Propagation Through Martian Dust at 8.5 and 32 GHz

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Independent studies of attenuation of X-band (8.5 GHz) and Ka-band (32 GHz) radio signals when traversing Martian dust were carried out by the authors. These analyses turned out remarkably similar. The computational method is essentially that of T. S. Chu but uses observed optical depth at 0.67 microns rather than "visibility" as the measure of optical attenuation from which to derive the microwave attenuation. An awkwardness in the approach is that the size distribution of Martian dust particles is not well known, but the mean is probably around 4 microns, whereas in the terrestrial case it is nearer 10 microns. As a consequence, there will be a larger tail of particles still in the Mie regime in the Martian case as compared to the terrestrial one. The computational error will, therefore, be somewhat larger for Martian than Earth-bound dust. Fortunately, the indicated attenuations are small enough for the worst case (1.3 dB at 32 GHz) that the error is academic.

I. Introduction

This article makes use of the approaches and results of studies of terrestrial sand and dust storms for the rather analogous problem on Mars. Dust storms on Mars are, if anything, more impressive than on Earth. Typically, in spring in the southern hemisphere, dust storms will start, grow, move northward, and frequently encircle the globe. In 1971, there was a huge storm which obliterated the surface features of the entire planet.

II. Terrestrial Approach

In the case of the Earth, the most convenient yardstick for a dust storm is "visibility," which is defined as the distance at which a mark disappears against the background. According to Middleton (Ref. 12), at the distance of disappearance, the luminance L of the object has decreased to 0.031 of its initial value L_0. As luminance is a measure of power, this translates to: L/L_0 = 10 log 0.031 = 15.086 dB, which is usually shortened to 15 dB. An approach developed by Chu (Ref. 6), and used by Ansari and Evans (Ref. 1) and Goldhirsh (Ref. 8), incorporates the visibility V into the expression for microwave attenuation coefficient $A(2)$:

$$A(\lambda) = \frac{189}{V(\text{km})} \; \frac{r}{d} \left[\frac{3\epsilon_i}{(\epsilon_r+2)^2 + \epsilon_i^2} \right] \text{dB/km}$$

where

r = particle radius, m

ϵ = $\epsilon_r - j\epsilon_i$ = complex dielectric constant

λ = wavelength, m

As shown above, particles are assumed to be uniform in size and to have known permittivity. The development assumes single scatter. This is not bad at microwave, but the optical visibility limit is well into the multiple scatter regime.

Particle size distributions for four dust storms in Khartoum have been published by Ghobrial (Ref. 7), who finds particles with sizes ranging from 0.1 to 300 microns (0.0001 to 0.3 mm). Wind tunnel measurements (Ref. 9) indicate that 0.08 mm is the most likely size of particle to be picked up by wind from the Earth's surface.

III. Mars

Mars has long captured the public fancy as possibly the most hospitable planet, next to Earth, for life. This is not so unreasonable, as can be seen in Table 1. However, the temperature is considerably colder, the atmospheric pressure at the surface less than 1% that of the Earth, and the atmosphere almost totally lacking in oxygen (95.3% CO_2, 2.7% N_2, 1.6% argon and perhaps 0.13% O_2; Ref. 13). Mars' orbit around the sun is considerably more eccentric than that of the Earth (206.7×10^6 km at perihelion and 249.1×10^6 km at aphelion) with the result that the insolation is some 45% greater during perihelion (late spring in the southern hemisphere) than at aphelion (late spring in the northern hemisphere).

Mars has been visited by spacecraft from both the US and USSR as is seen in Table 2. The most recent visits were by the two US Viking missions, and the data presented here came largely from that source.

Martian dust storms tend to originate in the late spring or summer in the southern hemisphere when the Martian surface temperatures and the temperature gradients are highest. The greatest storm on record started in September of 1971 and became planetwide (Ref. 11). Great storms (planetary scale) occur once or twice each Martian year (Ref. 19). Quite typically, a storm will move northward and reach planet-encircling proportions and last several weeks. The dust has been reported as high as 50 km above the surface. Optical depths as great as 6 at 0.67 microns have been measured and a dust density scale height of 10 km proposed (Refs. 15 and 16). The size and permittivity of Martian dust remain controversial. Figure 1 portrays a particle density distribution (Ref. 10) typical of those found in papers published in the late 1970s. The mean of the particle radius is 0.4 microns. Also shown is the geometric cross-section distribution, $GN(r)$, which is more directly pertinent to extinction calculations. Recent workers have favored somewhat larger particles, around 2 microns (Ref. 19 and Footnote 1) or greater (Ref. 5). The favored substances for the dust are basalt and montmorillonitic clays. Tabulated dielectric constant at 50 microns (the longest wavelength available) for the latter is $2.18 - j0.14$.[1]

Water was detected in the soils at the two Viking Lander sites, but the integrated water in the Martian atmosphere does not exceed 100 precipitable microns (Ref. 4).

IV. Attenuation by Dust

A simple slab model of a Martian dust storm is shown in Fig. 2. The assumption is made that the reflected components of the electric field E_r and E_{tr} are much less than the transmitted component E_t ($E_t \gg E_r$, $E_t \gg E_{tr}$). We define a complex propagation constant K_c:

$$K_c = \beta - j\alpha \tag{1}$$

where

$$\beta = K_0 n_r = \frac{2\pi n_r}{\lambda_0} = \text{phase constant} \tag{2}$$

$$\alpha = K_0 n_i = \frac{2\pi n_i}{\lambda_0} = \text{attenuation constant} \tag{3}$$

and

$$n_i = n_r - j n_i = \text{complex refractive index}$$

$$K_0 = \frac{2\pi}{\lambda_0}$$

where

λ_0 = free-space wavelength

One can then write for the electric field (Ref. 2)

$$E = E_t(0, 1, 0) \exp \{j(\omega t - Kz)\} \tag{4}$$

where $E_t(0, 1, 0)$ is the complex amplitude of the transmitted plane wave with electric vector polarized in the y direction and travelling downward (positive z direction). Substituting (1) into (4) yields

$$E = E_t (0,1,0) \exp(-\alpha z) \exp\{j(\omega t - \beta z)\} \tag{5}$$

[1]R. A. West, Jet Propulsion Laboratory, private communication, 1986.

which may also be written

$$E = E_t(0,1,0) \exp\left(-\frac{1}{2}\tau\right) \exp\left\{ j\left(\omega t - \frac{2\pi z}{\lambda}\right)\right\} \quad (6)$$

where τ is the optical depth. The attenuation coefficient A in decibels is then given by:

$$A \text{ (dB)} = 8.686\ \alpha \text{ (nepers)} \quad (7)$$

$$A \text{ (dB)} = 8.686\ K_0 n_i \text{ dB/m} \quad (8)$$

$$\text{Attenuation from dust} = 4.343\tau \text{ dB} \quad (9)$$

A. Chu's Development

We now turn to the work of Chu (Ref. 6) who wrote a much quoted article on "Effects of Sandstorms on Microwave Propagation." Chu considered sand of radius 0.01 to 0.1 mm (10 to 100 microns) with dielectric constant 2.5 $(1 - j0.01)$ to 10 $(1 - j0.01)$. He invoked the Rayleigh approximation at microwave and the very large sphere approximation in the visual range. The attenuation coefficient α is defined as

$$\alpha = \int_0^\infty N(a)C(a)\, da \quad (10)$$

where

$C(a)$ = extinction coefficient

$N(a)$ = number density

a = particle radius

For sand of radius a

$$\alpha = 4.34 \left[\frac{S}{(4/3)\pi a^3}\right]\left(\pi a^2 Q_{ext}\right) = \frac{3.25 S Q_{ext}}{a} \text{ dB/m} \quad (11)$$

where $Q_{ext} = C/\pi a^2$ is the extinction efficiency, and $S = (4/3)\pi a^3 N$ is the fraction of the volume actually made up of sand. As the size of particles become large with respect to wavelength, Q_{ext} becomes asymtotic to 2 (Refs. 17 and 18):

$$Q_{ext} = 2, a >> \lambda \quad (12)$$

As can be seen in Fig. 3, if the sphere is at all conducting, the extinction becomes very close to 2 by the time $2\pi a/\lambda = 15$ or $a = 2.4\lambda$. Hence, in the case treated by Chu, if we take 0.6 microns for the wavelength of white light, any particle larger than 1.5 microns would meet the requirements of (12).

The question of multiple scatter needs to be raised. Van de Hulst (Ref. 18) suggests that whenever the optical depth exceeds 0.3 multiple scattering becomes a factor. In this case, the limit of visibility occurs at $\tau = 3.47$, well into the multiple scatter regime. However, this limit occurs at the point where a mark disappears into the background, and it can be argued that this is the coherent component that one is tracking and that single scatter still applies.

The introduction of (12) is done by combining (11) and (12) and solving for N:

$$N = \frac{\alpha_0 a}{6.5\ [(4/3)\pi a^3]} \quad (13)$$

where α_0 is the optical attenuation coefficient in dB/m.

The next step is to make use of an expression presented, but not derived, by Van de Hulst (Ref. 18) for the effective refractive index m of a scattering medium:

$$\bar{m} = 1 - iS(0)\, 2\pi N K^{-3} \quad (14)$$

where $S(0)$ is the forward scattering function, and K is the free space phase constant. In the Rayleigh regime $S(0)$ is given by

$$S(0) = iK^3\left(\frac{\epsilon - 1}{\epsilon + 2}\right)a^3 + \frac{2}{3}K^6\left(\frac{\epsilon - 1}{\epsilon + 2}\right)^2 a^6 \quad (15)$$

The second term is negligible for $\lambda >> a$ as is the case at radio frequencies. Substituting (13) and (15) into (14) and using the terminology of (1) through (9), the phase shift is given by

$$K(R_e\, \bar{m} - 1) = \frac{3K}{13}\alpha_0 a\left[R_e\left(\frac{\epsilon - 1}{\epsilon + 2}\right)\right]\left(\frac{180}{\pi}\right) \text{ deg/m} \quad (16)$$

and the attenuation coefficient becomes

$$K(\text{Im}\, \bar{m}) = \frac{3K}{13}\alpha_0 a\left[\text{Im}\left(\frac{\epsilon - 1}{\epsilon + 2}\right)\right](8.68) \text{ dB/m} \quad (17)$$

B. Application to the Martian Problem

For a uniform slab the total attenuation and total phase shift for the wave of relations (4) through (6) is obtained by multiplying (16) and (17) by z, the distance traversed. For total attenuation (17) becomes

$$K(\text{Im}\, \bar{m})z = \frac{3K}{13}(\alpha_0 z)\, a\left[\text{Im}\left(\frac{\epsilon - 1}{\epsilon + 2}\right)\right](8.68) \text{ dB/m} \quad (18a)$$

and, substituting 4.34τ for $\alpha_0 z$, we may write

$$K(\mathrm{Im}\,\bar{m}) = \frac{3K}{13}\tau a\left[\mathrm{Im}\left(\frac{\epsilon - 1}{\epsilon + 2}\right)\right](37.7)\ \mathrm{dB/m} \qquad (18b)$$

This relation (18b) now gives the microwave attenuation for uniform spheres of known radius a and dielectric constant ϵ for a slab of constant particle density N and agrees with Eq. (13) of Goldhirsh (Ref. 8). Martian dust undoubtedly follows some particle distribution such as shown in Fig. 1, but the uncertainty as to the mean size is such that the assumption of a single particle radius is as good as any. Similarly, the dielectric constant can only be guessed at, but can reasonably be bounded. The dust density probably follows an experimental decay with height, so the equivalent slab will be used.

C. Equivalent Slab for a Martian Dust Storm

Pollack (Ref. 15) has suggested a scale height for dust particle density, H_d, of 10 km. Assuming H_d is a constant over the region of interest, we may write

$$\int_0^\infty N_0 \exp\left(-\frac{h}{H_d}\right) dh = N_0 H_d \qquad (19)$$

where the right-hand side is obtained by performing the indicated integration; and N_0 is the surface density of the dust. Thus, it is seen that the Martian dust storm may be represented by a slab of height $H_d = 10$ km and density N_0. A spherical model of such a slab is shown in Fig. 4.

D. Calculation of Microwave Attenuation

Performing the indicated complex arithmetic on (18b) leads to

$$A = 54.62\,\frac{\tau a}{\lambda}\left[\frac{3\epsilon_i}{(\epsilon_r + 2)^2 + \epsilon_i^2}\right]\mathrm{dB} \qquad (20)$$

where $\epsilon = \epsilon_r - j\epsilon_i$ and a, the particle radius, and λ are in meters.

For zenith angles of 0° to 80° we use:

$$\tau = \tau_z \sec\theta, \quad \theta < 80^\circ \qquad (21)$$

For zenith angles greater than 80° we need to consider refraction effects. The Martian atmosphere is 95% CO_2; CO_2 at 0°C and 1 atmosphere and for white light has an index of refraction of 1.000450. In terms of refractivity $N = (n - 1)10^6$; this may be written

$$N(CO_2) = 121.3\,p(\mathrm{mb})/T(\mathrm{K}) \qquad (22)$$

If $p = 6$ mb and $T = 280$ K on the Martian surface, the surface refractivity is $2.6N$ units as compared to about 300 on the surface of Earth, and refractive bending will be a second-order effect and can be ignored. Using the geometry in Fig. 4 for zenith angles θ greater than 80° or elevation angles ϕ between 0° and 10°, the optical depth τ is

$$\tau = \frac{\tau_z}{H_d}\left\{\left[(H_d + r_0)^2 - (r_0 \cos\phi)^2\right]^{1/2} - r_0 \sin\phi\right\},$$

$$\text{for } \phi = 90^\circ - \theta < 10^\circ \qquad (23)$$

Shown in Fig. 5 is the zenith angle dependence for the "best guess" and "worst case" calculations using relations (20) and (23). Dust storms under the worst case scenario only become significant for ray paths nearly tangential to the surface of Mars. Shown in Fig. 5 is the dependence of attenuation on choice of particle radius and dielectric constant.

V. Discussion

Attenuation through Martian dust storms has been computed for 8.5 and 32 GHz one-way radio transmission for the maximum expected optical depth ($\tau = 6$). These are first-order calculations based on single scatter. Due to uncertainties in the Martian dust parameters – particle size distribution and dielectric constant – "best guess" and "worst case" situations have been selected. Attenuation, even at 32 GHz, will not be significant, except for rays almost tangential to the Martian surface.

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Table 1. Some physical properties of Earth and Mars

Property	Earth	Mars
1. Mean distance from sun, km × 10^6	149.6	227.9 $\begin{cases} 206.7 \\ 249.1 \end{cases}$
2. Period of revolution, days	365.28	687
3. Rotation period, hours	23.9344	24.6321
4. Equatorial diameter, km	12,756	6,787
5. Mass (Earth = 1)	1	0.108
6. Density (Water = 1)	5.5	3.9
7. Atmosphere	Nitrogen Oxygen	Carbon dioxide Nitrogen, Argon
8. Water vapor (integrated column), cm^2	2.2	0.001
9. Water content in surface	0 – 30%	~1%
10. Mean atmospheric pressure, mb	1013.25	6
11. Mean surface temperature, °C	22	–23
12. Mean particle size in dust storms (diam), microns	0.5 to 100	0.1 to 10
13. Real part refractive index (clay 8.5 GHz)	[2.5 + 0.5 (% H_2O)]	
14. Imaginary part refractive index (clay 8.5 GHz)	[0.02 + 0.15 (% H_2O)]	
15. Real part refractive index (clay 32 GHz)	[2.5 + 0.3 (% H_2O)]	
16. Imaginary part refractive index (clay 32 GHz)	[0.06 + 0.1 (% H_2O)]	

Notes: 1. Data for 1 to 8 from Ref. 14.
2. Values for 13 to 16 derived for data for clay from Table 1, Ref. 1.

Table 2. Spacecraft missions to Mars[a]

Mission	Arrival date	Type
United States		
Mariner 4	July 15, 1965	Flyby
Mariner 6	July 30, 1969	Flyby
Mariner 7	August 4, 1969	Flyby
Mariner 9	November 14, 1971	Orbiter
Viking 1	June 19, 1976	Orbiter/Lander
Viking 2	August 7, 1976	Orbiter/Lander
Soviet		
Mars 2	November 27, 1971	Orbiter/Lander
Mars 3	December 2, 1971	Orbiter/Lander
Mars 4	March 1974	Orbiter
Mars 5	March 1974	Orbiter
Mars 6	March 1974	Lander
Mars 7	March 1974	Lander

[a]From Ref. 3.

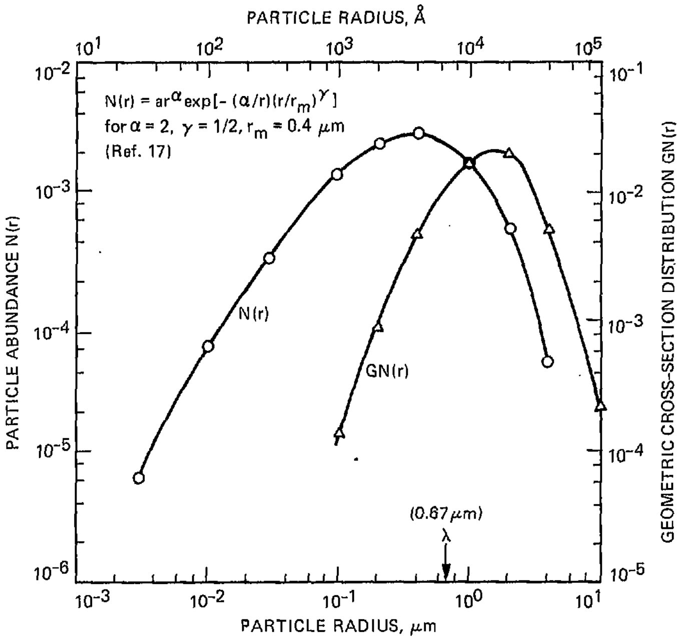

Fig. 1. Martian dust particle distribution

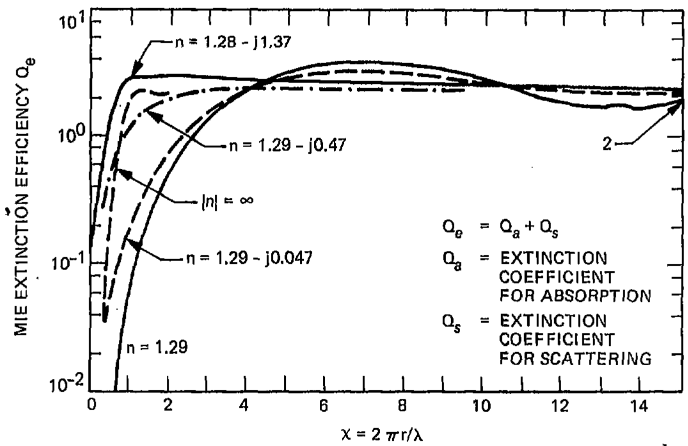

Fig. 3. The extinction efficiency Q_e for various types of spheres, shown in the range $0 < \chi < 5$ (Ref. 7)

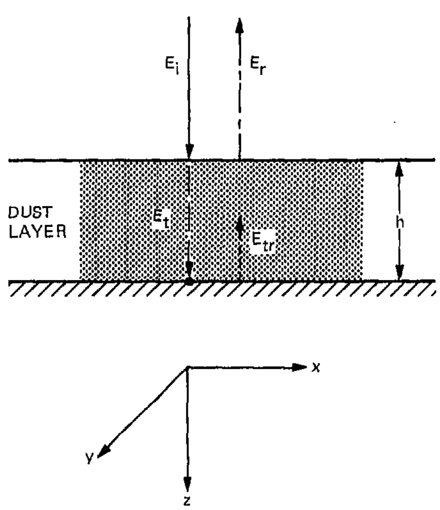

Fig. 2. Simple slab model of a Martian dust storm

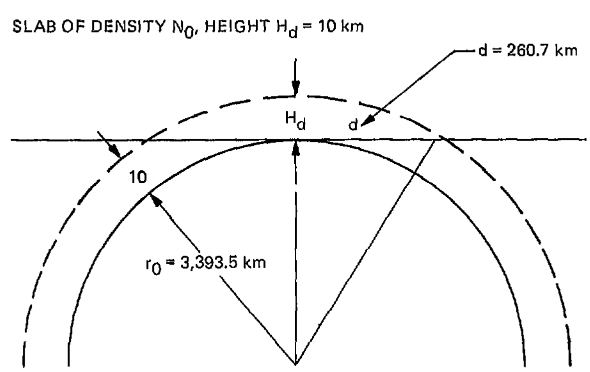

Fig. 4. Model of equivalent Martian atmosphere

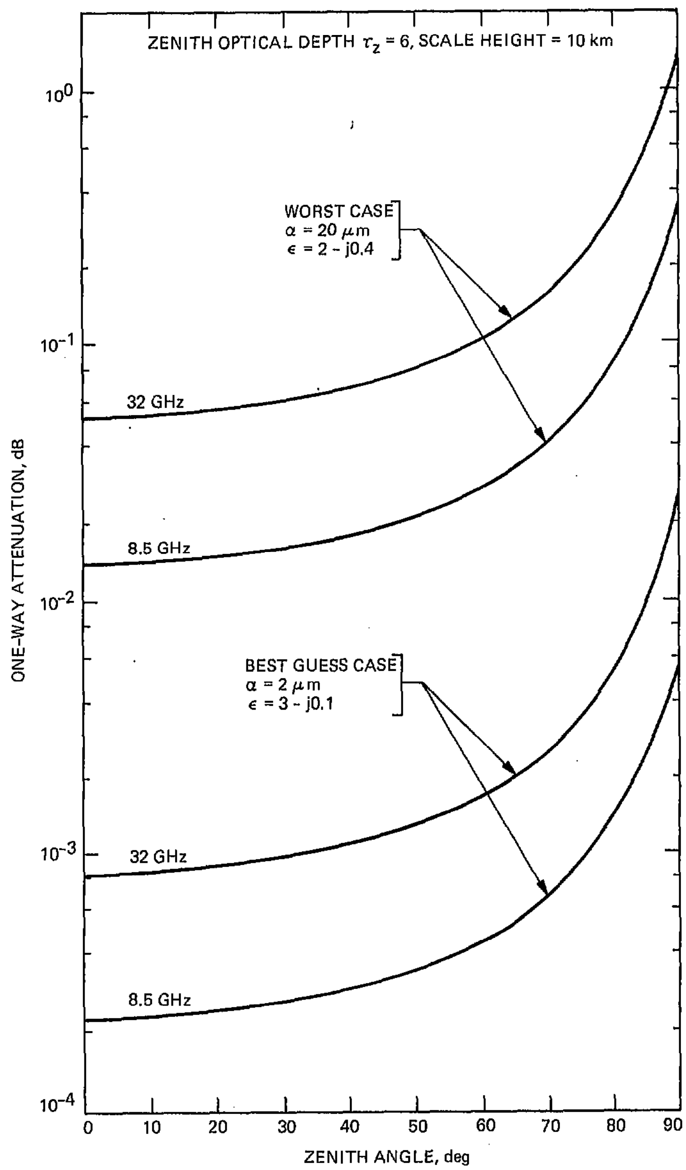

Fig. 5. Zenith angle dependence of dust attenuation in Martian

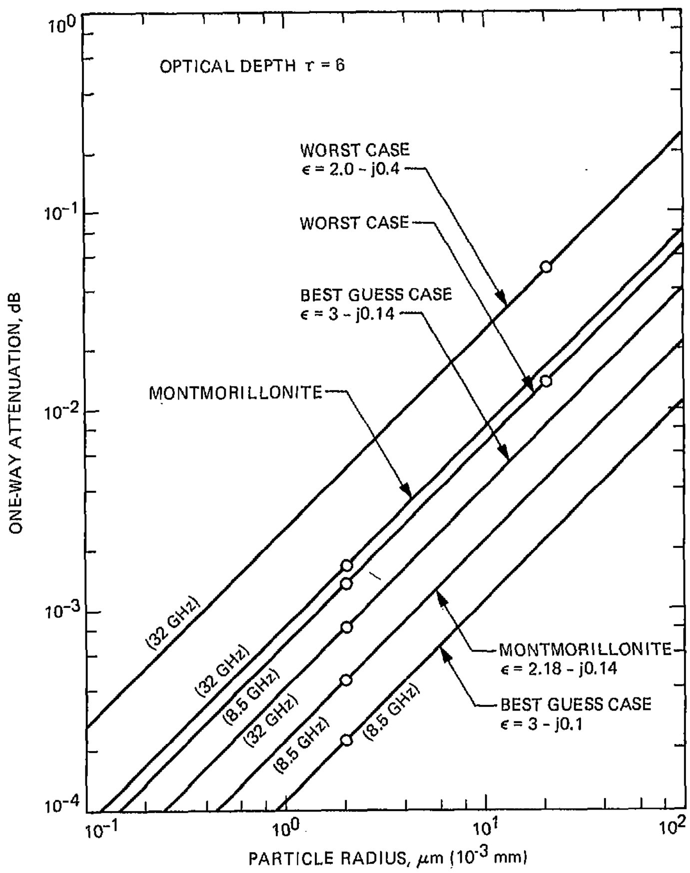

Fig. 6. Dependence of attenuation on choice of particle radius and dielectric constant