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Transmission line model for loss evaluation in sand and dust storms

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A theoretical investigation was conducted to examine the propagation characteristics of millimetre waves in sand and dust storms. The storm is considered to have three main constituents, i.e. sand, silt and clay. Reflection coefficient, transmission coefficient and absorption loss were calculated using the impedance concept as a function of frequency and visibility. The entire length of the link is equated to three transmission line sections in cascade, where the sections were characterized by medium parameters of the three constituents of the storm. The propagation parameters are found to depend both on frequency and visibility. Brewster's phenomenon is clearly observed by the system which is around 75° of angle of incidence. It has been found that for sparsely distributed particles the reflection coefficient is reduced by several orders of magnitude as compared to the case of zero visibility.

1 Introduction

Recently, considerable attention has been paid to evaluate the influence of precipitations on the performance of microwave and millimetre wave propagation. Like other precipitations, sand and dust particles in storms also affect the propagation of microwave and millimetre wave[1-5]. The presence of dust constituents in atmosphere causes considerable effect on microwave and millimetre wave propagation[6-8], affecting both phase and amplitude of the wave during propagation. Therefore, in the present work, an attempt has been made to evaluate the absorption loss of mm wave while propagating through media having different dust consituents. Utilizing the transmission line concept, equations have been developed to evaluate the reflection coefficient, transmission coefficient and absorption loss. The medium with sparsely distributed dust particles are characterized by equivalent dielectric constant which have been used to compute the various propagation parameters. Both normal and oblique incidence are considered, the details of which are given in the following sections.

2 Theoretical considerations

Let us take the length of a communication link which contains n types of dust particles blown to the height of the link due to dust storms. Since the wave is propagating through the medium which has sparsely distributed particles, it is quite logical to represent the entire length of the link into n sections in cascade having n different constituents as shown in Fig. 1. If it is assumed that all the n constituents have same number of particles per unit volume in the air, then each section of the link may have equal length. Let $\varepsilon_1, \varepsilon_2, \varepsilon_3, ..., \varepsilon_n$; $\mu_1, \mu_2, \mu_3, ..., \mu_n$; and $\sigma_1, \sigma_2, \sigma_3, ..., \sigma_n$ denote the usual medium parameters (permittivity, permeability and conductivity) for the n constituents, respectively. Further, let $\eta_1, \eta_2, \eta_3, ..., \eta_n$ denote the characteristic impedance of individual sections. For calculating the various propagation parameters two cases have been taken separately, namely (i) normal incidence, and (ii) oblique incidence.

2.1 Normal incidence

Let us consider Fig. 1 which is the transmission line equivalent to a communication link in sand and dust storms. In this, each section is characterized by a type of dust particles. If an electromagnetic wave is incident at the interface, then the transmission coefficients for successive interfaces between two adjacent media can be written as[9]

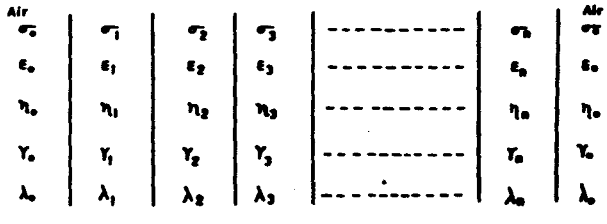

Fig. 1—Transmission line equivalent of a microwave link in sand and dust storm

$$\frac{2\eta_1}{\eta_1+\eta_0}, \frac{2\eta_2}{\eta_2+\eta_1}, \frac{2\eta_3}{\eta_3+\eta_2}, ..., \frac{2\eta_{n+1}}{\eta_{n+1}+\eta_n}$$

Here, η_{n+1} indicates the free-space characteristic impedance as the wave after passing through the dusty medium emerges in the air.

Apart from this, the wave, propagating through various sections, will also be governed by the propagation factors of individual sections. If γ_1, γ_2, γ_3, ..., γ_n be the respective propagation constants for individual sections, then the propagation factors, which will affect the propagation of wave, will be

$$e^{-\gamma_1 l_1}, e^{-\gamma_2 l_2}, e^{-\gamma_3 l_3}, ..., e^{-\gamma_n l_n}$$

Thus, the overall transmission coefficient for the given system can be given by

$$T=\left[\left(\frac{2\eta_1}{\eta_1+\eta_0}\right)\left(\frac{2\eta_2}{\eta_2+\eta_1}\right).....\left(\frac{2\eta_{n+1}}{\eta_{n+1}+\eta_n}\right)\right]$$
$$\times \exp[-(\gamma_1 l_1+\gamma_2 l_2+\gamma_3 l_3+....+\gamma_n l_n)] \quad ...(1)$$

Here, l_1, l_2, l_3, ..., l_n denote the length of equivalent dielectric transmission line sections, and multiple interactions within the structure are ignored.

Now, the reflection coefficient (R) for n sections in cascade can be given by

$$R=\frac{z_1-\eta_0}{z_1+\eta_0}, \frac{z_2-z_1}{z_2+z_1}, \frac{z_3-z_2}{z_3+z_2}, ..., \frac{z_{n+1}-z_n}{z_{n+1}+z_n} \quad ...(2)$$

where

$$z_n=\eta_n\left(\frac{z_{n+1}+\eta_n \tanh\gamma_n l_n}{\eta_n+z_{n+1}\tanh\gamma_n l_n}\right) \quad ...(3)$$

and

$z_{n+1}=\eta_0$ at the end of the system.

Further, the characteristic impedance of each section (dielectric region) can be denoted as

$$\eta_n=\eta_0/\sqrt{\varepsilon_{rn}} \quad ...(4)$$

where

η_0 = Characteristic impedance of free space

ε_{rn} = Relative permittivity of the nth section.

Now putting the value of η_1, η_2, η_3, ..., η_n in Eq. (1), one has

$$T=\frac{M}{N}\exp[-\{\gamma_1 l_1+\gamma_2 l_2+\gamma_3 l_3+....+\gamma_n l_n\}] \quad ...(5)$$

where,

$$M=2^n\sqrt{\varepsilon_{r1}}\sqrt{\varepsilon_{r2}}\sqrt{\varepsilon_{r3}}....\sqrt{\varepsilon_{rn}}$$

and

$$N=(1+\sqrt{\varepsilon_{r1}})(\sqrt{\varepsilon_{r2}}+\sqrt{\varepsilon_{r3}})....(\sqrt{\varepsilon_{rn}}+\sqrt{\varepsilon_{r(n+1)}})$$

Further, the propagation constant for each section can be given as

$$\gamma_n=j\omega\sqrt{\mu_n\varepsilon_n}\left(1-\frac{j\sigma_n}{\omega\varepsilon_n}\right)=\frac{j2\pi}{\lambda_n}\left(1-\frac{j\sigma_n}{2\omega\varepsilon_n}\right) \quad ...(6)$$

where,

σ_1, σ_2, σ_3, ..., σ_n denote the conductivity of different sections; μ_1, μ_2, μ_3, ..., μ_n denote the permeability of dielectric media; ε_1, ε_2, ε_3, ..., ε_n denote the permittivity of dielectric media and λ_1, λ_2, λ_3, ..., λ_n denote the wavelength of the signal propagating in different sections of the dielectric media.

Combining Eqs (5) and (6), we have

$$T=\frac{M}{N}\exp\left[-\left[\left\{\frac{j2\pi}{\lambda_1}\left(1-\frac{j\sigma_1}{2\omega\varepsilon_1}\right)l_1 + \frac{j2\pi}{\lambda_2}\left(1-\frac{j\sigma_2}{2\omega\varepsilon_2}\right)l_2+...+\frac{j2\pi}{\lambda_n}\left(1-\frac{j\sigma_n}{2\omega\varepsilon_n}\right)l_n\right\}\right]\right] \quad ...(7)$$

where,

$$L=l_1+l_2+l_3+....+l_n \quad ...(8)$$

and

$$l_1=l_2=l_3=....=l_n$$

Now, to get the value of reflection coefficient we must know the value of z_1, z_2, z_3, ..., z_n. Combining Eqs (3) and (4) one gets

$$z_n=\frac{\frac{\eta_0}{\sqrt{\varepsilon_{rn}}}\left(z_{n+1}+\frac{\eta_0}{\sqrt{\varepsilon_{rn}}}\tanh\gamma_n l_n\right)}{\left(\frac{\eta_0}{\sqrt{\varepsilon_{rn}}}+z_{n+1}\tanh\gamma_n l_n\right)} \quad ...(9)$$

Combining Eqs (2), (4), and (6) one gets the reflection coefficient as

$$R=\left(\frac{A}{B}-\eta_0\right)\bigg/\left(\frac{A}{B}+\eta_0\right) \quad \ldots(10)$$

where,

$$A=\frac{\eta_0}{\sqrt{\varepsilon_{r1}}}\left(z_2+\frac{\eta_0}{\sqrt{\varepsilon_{r1}}}\tanh\left\{\frac{j2\pi}{\lambda_1}\left(1-\frac{j\sigma_1}{2\omega\varepsilon_1}\right)l_1\right\}\right.$$

and

$$B=\frac{\eta_0}{\sqrt{\varepsilon_{r1}}}+z_2\tanh\left\{\frac{j2\pi}{\lambda_1}\left(1-\frac{j\sigma_1}{2\omega\varepsilon_1}\right)l_1\right\}$$

2.2 Oblique incidence

In this case, let the electromagnetic wave is incident at an angle θ. Then, θ_n will be the angle of refraction through the composite structure.

Thus, one has from Snell's law

$$\gamma_n \sin\theta_n=\gamma_0 \sin\theta \quad \ldots(11)$$

or,

$$\cos\theta_n=\sqrt{1-\left(\frac{\gamma_0 \sin\theta}{\gamma_n}\right)^2} \quad \ldots(12)$$

where,

γ_0 = Propagation constant for free space = $j2\pi/\lambda_0$

The Maxwell's equations for the dielectric medium having permittivity, ε, is given as

$$\nabla\times\mathbf{H}=\mathbf{J}_c+\frac{\partial\mathbf{D}}{\partial t}$$

$$=\sigma\mathbf{E}+j\omega\varepsilon\mathbf{E}$$

$$=j\omega\varepsilon\left(\frac{\sigma}{j\omega\varepsilon}+1\right)\mathbf{E} \quad \ldots(13)$$

Here. $(\sigma/j\omega\varepsilon+1)$ denotes complex effective permittivity of the lossy dielectric medium. The characteristic impedance of such media may, therefore, be given by

$$\eta=\sqrt{\frac{\mu}{\varepsilon\left(1+\frac{\sigma}{j\omega\varepsilon}\right)}}$$

$$=\sqrt{\frac{j\omega\mu}{(\sigma+j\omega\varepsilon)}} \quad \ldots(14)$$

The propagation constant offered by the lossy dielectric medium is given by

$$\gamma=\{j\omega\mu(\sigma+j\omega\varepsilon)\}^{1/2} \quad \ldots(15)$$

and

$$\frac{\eta}{\gamma}=\frac{\left\{\frac{j\omega\mu}{(\sigma+j\omega\varepsilon)}\right\}^{1/2}}{\{j\omega\mu(\sigma+j\omega\varepsilon)\}^{1/2}}$$

Therefore,

$$\eta=\frac{\gamma}{(\sigma+j\omega\varepsilon)} \quad \ldots(16)$$

If the e.m. wave is incident at an angle θ with the direction of propagation, the effective characteristic impedance offered by the various sections of the dielectric media can be given by

$$\eta_n=\frac{\gamma_n\cos\theta_n}{(\sigma_n+j\omega\varepsilon_n)} \quad \ldots(17)$$

where,

θ_n = Angle of refraction for nth section

σ_n = Conductivity of nth section

n = 1, 2, 3, ...

If θ_1, θ_2, θ_3, ..., θ_n denote the angle of refraction in the individual sections of the equivalent dielectric media, then the axial component of the propagation constant will assume the values as $\gamma_1\cos\theta_1$, $\gamma_2\cos\theta_2$, ..., $\gamma_n\cos\theta_n$. Under this condition the transmission coefficient for oblique incident can be obtained by augmenting the propagation constant in Eq. (1) and, therefore,

$$T=\left(\frac{2\eta_0}{\eta_1+\eta_0}\right)\left(\frac{2\eta_1}{\eta_2+\eta_1}\right)\left(\frac{2\eta_2}{\eta_3+\eta_2}\right)\cdots\left(\frac{2\eta_n}{\eta_{n+1}+\eta_n}\right)$$

$$\times\exp[-[\{\gamma_1\cos\theta l_1+\gamma_2\cos\theta l_2+\ldots+\gamma_n\cos\theta_n l_n\}]] \quad \ldots(18)$$

Now, the overall transmission coefficient for oblique incidence can be obtained by combining Eqs (6) and (18) as follows

$$T=\left(\frac{2\eta_0}{\eta_0+\eta_1}\right)\left(\frac{2\eta_1}{\eta_1+\eta_2}\right)\left(\frac{2\eta_2}{\eta_2+\eta_3}\right)....\left(\frac{2\eta_n}{\eta_n+\eta_{n+1}}\right)$$
$$\times\exp\left[-\left[\left\{\frac{j2\pi}{\lambda_1}\left(1-\frac{j\sigma_1}{2\omega\varepsilon_1}\right)l_1\cos\theta_1 + \frac{j2\pi}{\lambda_2}\left(1-\frac{j\sigma_2}{2\omega\varepsilon_2}\right)l_2\cos\theta_2+..... + \frac{j2\pi}{\lambda_n}\left(1-\frac{j\sigma_n}{2\omega\varepsilon_n}\right)l_n\cos\theta_n\right\}\right]\right] \quad ...(19)$$

where the values of η_0, η_1, η_2, ..., η_n for oblique incidence can be obtained from Eq. (17) as

$$\eta_0=\gamma_0\cos\theta/(\sigma_0+j\omega\varepsilon_0)$$

$$\eta_1=\gamma_1\cos\theta_1/(\sigma_1+j\omega\varepsilon_1)$$

$$\eta_2=\gamma_2\cos\theta_2/(\sigma_2+j\omega\varepsilon_2)$$

....

$$\eta_n=\gamma_n\cos\theta_n/(\sigma_n+j\omega\varepsilon_n)$$

The reflection coefficient can be obtained by combining equations (2) and (6) and taking the axial component of propagation constant as

$$R=-\left(\frac{A_1}{B_1}-\eta_0\right)\Big/\left(\frac{A_1}{B_1}+\eta_0\right) \quad ...(20)$$

where,

$$A_1=\frac{\eta_0}{\sqrt{\varepsilon_{r1}}}\left(z_2+\frac{\eta_0}{\sqrt{\varepsilon_{r1}}}\tanh\left\{\frac{j2\pi}{\lambda_1}\left(1-\frac{j\sigma_1}{2\omega\varepsilon_1}\right)l_1\cos\theta_1\right\}\right)$$

and

$$B_1=\frac{\eta_0}{\sqrt{\varepsilon_{r1}}}+z_2\tanh\left\{\frac{j2\pi}{\lambda_1}\left(1-\frac{j\sigma_1}{2\omega\varepsilon_1}\right)l_1\cos\theta_1\right\}$$

So far we have considered the closely packed particles for the system which is very unlikely to be found in sand and dust storms. However, in practice, the particles are sparsely distributed and, therefore, to obtain the various propagation parameters one has to consider the equivalent dielectric for respective sections.

3 Evaluation of equivalent dielectric constant

In order to derive the equivalent dielectric constant we shall consider the distribution of spherical dust particles having permittivity ε_s embedded in background medium of permittivity ε_0 (air)[10]. Therefore, one has the value of ε_{eff} as

$$\varepsilon_{\text{eff}}=\frac{\varepsilon_0\{1+2n_0\,v(\varepsilon_s-\varepsilon_0)/(\varepsilon_s+2\varepsilon_0)\}}{\{1-vn_0(\varepsilon_s-\varepsilon_0)/(\varepsilon_s+2\varepsilon_0)\}} \quad ...(21)$$

Eq. (21) can be further modified to

$$\varepsilon_{\text{eff}}=\frac{\varepsilon_0(1+2v_t y)}{(1-v_t y)} \quad ...(22)$$

where,

$$y=(\varepsilon_s-\varepsilon_0)/(\varepsilon_s+2\varepsilon_0)$$

and,

v_t = Total volume of n_0 dust particles in unit volume of storm.

The total volume of the number of particles in unit volume of storm is related to the visibility as[11]

$$v_t=(9.43\times10^{-9})/V\gamma' \quad ...(23)$$

where,

V= Visibility in km

γ' = Constant having value 1.07

The transmission coefficient now, for the sparsely distributed particles, can be obtained by combining Eqs (7) and (22) as

$$T=\frac{M_1}{N_1}\exp\left[-\left[\left\{\frac{j2\pi}{\lambda_1}\left(1-\frac{j\sigma_1}{2\omega\varepsilon_{1_{\text{eff}}}}\right)+\frac{j2\pi}{\lambda_2}\left(1-\frac{j\sigma_2}{2\omega\varepsilon_{2_{\text{eff}}}}\right)+....\frac{j2\pi}{\lambda_n}\left(1-\frac{j\sigma_n}{2\omega\varepsilon_{n_{\text{eff}}}}\right)\right\}\frac{L}{n}\right]\right] \quad ...(24)$$

where,

$$M_1=2^n\sqrt{\varepsilon_{r1_{\text{eff}}}}\sqrt{\varepsilon_{r2_{\text{eff}}}}\sqrt{\varepsilon_{r3_{\text{eff}}}}....\sqrt{\varepsilon_{rn_{\text{eff}}}}$$

$$N_1=(1+\sqrt{\varepsilon_{r1_{\text{eff}}}})(\sqrt{\varepsilon_{r2_{\text{eff}}}}+\sqrt{\varepsilon_{r3_{\text{eff}}}})....(\sqrt{\varepsilon_{rn_{\text{eff}}}}+\sqrt{\varepsilon_{r(n+1)_{\text{eff}}}})$$

$$l_1=l_2=l_3=.....=l_n=\frac{L}{n}$$

and the effective relative permittivity of the medium in nth section is

$$\varepsilon_{rn_{\text{eff}}}=\frac{\varepsilon_0(1+2v_t y_n)}{(1-v_t y_n)} \quad ...(25)$$

Finally the transmission coefficient for the sparsely distributed particles in the air for normal incidence can be written as

$$T=\frac{2^{2n}\cdot m_1\cdot m_2\cdot m_3 \,......\, m_n}{(1+m_1)(m_2+m_3).....(m_n+m_{n+1})} \times \exp\left\{-\left[\left\{\frac{j2\pi}{\lambda_1}\left(1-\frac{j\sigma_1}{2\omega\varepsilon_0 m_1^2}\right)+\frac{j2\pi}{\lambda_2}\left(1-\frac{j\sigma_2}{2\omega\varepsilon_0 m_2^2}\right)+..... +\frac{j2\pi}{\lambda_n}\left(1-\frac{j\sigma_n}{2\omega\varepsilon_0 m_n^2}\right)\right\}\frac{L}{n}\right]\right\} \quad ...(26)$$

where,

$m_1=\{(1+2v_t y_1)/(1-v_t y_1)\}^{1/2}$;

$m_2=\{(1+2v_t y_2)/(1-v_t y_2)\}^{1/2}$;

$m_3=\{(1+2v_t y_3)/(1-v_t y_3)\}^{1/2}$; ..... etc.

Further, combining Eqs (6), (10) and (22) one has the reflection coefficient as

$$R=\left(\frac{A_2}{B_2}-\eta_0\right)\Big/\left(\frac{A_2}{B_2}+\eta_0\right) \quad ...(27)$$

where,

$$A_2=\frac{\eta_0}{m_1}\left[z_2+\frac{\eta_0}{m_1^2}\tanh\left\{\frac{j2\pi}{\lambda_1}\left(1-\frac{j\sigma_1}{2\omega\varepsilon_0 m_1^2}\right)l_1\right\}\right]$$

and

$$B_2=\frac{\eta_0}{m_1}+z_2\tanh\left\{\frac{j2\pi}{\lambda_1}\left(1-\frac{j\sigma_1}{2\omega\varepsilon_0 m_1^2}\right)l_1\right\}$$

In general total power dissipated (P_{abs}) within these sections can be calculated by utilizing the concept of energy balance. For general case the absorbed power can be written as

$$P_{abs}=P_{inc}(1-|R|^2-|T|^2) \quad ...(28)$$

4 Numerical computations

The values of transmission coefficient (T), reflection coefficient (R), and absorption loss were calculated using Eqs (7), (10), (19), (20), (26), (27) and (28) for different values of path lengths (L), frequencies, angle of incidence, and visbility. The typical values of permittivity, permeability and conductivity were $\varepsilon_{r1}=(3.776-j0.020)$, $\varepsilon_{r2}=(4.021-j0.214)$, $\varepsilon_{r3}=(4.495-j0.255)$; $\mu_1=\mu_2=\mu_3=1$ and $\sigma_1=2\times10^{-5}$ mho/m, $\sigma_2=1.6\times10^{-5}$ mho/m, $\sigma_3=2\times10^{-4}$ mho/m for sand, silt and clay, respectively. The data obtained are shown in Figs 2-8.

5 Discussion

The examination of Fig. 2 reveals that reflection coefficient increases with increasing frequency, whereas the transmission coefficient decreases with increasing frequency. Further, the loss due to absorption is found to increase with increasing frequency (Fig. 3). The entire phenomena can be explanined as follows:

For zero visibility, the medium is almost completely packed with sand and dust particles. Any lossy dielectric medium will have a complex permittivity

$$\varepsilon^*=\varepsilon\left(1-j\frac{\sigma}{\omega\varepsilon}\right) \quad ...(29)$$

the imaginary part of which is a function of conductivity and frequency. It may be mentioned that there are two types of loss mechanism which attenuate the wave in addition to reflection loss. First, the conductivity of the dielectric contributes to the loss of energy in the form of heat. Secondly, the dipoles created due to the polarization process experience certain amount of friction (damping force) when they flip back and forth in an alternating electromagnetic field. Consequently, these dipoles extract energy from the impressed field which is dissipated in the form of heat. Since the

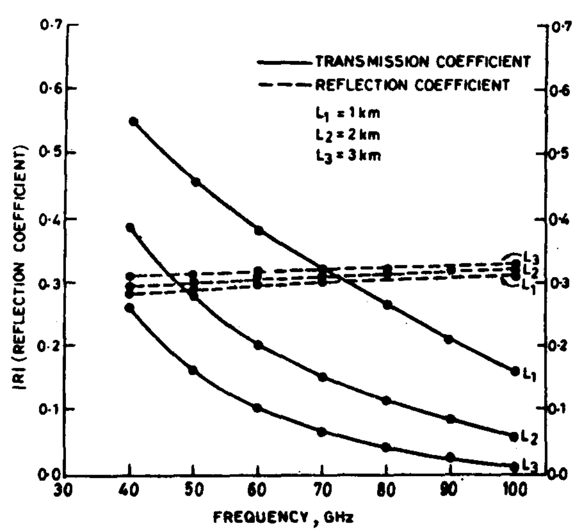

Fig. 2—Variation of transmission and reflection coefficients with frequency for different path lengths

losses due to dielectric conductivity and polarization damping force are in the form of dissipated heat, it is logical to represent the two losses in terms of conductivity. Under this condition equation (29) can be augmented taking into account the conduction and polarization damping losses which will give rise to more generalized complex permittivity as

$$\varepsilon^* = \varepsilon' - j\,\varepsilon'' - j\,\frac{\sigma}{\omega}$$

or

$$\varepsilon^* = \varepsilon' - j\left(\frac{\sigma + \omega\varepsilon''}{\omega}\right) \quad \ldots (30)$$

From this we can write the effective conductivity as

$$\sigma_{\text{eff}} = \sigma + \omega\,\varepsilon'' \quad \ldots (31)$$

and loss tangent or dissipation factor as

$$\tan\delta = \frac{\sigma_{\text{eff}}}{\omega\,\varepsilon'} = \frac{\sigma + \omega\,\varepsilon''}{\omega\,\varepsilon'} \quad \ldots (32)$$

It is evidently clear from Eqs (31) and (32) that increasing frequency enhances the effective conductivity and loss tangent of the medium. These, in turn, raise the effective absorption loss along with reflection in the system. This justifies the increase in absorption loss with increasing frequency. It may, therefore, be concluded that it is the polarization damping force that predominantly controls the loss in the medium, when frequency of the propagating signal is increased.

The variation of reflection and transmission coefficients as a function of angle of incidence are shown in Fig. 4 for oblique incidence for different frequencies. The reflection coefficient decreases with increasing angle of incidence, it attains minimum value around 75° of angle of incidence and thereafter again rises. There is a clear Brewster's phenomenon around 75° of angle of incidence. The transmission coefficient is found to have maximum value at around 75° for all the frequencies. This further, corroborates the Brewster's phenomenon. The loss shown as a function of angle of incidence in Fig. 5 decreases with increasing angle of incidence and has the minimum value at around

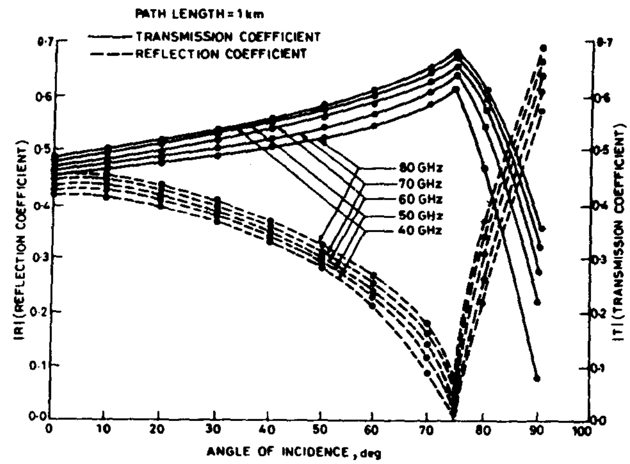

Fig. 4—Variation of transmission and reflection coefficients with angle of incidence for different frequencies (oblique incidence)

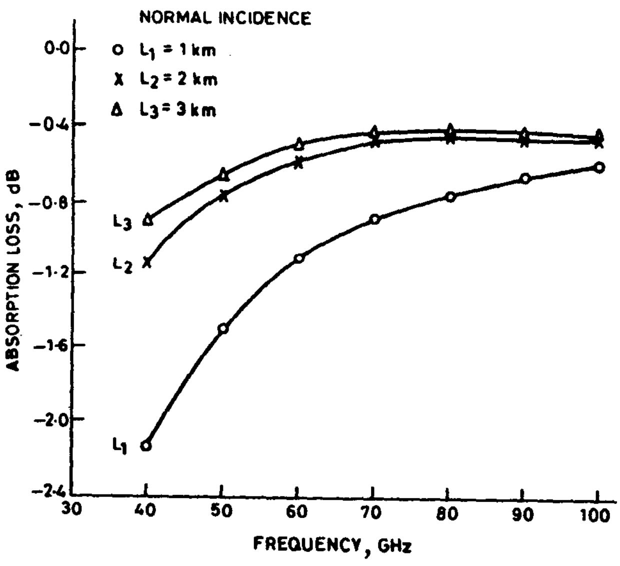

Fig. 3—Variation of absorption loss with frequency for different path lengths

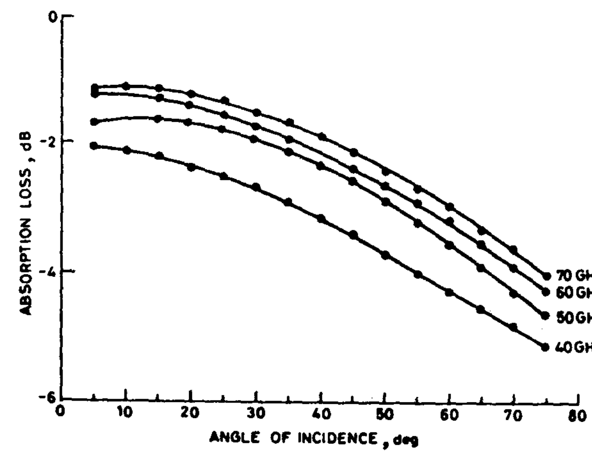

Fig. 5—Variation of absorption loss with angle of incidence for different frequencies (oblique incidence)

75°. The level of loss, in general, increases with increasing frequency. This is in accordance with the fact that increasing frequency raises significantly the effective conductivity and dissipation factor of the medium because of the dominating role of the polarization damping factor at increased frequencies. It must be mentioned that, in practice, the previous cases considered so far never exist. There is hardly any time when the visibility reduces to zero. This implies that in actual sand and dust storms one always has sparsely distributed particles suspended in the air during the storm period and, therefore, for such systems the term visibility is introduced to take into account the effect of concentration of the particles raised in the air. Calculations for reflection coefficient, transmission coefficient, and loss were made using equivalent.dielectric concept. The reflection coefficient increases with increasing frequency, whereas transmission coefficient decreases linearly with frequency as indicated in Fig. 6. Further, it is noticed that for sparsely distributed dust particles, the reflection coefficient is reduced by several order of magnitude as compared to the case of zero visibility. Likewise, the transmission coefficient is almost double as compared to the zero visibility condition. This is in accordance with the fact that sparsely distributed particles can be taken embedded in the air medium and, therefore, the effective permittivity of the combined medium will be between the dust particle and air. This modified permittivity will definitely offer better matching condition with air in which the incident wave is travelling before impinging on the dusty medium. Under this condition the propagation characteristics of the electromagnetic wave definitely improve as has been observed by low reflection and enhanced transmission.

The calculated values for reflection and transmission coefficients are also shown in Fig. 6 as a function of visibility for different frequencies. It has been found that with increasing visibility the reflection coefficient decreases, whereas the transmission coefficient increases for all the frequencies considered. The high reflection and low transmission at low visibility are attributed to the higher effective permittivity of the combined medium ($\varepsilon_0 << \varepsilon_{eff} < \varepsilon_d$); effective permittivity will be much higher than the air, but nearer to permittivity of the dielectric particles which is very likely to occur due to high particle concentration at low visibility. Since the dust particles are non-magnetic material, the relative permeability can be taken as unity. Under this condition, there will be higher mismatch between the air and the dusty medium.

The case is otherwise at higher visibiltiy. The particle concentration will be very low at higher visibility and therefore, the effective permittivity of the combined medium (particle and air) will relatively be nearer to that of air (i.e., $\varepsilon_0 << \varepsilon_{eff} << \varepsilon_d$). This may provide better matching condition between air and dusty medium, resulting essentially into low reflection and high transmission as has been observed (Fig. 6).

The adsorption loss is high at low visibility which is shown in Fig. 7. This is because of two factors:

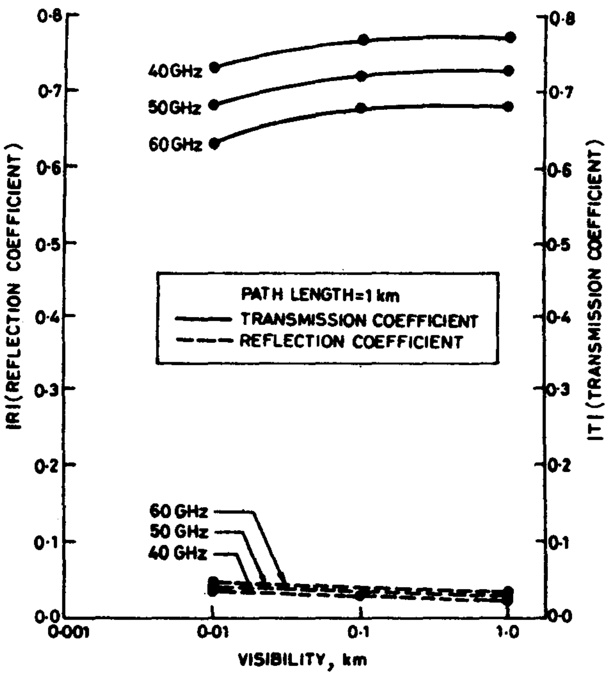

Fig. 6—Variation of transmission and reflection coefficients with visibility for different frequencies (normal incidence)

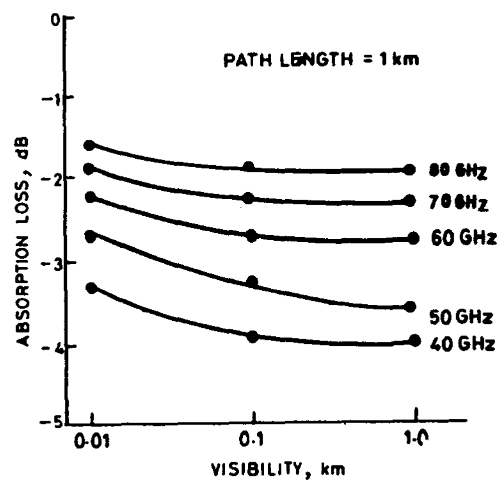

Fig. 7—Variation of absorption loss with visibility for different frequencies

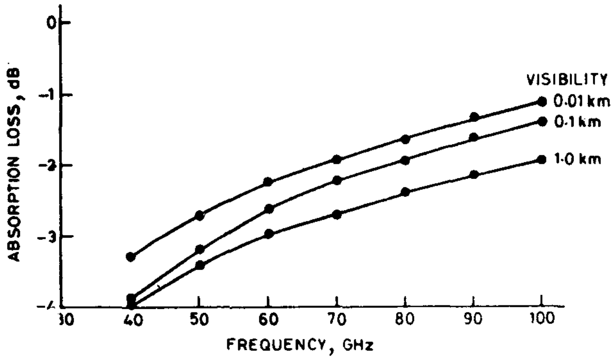

Fig. 8—Variation of absorption loss with frequencies for different visibilities (normal incidence)

(i) At low visibility, the particle concentration is very high which renders the effective permittivity of the dusty medium nearer to dust particle permittivity. This increases the loss by offering higher mismatch between air and dusty medium and hence higher reflection loss and low transmission.

(ii) The increased number of particles at low visibility inherently enhance the dielectric loss.

The reduced absorption loss at higher visibility is basically due to following two reasons:

(i) At high visibility the particle concentration is very low which renders the effective permittivity of the dusty medium very near to that of air. This provides better matching between air and dusty medium and hence low reflection loss and high transmission.

(ii) The reduced particle concentration at higher visibility intrinsically will offer low dielectric loss.

Examination of Fig. 8 reveals that the loss in the dusty medium increases with increasing frequency and decreasing visibiltiy. This is the logical conclusion. Increasing frequency, as can be seen from Eqs (30) and (31), will give rise to increased effective conductivity as well as loss tangent of the medium, whereas reduced visibility will offer increased particle concentration in the medium resulting into higher reflection and low transmission. Thus, increasing frequency and decreasing visibility will raise the overall loss in the propagating field in sand and dust storms as has been observed from Fig. 8.

It may, therefore, be concluded that the loss in the propagating electromagnetic wave in sand and dust storms depends heavily on the frequency and visibility. The loss is significantly high at higher frequencies and at low visibility because of enhanced effective conductivity as well as tangent loss at high frequency and higher reflection and low transmission at low visibility.

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