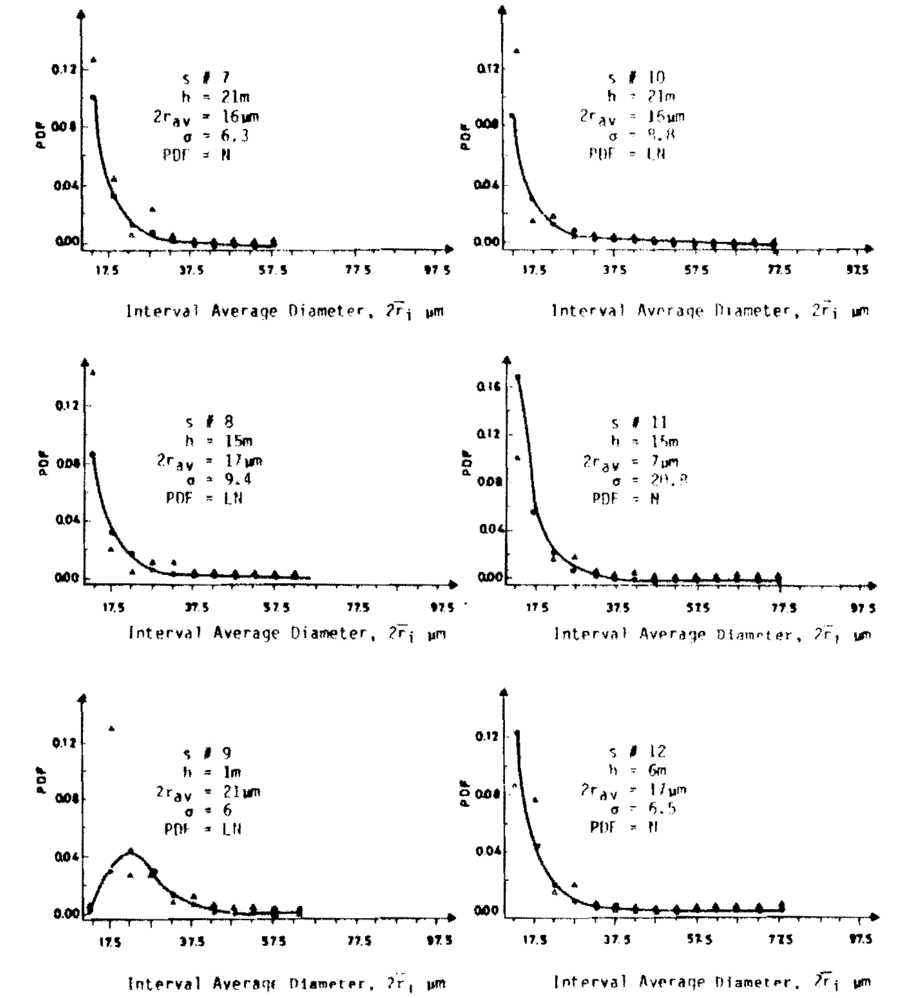
$$r_{ae} = r_{0e}\left(\frac{h}{h_0}\right)^{-\gamma_e}, \qquad \gamma_e = 0.04 \tag{13}$$

where r and r_0 are radii at heights h and h_0, respectively. It is interesting to note that a similar power law has been found for the variation of aerosol concentration N with height [2]

$$N = N_0\left(\frac{h}{h_0}\right)^{-\Gamma}, \qquad \Gamma > 0.29 \tag{14}$$

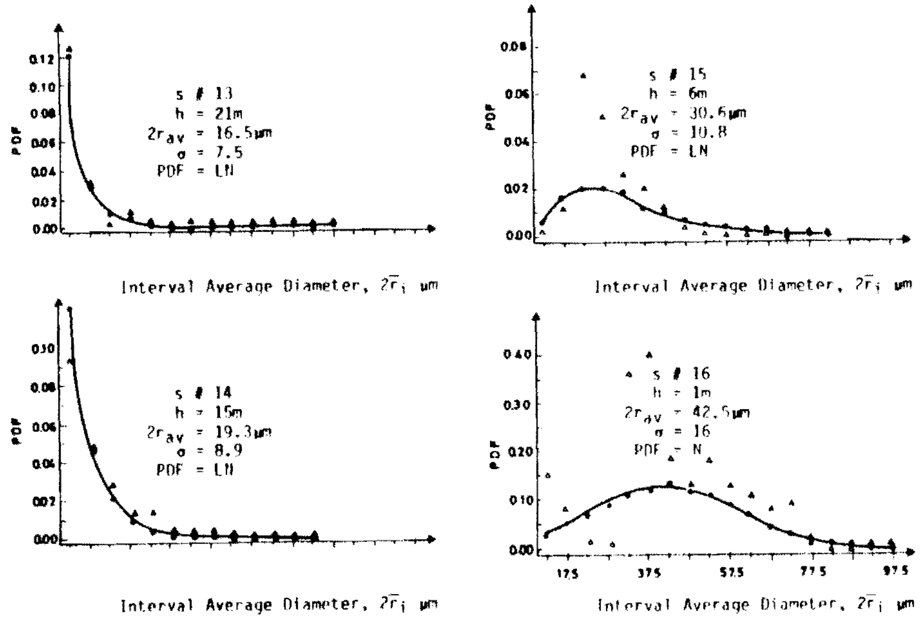
where Γ is a constant that depends on a particle's sedimentation and friction velocities.

Fig. 4 shows the variation of calculated attenuation A in decibels with height h, visibility V_0, and relative humidity $RH\%$ for a 50-km hop and 37 GHz using (5). Generally, the variation of A with h follows a power law similar to the dust-size variation. The rate of the decrease of A with the h increase may be of the order of 20-percent dB for a 10-m increase in height. The relative influence of V_0 and $RH\%$ on attenuation can be interpreted by comparing events I and II, which reveal that relative humidity has a dominating effect on A for a moderate dust storm ($0.5 < V_0 < 1.5$ km). Comparing events III or IV with



Event (III)
(c)

Event (IV)
(d)



Event (V)
(e)

Fig. 2. (*Continued.*)

TABLE II
DUST SIZE ANALYSIS AND PERCENT DECREASE OF ATTENUATION VERSUS HEIGHT FOR FIVE DUST STORM EVENTS

Dust-storm event	Dust size analysis			% decrease of attenuation with height	Height
	PDF	r_{av} (μm)	r_e (μm)	% (dB)	h (m)
I	LN	9.2	15.45	34%	21
	N	9.8	19.9	15%	15
	LN	14.0	24.0	-	1
II	N	8.5	13.2	53%	21
	P	9.0	15.7	44%	15
	P	18.5	28.0	-	1
III	N	8.0	11.4	31%	21
	LN	8.5	15.5	11%	15
	LN	10.5	16.3	-	1
IV	LN	7.2	10.0	19%	21
	N	7.5	11.8	15%	15
	N	8.5	12.3	-	6
V	LN	8.3	13.0	51%	21
	LN	9.2	14.6	45%	15
	LN	15.3	19.8	26%	6
	N	21.3	26.8	-	1

LN : Lognorma, N : normal, p : power.
PDF : Probability density function.
r_{av} : average particle radius.
r_e : effective radius.

V indicates that visibility has more influence than *RH%* for severe dust storms. The relatively low attenuation at 37 GHz suggests the feasibility of using millimeter-wave radar for tropospheric detection of dust storms over large distances (>20 km) and near ground. The proximity of typical dust storms to the ground is considered one of the difficulties of automatic detection. Moreover, higher frequency terrestrial radar (e.g., 95 GHz) in the atmospheric second window appears to be promising. Further studies are needed for comparison with satellite techniques of dust-storm remote sensing [20].

VI. CONCLUSIONS

The attenuation of millimeter waves in dust storms varies with optical visibility, the particles' permittivity, and the ratio of third to second moments of the airborne size distribution. Measurements during five dust storms in Riyadh reveal that the size distributions of large particles (10–100 μm) vary with height above ground and with dust-storm conditions. Analysis of measured distributions shows that normal and lognormal functions fit more adequately than power law or exponential functions. A de-

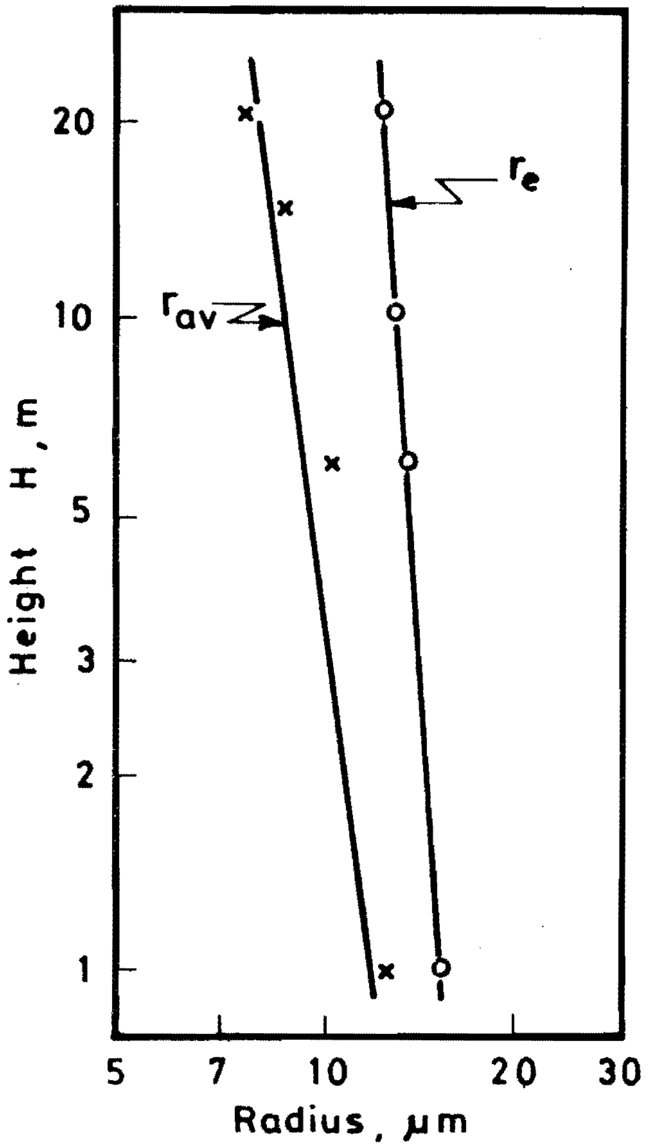


Fig. 3. Height dependence of the particle's average and effective radii, r_{av} and r_e, respectively.

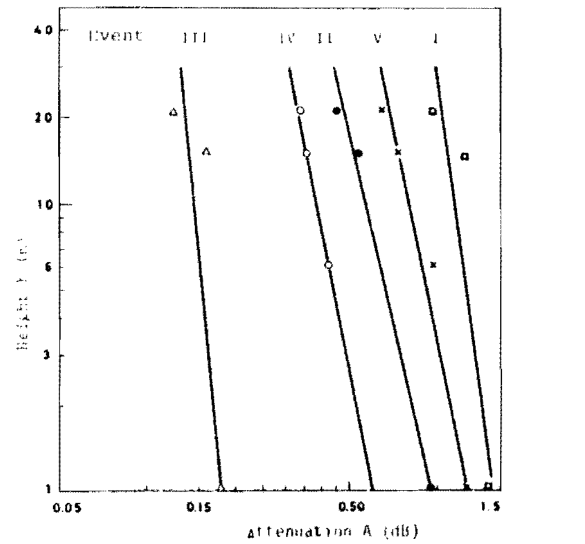


Fig. 4. Height dependence of attenuation A (in decibels) at 37 GHz for five dust storms (I to V) over 50-km hop.

creasing power law is found to relate the average and effective radii of dust with height increases, which is similar to other findings of the variation of concentration of aerosols, but with a different exponent. Millimeter-wave attenuation varies with antenna height according to a power law as well. Remote sensing of dust storms using millimeter-wave radar seems to be a promising approach over long distances and near ground.

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Abobakr S. Ahmed (M'77–SM'81) received the B.Sc. degree from Cairo University, Cairo, Egypt, in 1961 and the M.Sc. degree from Al-Azhar University, Cairo, in 1973.

Since 1961, he has been working in the electronics and microwave industries. In 1975, he joined the Research Center, College of Engineering, King Saud University, where he is currently involved in research including millimeter-wave propagation, satellite communication, and dielectrics.

Adel A. Ali (M'82) was born in Alexandria, Egypt. He received the B.Sc. degree in electrical engineering from Alexandria University in 1967, and the M.Sc. and Ph.D. degrees from the University of Manitoba, Canada, in 1973 and 1976, respectively, both in electrical engineering.

From 1976 to 1978, he was a Transmission and Special Services Engineer with Manitoba Telephone Systems, Winnipeg, Canada. Since 1978, he has been with the Electrical Engineering Department, King Saud University, where he is now an Associate Professor. He also served as a consultant to the Ministry of PTT, Saudi Arabia. His research interests include communication theory, microwave propagation, and coding.

Mohammed A. Alhaider (S'71–M'82–SM'84) received the B.Sc. degree from King Saud University, Riyadh, Saudi Arabia, in 1968 and the M.Sc. and Ph.D. degrees from Carnegie-Mellon University, Pittsburgh, PA, in 1972 and 1977, respectively, all in electrical engineering.

Since 1977 he has been with the College of Engineering, King Saud University, where he is currently an Associate Professor and Supervisor of the DPC at KSU. His areas of interest include optical and microwave communications and acoustooptic interactions in thin films.