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Propagation Effects of Ground and Ionosphere on Electromagnetic Waves Generated By Oblique Return Stroke

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ABSTRACT: *Accounting the well accepted features of lightning discharges, the influences of the path of propagation, between the finitely conducting ground and the ionosphere, on the shape and amplitude of the VLF electric fields radiated by oblique return stroke have been studied. The effect of orientation of oblique return stroke on reflection coefficients has been discussed. Attenuation factor and spectrum of VLF electric fields have been studied for different orientations of the oblique return stroke. On considering the propagation effects on the radiated electromagnetic waves due to the ground and the ionosphere, it is shown that spectrum of VLF electric fields radiated by the oblique channel is of Gaussian shape.*

Keywords – *Attenuation factor, Electrical conductivity, Electric field, Geometrical path difference, Ionosphere, Lightning discharge, Parallel polarization, Reflection coefficient, Return stroke.*

I. INTRODUCTION

Lightning discharges produce the wide spectrum of electromagnetic waves which propagate between the earth and the ionosphere. The characteristics of currents in lightning return strokes are embedded in the lightning generated electromagnetic fields. Accurate knowledge concerning the characteristics of electromagnetic fields produced by lightning discharges is needed for investigating the production of sprites, elves, jets etc. which are together called transient optical events [1 - 7], the energetic radiation from lightning [8 - 9] and interaction of lightning with various objects and electrical systems.

Considering ground as a perfect conductor, few researchers [10 – 11] have studied the shape and amplitude of the electromagnetic fields generated by the oblique lightning channel. So far, in these studies they have not considered the effect of the finitely conducting ground and the ionosphere on the radiated VLF waves associated with the oblique return stroke. The varying conductivity of the ground distorts the amplitudes, rise times and shapes of electromagnetic radiation generated by the lightning return stroke [12 - 20]. The attenuation factor, introduced by the finitely conducting ground and the ionosphere, should be accounted for the precise measurements and analysis of VLF electric fields. In propagating between finitely conducting ground and ionosphere, the radiated VLF electromagnetic fields change in various degrees depending on the geometry and electrical characteristics of the propagation paths [21 - 27]. To minimize the propagation effects caused by the finitely conducting ground, many researchers [28 - 31] have measured the electromagnetic fields generated by lightning discharges striking the sea, so that the propagation path of the electromagnetic signals is over sea-water. Since sea water is a better conductor than soil, electromagnetic waves propagating over sea water are subjected to much less severe propagation effects compared with the electromagnetic fields propagating over ground. However, in that study no attempt was made to consider the ionospheric effect on the propagation of electromagnetic waves generated by the oblique return stroke.

Prasad and Singh [32] have reported in their study that the electromagnetic waves, in the frequency range from 1 kHz to 50 kHz are subjected to severe propagation effects in propagating between conducting ground below and ionosphere above. However, in this presentation they have not considered the effects of the orientation on the attenuation of radiated VLF waves. They have argued qualitatively that with the changes in orientation of the return channel from verticality, the pattern of the radiated electromagnetic energy accordingly alters and give rise to a variability of maximum radiated energy. Thus we find that the orientation of lightning strokes is one of the most important parameters which control the magnitude and the frequency spectrum of the radiated VLF waves.

This presentation is intended to provide study of the propagation effects of the finitely conducting ground and the ionosphere on the radiated VLF electric field generated by the oblique orientations of the return stroke. It is discussed that orientation of oblique return stroke influences the reflection coefficients for the ground and the ionosphere. Further in this study, it is reported that oblique orientation of return stroke affects the attenuation introduced due to the ground below and the ionosphere above to the radiated VLF electromagnetic waves.

II. RADIATED ELECTRIC FIELD FROM OBLIQUE RETURN STROKE

The current moment associated with oblique return stroke channel determines the strength and spectral features of the radiated electromagnetic waves. The current moment is defined as [32]

$$M_c(t) = I_t\, l \cos \Phi \tag{1}$$

In Eq. (1), $I_t[= I_0\{\exp(-\propto t) - \exp(-\beta t)\}]$ is the current at the time t [33], t is the time in second counted from the starting point of the return stroke located at the finitely conducting ground, I_0[=22 kA] is the peak value of current and is taken as constant for a particular stroke, $\propto$[=1.6x10^4 s^{-1}] and β[=50x10^4 s^{-1}] are constants which depend on the charge density and dimension of the channel, $l[= \int_0^t V_t dt]$ is the length of the return stroke channel from the ground to the charge centre of the cloud, Φ is the angle made by the return stroke from the vertical, $V_t[=V_0\{\exp(-at) - \exp(-\beta t)\}]$ is the return stroke velocity [34 - 35], where V_0[=3x10^8 ms^{-1}], $a[= 6\text{x}10^4 s^{-1}]$ and b[=7x10^5 s^{-1}] are the constants whose values have been calculated by Srivastava and Tantry [36].

From the simple antenna theory, the component of the direct radiated electric field at a distance, r from the lightning discharge channel is written as

$$E_d(r,t,\theta,\Phi) = \frac{1}{4\pi\varepsilon_0}\frac{1}{c^2 r}\frac{dM_c(t)}{dt} \tag{2}$$

Where, ε_0 is the permittivity of free space and c is the velocity of light.

The value of $M_c(t)$ from Eq. (1) is substituted into Eq. (2), the direct component of the radiated electric field is written as

$$E_d(r,t,\theta,\Phi) = \frac{30\, I_0 V_0 \cos\Phi \sin(\theta+\Phi)}{cabr} f(t) \tag{3}$$

Where, θ is the observation angle made by the line joining the observation point to the mean direction of the lightning discharge channel and factor f (t) is obtained by Prasad and Singh [32] which is very similar to that given by Srivastava and Tantry [36]:

$$\begin{aligned} f(t) = {} & (b-a)[\propto \exp(-\propto t) - \beta \exp(-\beta t)] - \\ & b[(a+\propto)\exp\{-(a+\propto)t\} - (a+\beta)\exp\{-(a+\beta)t\}] + \\ & a[(b+\propto)\exp\{-(b+\propto)t\} - (b+\beta)\exp\{-(b+\beta)t\}] \end{aligned} \tag{4}$$

III. FREQUENCY SPECTRUM

Magnitude of the frequency spectrum of direct radiated electric field is written as [32]

$$|E_d(\omega)| = \left| \int_0^\infty E_d(r,t,\theta,\Phi)\, exp(-i\omega t)\, dt \right| \tag{5}$$

Where, ω is the frequency, in rad s^{-1}, at which wave is radiated.

Substituting for $E_d(r,t,\theta,\Phi)$ from Eqs.(3) and (4) into Eq. (5), we obtain

$$\begin{aligned} |E_d(\omega)| = \frac{30 I_0 V_0 \cos\Phi \sin(\theta+\Phi)}{cabr} \Bigg[\Bigg\{ \left(\frac{\beta^2(b-a)}{\beta^2+\omega^2} + \frac{b(a+\alpha)^2}{(a+\alpha)^2+\omega^2} + \frac{a(b+\beta)^2}{(b+\beta)^2+\omega^2} \right) - \Bigg(\frac{\propto^2(b-a)}{\propto^2+\omega^2} + \\ \frac{b(a+\beta)^2}{(a+\beta)^2+\omega^2} + \frac{a(b+\alpha)^2}{(b+\alpha)^2+\omega^2} \Bigg) \Bigg\}^2 + \omega^2 \Bigg\{ \left(\frac{\alpha(b-a)}{\alpha^2+\omega^2} + \frac{b(a+\beta)}{(a+\beta)^2+\omega^2} + \frac{a(b+\alpha)}{(b+\beta)^2+\omega^2} \right) - \\ \left(\frac{\beta(b-a)}{\beta^2+\omega^2} + \frac{b(a+\propto)}{(a+\propto)^2+\omega^2} + \frac{a(b+\beta)}{(b+\beta)^2+\omega^2} \right) \Bigg\}^2 \Bigg]^{1/2} \end{aligned} \tag{6}$$

IV. REFLECTION OF LIGHTNING GENERATED VLF ELECTROMAGNETIC WAVES FROM GROUND AND IONOSPHERE

4.1 Reflection From Ground

Parallel polarization of the lightning generated VLF waves dominates [32, 37]. Therefore, study of the reflection factor for parallel polarized electromagnetic waves is of our interest. The earth is not a good conductor; for computation of reflection coefficient, it can be considered as a partially conducting dielectric. The complex reflection factor, R_g for ground is given as [37]

$$R_g = \frac{(\varepsilon_r - ix)\cos\theta_g - \sqrt{(\varepsilon_r - ix) - \sin^2\theta_g}}{(\varepsilon_r - ix)\cos\theta_g + \sqrt{(\varepsilon_r - ix) - \sin^2\theta_g}} \tag{7}$$

In Eq. (7), ε_r is the relative permittivity of the earth, $x = \sigma/\omega\varepsilon_0$, where σ is the electrical conductivity of the ground and θ_g is the angle of incidence.

It is apparent from Eq. (7) that the reflection factor is a complex quantity and that the reflected wave will differ in both in magnitude and phase from the incident wave. The reflection factor R_g depends on angle of incidence from normal. Therefore, it will depend on orientation of lightning return stroke.

4.2 Reflection From Ionosphere

The ionosphere is an assembly of charged particles in which the time average charge density is zero. The reflection of the lightning generated VLF electromagnetic waves by the ionosphere is a function of frequency. The wave length of VLF electromagnetic wave is sufficiently long. There is great change in ionization density in the course of wavelength. The ionospheric boundary then may be considered as a reflecting surface, for which the reflection coefficient, R_i for parallel polarized wave is given as [37]

$$R_i = \frac{(\varepsilon_r' - ix')\cos\theta_i - \sqrt{(\varepsilon_r' - ix') - \sin^2\theta_i}}{(\varepsilon_r' - ix')\cos\theta_i + \sqrt{(\varepsilon_r' - ix') - \sin^2\theta_i}} \tag{8}$$

In Eq. (8), ε_r' is the relative permittivity of the ionosphere, $x' = \sigma'/\omega\varepsilon_0$, where σ' is the electrical conductivity of the ionosphere and θ_i is angle of incidence.

It is apparent from Eq. (8) that the reflection coefficient for ionosphere depends upon the frequency, angle of incidence of VLF wave and orientation of the oblique return stroke.

V. EXPRESSION FOR ATTENUATION FUNCTION

For the expression of the attenuation function the practical situation is considered in Fig. (1). At the observation point P(r, θ, Φ), in addition to the direct field component, two more indirect field components arrive. One component is reflected from the ground and the other one is reflected from the ionospheric boundary.

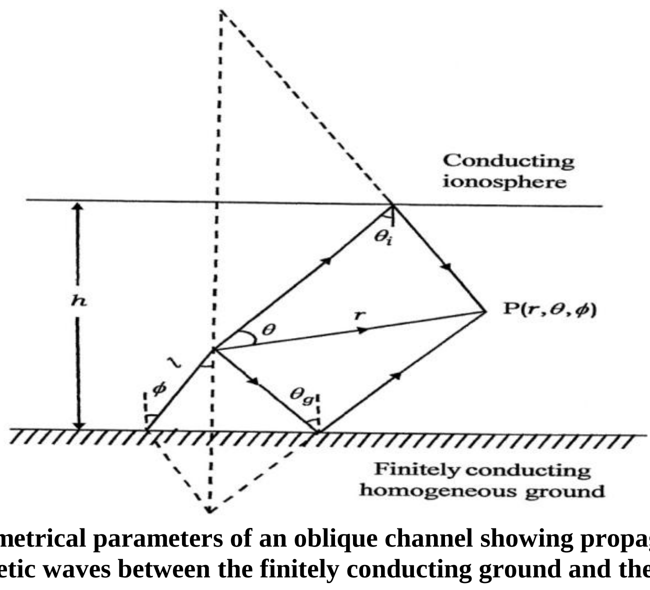

Fig. (1) Geometrical parameters of an oblique channel showing propagation of VLF electromagnetic waves between the finitely conducting ground and the ionosphere.

The distance of the point of observation and angles of incidence to the ground and to the ionosphere determine the correct phase of the three field components and their resultant value. The angles of incidence, θ_g and θ_i are related with the angle of direct observation, θ and orientation, Φ of the lightning return stroke. Expressions of θ_g and θ_i are written as

$$\theta_g = sin^{-1}\left[\frac{r\,sin\,(\theta+\Phi)}{r+(\Delta r)_g}\right] \quad \text{and} \quad \theta_i = sin^{-1}\left[\frac{r\,sin\,(\theta+\Phi)}{r+(\Delta r)_i}\right] \tag{9}$$

Where, $(\Delta r)_g$ and $(\Delta r)_i$ are the geometrical path difference with respect to the direct wave of ground reflected and ionosphere reflected waves, respectively and depend on the observation distance, observation angle and orientation of return stroke lightning channel.
Expressions of $(\Delta r)_g$ and $(\Delta r)_i$, in terms of the ionosphere height, h and average length, l of lightning return stroke, are written as

$$(\Delta r)_g = [\{r\cos(\theta+\Phi) + 2l\cos\Phi\}^2 + r^2 sin^2(\theta+\Phi)]^{\frac{1}{2}} - r \tag{10}$$

and

$$(\Delta r)_i = \left[\left\{2h - 2l\,cos\,\Phi - r\,cos(\theta+\Phi)\right\}^2 + r^2 sin^2(\theta+\Phi)\right]^{\frac{1}{2}} - r \tag{11}$$

The electric fields of the ground reflected and the ionospheric reflected waves E_g and E_i are written as [32, 36, 38]

$$E_g(\omega) = \frac{r^2 R_g\,exp\left[-i\left(2\pi/_\lambda\right)(\Delta r)_g\right]}{\{r+(\Delta r)_g\}^2} E_d(\omega) \tag{12}$$

and

$$E_i(\omega) = \frac{r^2 R_i\,exp\left[-i\left(2\pi/_\lambda\right)(\Delta r)_i\right]}{\{r+(\Delta r)_i\}^2} E_d(\omega) \tag{13}$$

The values of R_g and R_i are taken from Eqs. (7) and (8), respectively. The complex reflection coefficients are controlled by the electrical properties of reflecting surfaces, angles of incidence at reflecting surfaces and nature of polarization.
The resultant electric field, $\boldsymbol{E_r(\omega)}$ at the observation point P(r, θ, Φ) is the vector sum of three components:

$$\boldsymbol{E_r(\omega) = E_d(\omega) + E_g(\omega) + E_i(\omega)} \tag{14}$$

Substituting for $E_g(\omega)$ and $E_i(\omega)$, respectively, from Eqs. (12) and (13) into Eq. (14), the expression for $|E_r(\omega)|$ is written as

$$|E_r(\omega)| = \left|\left[1 + \frac{r^2 R_g\,exp\left\{-i\left(2\pi/_\lambda\right)(\Delta r)_g\right\}}{\{r+(\Delta r)_g\}^2} + \frac{r^2 R_i\,exp\left\{-i\left(2\pi/_\lambda\right)(\Delta r)_i\right\}}{\{r+(\Delta r)_i\}^2}\right] E_d(\omega)\right| \tag{15}$$

The quantity within square bracket is termed as attenuation factor F [32].

VI. RESULTS AND DISCUSSIONS

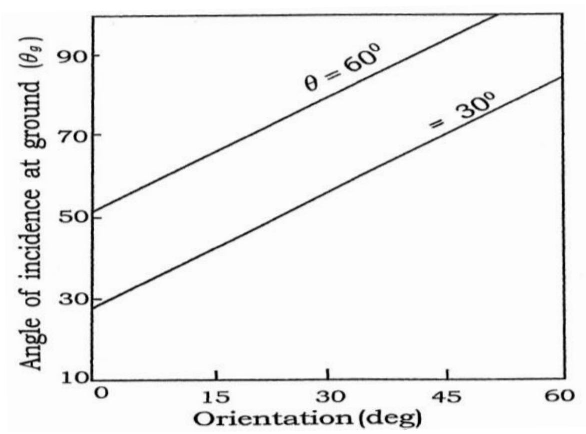

Fig. (2) Variation of angle of incidence (θ_g) at the ground with orientation of the lightning channel.

6.1 Angles Of Incidence For The Ground And The Ionosphere

It is evident from Eq. (9) that the angles of incidence for the ground and the ionosphere depend up on
the orientation of the return stroke lightning channel. The manners, in which the angles of incidence, for the ground and the ionosphere vary, are shown in Figs. (2) and (3), respectively for observation distance, r = 100 km. In this computation values of ionosphere height and average channel length are taken as 90 km and 5 km, respectively.

Variation of angle of incidence, θ_g for homogeneous ground with orientation of return stroke is shown in Fig. (2). In the orientation range from 0° to 60°, the minimum value of angle of incidence is seen at 0° (i.e. for vertical channel). It is obvious from the figure that angle of incidence increases linearly with increased orientation. Slope of the curve is found to be about 43° and is same for the both observation angles, θ = 30° and 60°.

Variation of angle of incidence at the boundary of the ionosphere with orientation of lightning channel is depicted in Fig. (3). Curves are plotted for angles of observation, θ = 30° and 60°. It is obvious from the figure that the angle of incidence has maximum value at orientation, $\Phi = 14.5°$ for observation angle, θ = 60° while it is maximum at Φ =30° for θ =30°. As the angle of observation decreases, the maxima of the incident angle shift to lower values. The angle of incidence decreases from the maximum value with increased orientation of return stroke. Angle of incidence at θ = 60° decreases more rapidly than it is at θ =30°, from the respective maximum values.

Thus, we find that the orientation of oblique return stroke affects the angle of incidence, significantly.

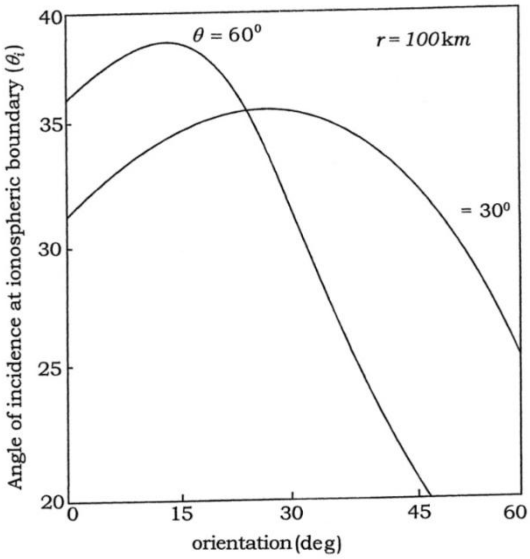

Fig. (3) Variation of angle of incidence, θ_i at ionosphere with orientation of the lightning channel.

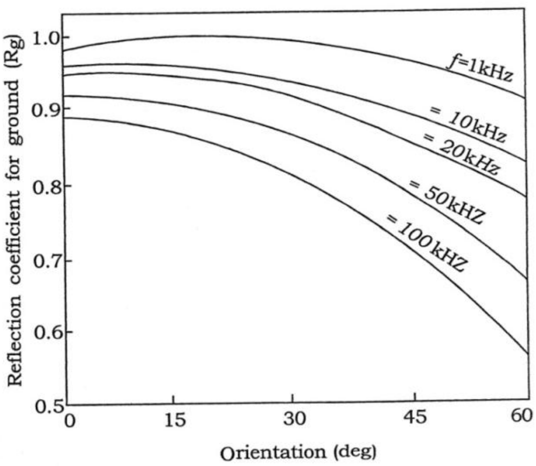

Fig. (4) Variation of the reflection coefficient for ground with orientation of the lightning channel range of for the frequency from 1 kHz to 100 kHz. Curves are plotted for r = 100 km and, θ= 30 °.

6.2 Reflection Factors For The Ground And The Ionosphere

In this computation it is considered that VLF electric field radiated by oblique return stroke is parallel to the plane of incidence. For the sake of calculation, value of the electrical conductivity of the earth is taken as 10^{-3} Ω m^{-1} its relative permittivity as 10 and average channel length as 5 km. The observation angle, θ is taken as 30° and distance of observation as 100 km.

The manner in which the reflection factor, R_g varies with orientation of the return stroke is shown in Fig. (4). According to the pattern shown in the figure, reflection coefficient decreases, with increased orientation in the frequency range from 1 kHz to 100 kHz. The maximum value of reflection factor is seen for the vertical return stroke (i.e. for Φ = 0°) in the range of orientation from 0° to 60°.

Variation of the reflection coefficient of the radiated VLF electromagnetic waves associated with oblique orientation of lightning channel for ionosphere versus orientation is depicted in Fig. (5). In this computation the values of relative permittivity of ionosphere, ionospheric height and average channel length are taken as 1, 90 km and 5 km, respectively. At low frequencies the conductivity of the ionosphere remains almost constant and it is equal to 10^{-5} Ωm^{-1}. The study is made for θ =30° and r = 100 km. It is clear from the figure that decrease in reflection coefficient goes on decreasing with increasing frequency from 1 kHz to 100 kHz for a given orientation. At 100 kHz the reflection factor decreases from its maximum value to minimum as orientation increases from 0° to 30° and there after it increases. The reflection factor is same at orientations 0° (i.e. for vertical channel) and 60° for the frequency range from 1 kHz to 100 kHz.

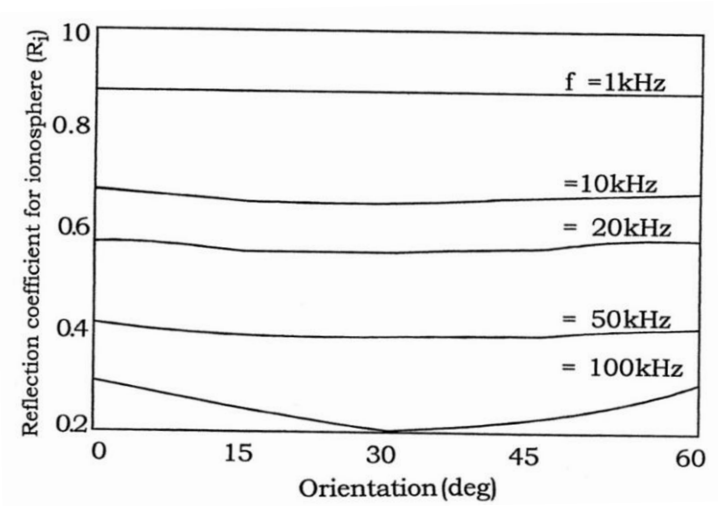

Fig. (5) Variation of reflection coefficient for ionosphere with orientation of channel for the range of frequency from 1 kHz to 100 kHz. Curves are plotted for, θ = 30° and, r = 100 km.

Thus, it is apparent from this study that the reflection coefficients have the maximum values for the ground and ionosphere when the lightning return stroke is vertical.

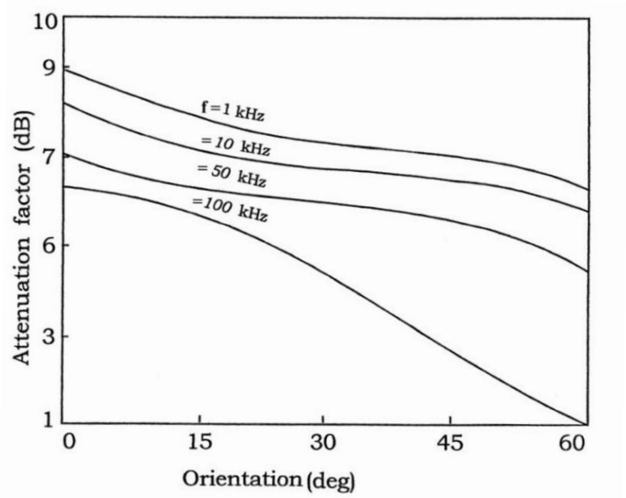

Fig. (6) Variation of amplitude of the attenuation factor in dB with orientation of lightning channel for the frequency range from 1 kHz to 100 kHz. Curves are plotted for θ = 30° and r = 100 km.

6.3 The Attenuation Factor

The variation of the attenuation factor in decibel (i.e. $20\log_{10}|F|$) versus orientation of the lightning channel for frequencies 1, 10, 50, and 100 kHz is shown in Fig. (6). In this computation observation angle and observation distance are taken as 30° and 100 km, respectively. It is clear from the figure that the attenuation factor decreases non - linearly for the frequency range from 1 to 100 kHz with increased orientation. In the orientation range from 0° to 60°, the maximum value of the attenuation factor is seen at the orientation $\Phi = 0°$ (i.e. for the vertical channel). As the frequency of the radiated VLF wave generated by the oblique return stroke increases, the maxima of attenuation factor shift to lower values.

Present calculation is devoted to compute the attenuation factor in dB for vertically polarized VLF wave generated by oblique orientation of return stroke for definite value of conductivity and relative dielectric constant for the ground. This assumption is far from reality because ground conductivity and relative dielectric constant depend on the soil contents.

Fig. (7) shows the manner in which the attenuation factor in dB varies with frequency for the orientation range from 0° to 45°. It is obvious from the figure that the attenuation factor decreases from maximum value as the frequency increases from 1 kHz to 100 kHz. In this frequency range, the maximum value of the attenuation factor is seen at 1 kHz for $\Phi = 0°$. As orientation of the channel increases, the maxima of the attenuation factor shift to lower values. Prasad and Singh [32] have reported that the attenuation factor is oscillatory in higher frequency regime for θ=60° and 90° and create differences of about 36 percent and 16 percent respectively which are significantly above the sensitivity of the measuring system.

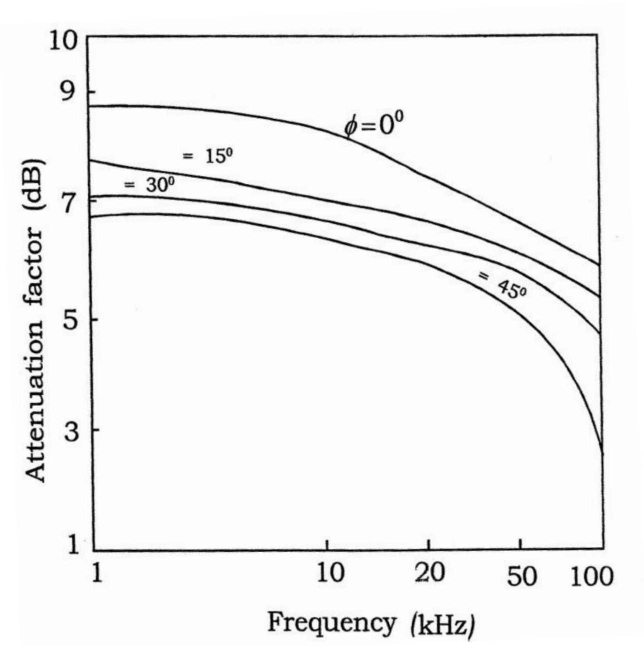

Fig. (7) Variation of amplitude of attenuation factor in dB with frequency for the orientation range from 0° to 45°. Curves are plotted for θ = 30° and observation distance, r = 100 km.

In this section, the attenuation factor is computed for $\theta = 30°$ only. This result is very similar to that reported by Prasad and Singh [32]

6.4 Propagation Effects On The Radiated Electric Field

Fig. (8) depicts the propagation effects on the spectrum of VLF electric field in propagating a distance, 100 km at $\theta = 30°$ when ground and ionosphere conductivities are 10^{-3} and 10^{-5} Ωm^{-1}, respectively. In the figure curve, 1 is plotted for orientation $\Phi = 0°$; curve, 2 for Φ =15° and curve, 3 for $\Phi = 30°$. The dielectric constants are taken as 10 and 1 for the ground and the ionosphere, respectively. The radiated electric field is maximum for the vertical channel (i.e. for $\Phi = 0°$). The maxima of the electric field shift to lower values with increased orientation from o° to 30°. It is apparent from Fig. (8) that the radiated electric field is maximum at 2.5 kHz for the orientation range from 0° to 30°. The radiated electric field is seen to increase to attain the maxima as the frequency varies from 1 kHz to 2.5 kHz and there after its value decreases. It is clear from the figure that the finitely conducting ground and the ionosphere influence the shape and amplitude of the radiated VLF electric fields generated by the oblique orientation of lightning return stroke, significantly. Thus it is important to note that the effects of orientation on the radiated VLF electric fields are significant and hence the measuring systems should be designed accordingly.

VII. CONCLSIONS

In this article it has been out lined that the well known radiation process is responsible for the radiation of

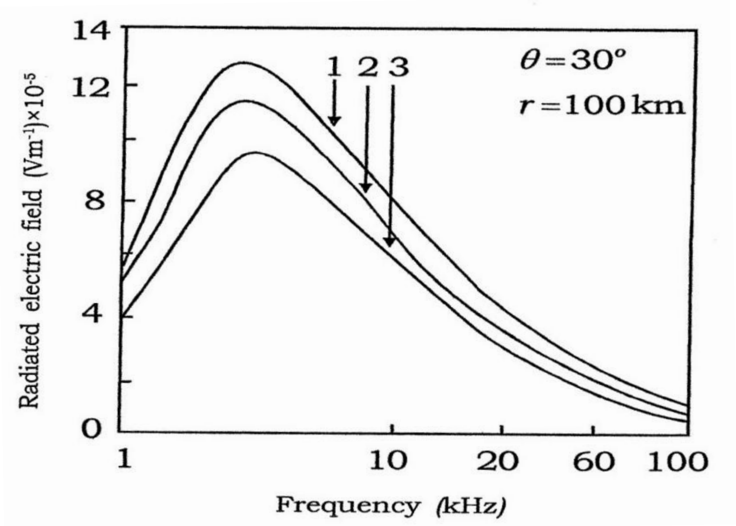

Fig. (8) Graph shows effects of the finitely conducting ground below and the ionosphere above on VLF electric fields radiated by oblique orientation of lightning channel. Curve 1, θ = 30°, Φ = 0°; curve 2, θ = 30°, Φ = 15° and curve 3, θ = 30°, Φ = 30°.

VLF electromagnetic waves generated by the oblique orientation of the lightning channel. For the study it is assumed that Bruce and Golde [33] type of current flows within the return stroke. The propagation effects of the finitely conducting ground and the ionosphere on VLF electric fields radiated by such oblique channel have been studied for different orientations. The orientations of the lightning discharge produce changes in the effects of fields at receiving point. The magnitude of VLF energy received at observation point governed by the orientations of the lightning channel, magnitudes and phases of three field components, namely: (1) direct, (2) reflected from the ground, and (3) reflected from the ionosphere. The attenuation of incident VLF electric fields has been investigated and is shown that it changes with orientations of the lightning channel. From the study it is clear that the changes in amplitude of VLF fields are significant and should be considered for designing the measuring instruments.

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