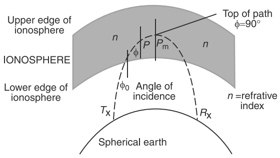
Chapter 4



Sky Wave Propagation

Topics in this chapter include:

- Introduction
- Structural details of ionosphere
- Wave propagation mechanism
- Refraction and reflection of sky waves
- Ray path, skip distance and MUF
- Critical frequency and virtual height
- Impact of solar activity
- Multi-hop propagation
- Takeoff angle
- Energy loss in ionosphere
- Primary and secondary services
- Wave characteristics

4–1 Introduction

This mode of wave propagation is confined to the high-frequency range and its application to the broadcast services with the exception of OTH radars. The propagation of sky waves (also called ionospheric waves) revolves around the refraction mechanism in the ionosphere. The electromagnetic waves are launched towards the ionosphere wherefrom, under suitable conditions, they return to the earth due to the refraction mechanism. Their satisfactory return depends on a number of factors including frequency of operation, angle of takeoff and ionospheric conditions. In the following text, various aspects of ionospheric propagation are discussed in detail.

4–2 Structural Details of the Ionosphere

The ionosphere is a region above the earth and is composed of ionized layers. In general, four layers, namely D, E, F_1 and $F_2$are assumed to exist at different heights. The distances of these layers, from the earth, are normally referred to the heights at which the concentration of ionized electrons is maximum. These layers are shown in Fig. 4–1.

D layer It exists between 50 to 90 km above the earth's surface. It is a daytime phenomena and is largely absent in the night. Ionization in the D layer is low because less ultraviolet light penetrates to this level. At VLF, the space between the D layer and the ground acts as a huge waveguide, making communication possible but only with large antennas and high power transmitters. At LF and MF ranges, this layer is highly absorptive and limits daytime communication to about 300 km. It is responsible for much of the daytime attenuation of HF waves. This layer starts losing its absorptive nature in the MHz range and at 30 MHz, waves cross the D layer un-attenuated. Its structural details are not yet known with certainty.

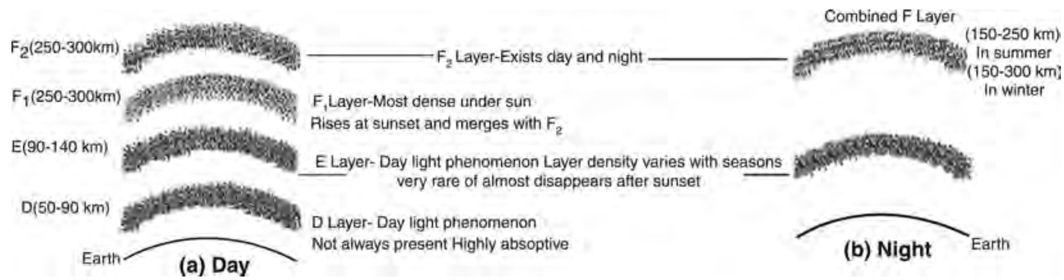


Figure 4–1 Ionospheric layers with some of the salient features.

E layer It exists between 90 to 140 km above the earth's surface, with maximum density at about 110 km. It is almost constant with little diurnal or seasonal variations. It is closely governed by the amount of ultraviolet light from the sun and uniformly decays with time at night. This layer permits medium distance communication in LF and HF bands. At night, the D layer slightly rises and the E layer slightly lowers to form one layer, which is again called the E layer.

F_1 layer It exists between 150 to 250 km above the earth's surface in summer and 150 to 300 km in winter. This layer is also almost constant with little diurnal or seasonal variations.

F_2 layer It exists between 250 to 400 km. At night, the F_1 layer slightly rises and the F_2 layer slightly lowers to form one layer, which is again called the F_2 layer. It is sometimes also referred as the F layer. It is more variable in nature. The F_2 layer is responsible for most of the HF long-distance communication.

Sporadic E It is the result of an anomalous phenomenon and falls under the category of *irregular variations*. Its occurrence is quite unpredictable and is observed both during day and night. The cause of its appearance is still uncertain. It occasionally appears in and around the E layer, at discrete locations and then disappears. It often occurs in the form of clouds of charged particles of varying size from a fraction of a kilometre to several hundred kilometres across. It can be so thin that radio waves penetrate it and are returned by the upper layers, or it can extend up to hundreds of km. This layer may appear anywhere between the E and F_1 layers or within the range of the E layer itself.

The negative aspects of the sporadic E layer are that it sometimes prevents the use of higher, more favourable layers and at some frequencies it may also result in (i) additional absorption, (ii) multipath problem, and (iii) additional delay in return of the waves. Its positive aspects include that it has greater critical frequency and thus permits long-distance communication at much higher frequencies than the usual ones for well-defined layers. Sometimes the locations falling in skip zones can be illuminated by the returns from the sporadic E layer.

A few authors have also mentioned about the existence of a C layer between heights of 50 to 70 km. It is said to exist only during the day and disappears in the night. Its impact on wave propagation is of little significance.

In addition to Fig. 15.47, a complete picture showing different layers encircling the earth during day and night is again illustrated by Fig. 4–2. Details about Van-Allen-Belts were included in Chapter 22. Further details about characteristics of various ionospheric regions are included in Table 4–1.

4–3 Wave Propagation Mechanism

4–3a Refraction In The Absence Of Earth's Magnetic Field

To understand the refraction mechanism, first assume that the earth's magnetic field is either absent or its effect is almost negligible. Later the effect of earth's magnetic field on the propagation mechanism can be

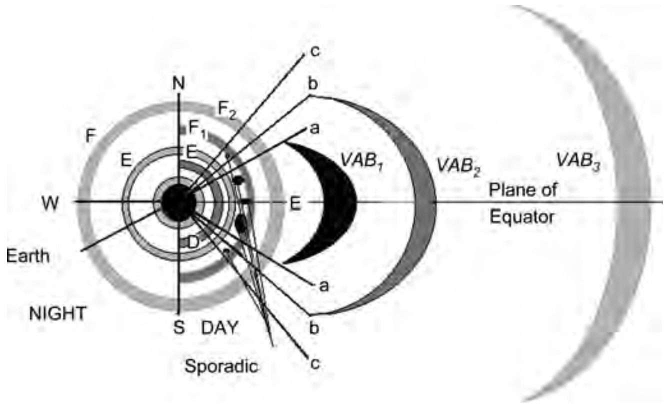


Figure 4–2 Ionospheric layers and Van-Allen-Belts girdling the earth.

Table 4–1 Characteristics of the various regions of the ionosphere

Particulars	D	E	F1	F2
Likely origin	Ionization of NO with Lyman-alpha radiation, Ionization of all gases by soft X-rays	Ionization of all gases by soft X-rays	Ionization of O with fast decrease of recombination coefficient with height	Ionization of O by UV, X-rays and probably corpuscular radiation
Height in km	60–90 by day, disappears at night	100–140	180–240 by day, disappears at night	230–400
Molecular density/cm^3	10^{14}–10^{16}	5×10^{11}–10^{13}	About 10^{11}	About 10^{10}
Electron or ion density/cm^3	10^2–10^3 for electrons 10^6–10^8 for ions	Up to 10^5 to 4.5×10^5 by day, fixed at about 5×10^3 to 10^4 at night	$2 \times 10^5 - 4.5 \times 10^5$	Max. 2×10^6 by day in winter, max. 2×10^5 by day in summer, 3×10^5 at night in winter
Collision /second	10^7 at lower edge	10^5	10^4	10^3–10^4
Recombination coefficient cm^3/second	10^{-5}–10^{-7}	10^{-8}	4×10^{-9}	8×10^{-11} by day 3×10^{-11} at night

incorporated to get the real picture. With this assumption, the following two interpretations about the bending of ionospheric waves are generally accepted.

Interpretation-I The wave phenomena can be mathematically derived in terms of electric and magnetic field vectors '**E**' and '**H**' from Maxwell's equations. Further, the ionosphere, a region wherein the matter is completely in the ionized state, is composed of ionized particles, viz., electrons and protons. A charge 'Q' in an electric field '**E**' experiences a force '**F**' in accordance with the relation $\mathbf{F} = Q\ \mathbf{E}$. The force exerted on electrons causes them to vibrate, in sinusoidal fashion, along with the lines of electric flux. These vibrating electrons can be visualized as small loops with the current I_L. The current density $\mathbf{J}_L$ is proportional to the velocity of vibration '**U**', in accordance with the relation $\mathbf{J} = \rho_e\ \mathbf{U}$, where '$\rho_e$' is the electron charge density. The maximum velocity $\mathbf{U}_{max}$ lags behind **E**. Thus the current I_L resulting from these vibrating electrons is inductive in nature. In view of the Maxwell's equation, $\nabla \times \mathrm{H} = \partial \mathbf{D}/\partial t = \varepsilon\ \partial \mathbf{E}/\partial t$

or the displacement current density $\mathbf{J}_d$ with the conduction current $\mathbf{J}_c$ is assumed to be zero in free space, Thus, the displacement current or the capacitive current (I_d) already exists within the medium due to the presence of electric the vector field **E**. These two currents (I_L and I_d), being of inductive and capacitive nature subtract, resulting in the decrease of net current, due to the presence of ionized electrons. Since $J_d = \varepsilon\, \partial\mathbf{E}/\partial t$, and there is no change in **E**, the decrease in the net current is viewed by the wave as a change (reduction) of ε. A decrease in ε will result in bending of path of the wave, from a high electron-density region to a low electron-density region. Since the average velocity of the vibrating electrons is inversely proportional to the frequency 'f', the magnitude of current is greater for lower frequencies and smaller for higher frequencies. When f is lower enough, the capacitive and inductive currents are equal and the resultant current is zero, amounting to $\varepsilon = 0$. The wave which was gradually bending away from the normal due to smooth change in ε towards the lower side suddenly finds its value to be zero. At this point, the wave starts bending downward and travels back to the ground, where it may be received by a user antenna.

Interpretation-II According to the second interpretation, each vibrating electron acts as a small radio antenna extracting energy from the passing wave. This extracted energy is later re-radiated by these microscopic antennas. Since I_L due to this re-radiated energy lags **E** by 90°, these electrons, acting as parasitic antennas, are tuned to offer an inductive reactance, The net effect is to alter the direction in which the resultant energy flows. Though ions in the path also behave in the same manner as electrons but since they are heavier they vibrate at a much slower rate than the electrons, under the influence of the electric field, and hence have negligible effect on the propagation mechanism.

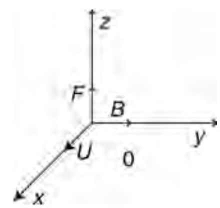


Figure 4–3 F, U and B along orthogonal coordinates x, y and z.

The above two interpretations ultimately result in smooth bending of the wave towards the earth in the absence of a magnetic field. Since the earth's magnetic field is a real entity, its impact on the bending process needs special consideration, which is given as below.

4–3b Refraction in the Presence of the Earth's Magnetic Field

The vector force **F** on a charge in motion (having a velocity **U**) in the presence of the earth's magnetic field **B** is given by the relation $\mathbf{F} = Q\,(\mathbf{U} \times \mathbf{B})$. These (orthogonal) vectors are illustrated in Fig. 4–3.

At high frequency, a component of **B** at right angles to **E** of the incident wave causes vibrating electrons to follow elliptic paths. The new **E** (=$\mathbf{F}/Q$) will have two components, one parallel and the other perpendicular to **E** of the wave. Thus, the polarization of **E** will be rotated by 90° in space with respect to the incident wave. Since some of the portions of such paths have components at right angles to **E** of the wave, the electrons, from the passing wave, absorb some energy. This energy is re-radiated with polarization that is rotated by 90° in space with respect to the polarization of the incident wave. Thus, the earth's magnetic field (shown in Fig. 4–4) will normally cause a plane-polarized radio wave to become elliptically polarized after it travels some distance in the ionosphere.

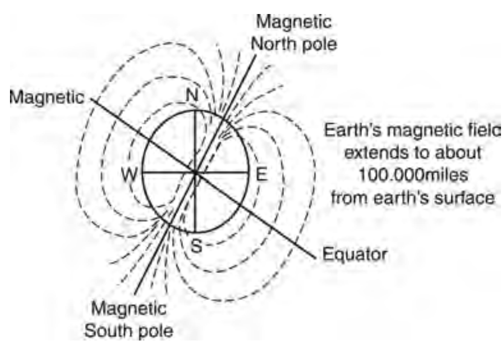


Figure 4–4 The earth's magnetic field and its orientation.

As stated earlier, the average velocity is inversely proportional to the frequency. Thus, at higher frequencies electrons vibrate along very narrow elliptical paths, whereas at lower frequencies, the effect on is greater vibrating electrons. As frequency decreases, the amplitude of vibration increases, or the minor axis of the ellipse increases, and the ellipse becomes larger and larger. If the frequency is further decreased, a cyclotron resonance occurs, the ellipse breaks and electrons start following a spiral path of steadily increasing radius. The frequency (≅1400 kHz) at which this resonance occurs is called the ***gyro frequency*** 'f_g'. Figure 4–5 illustrates the whole process of change with frequency and breaking of the ellipse at gyro frequency. At still lower frequencies, electrons follow a relatively complicated path having components of motion, both parallel and perpendicular to the plane of polarization.

The effect of the magnetic field will greatly depend on relative orientation of flux lines with respect to the plane of polarization of the wave, i.e., there will be no effect at all if **B** and **E** are parallel, and there will be maximum effect if these are perpendicular. The magnetic field also causes the wave to split into two components. These components, termed as *ordinary* and *extraordinary waves*/rays, will have elliptic polarization that rotates in opposite directions. The two will bend by different amounts by the ionized medium and travel different paths. Their rates of energy absorption and velocities also differ. This action of splitting is termed as ***magneto-ionic splitting*** and its extent and amplitudes depend on |**B**|, i.e., the magnitude of the earth's magnetic field in the region of interest.

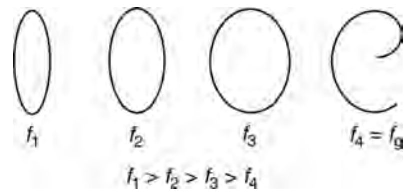


Figure 4–5 Effect of frequency on vibrating electrons.

4–4 Refraction and Reflection of Sky Waves by Ionosphere

In view of Fig. P17–3–9 and Fig. 4–6, the refraction phenomena in the ionosphere is governed by the following relations:

$$n = \sqrt{\varepsilon} = \sqrt{(1 - 81N/f^2)} \quad (1)$$

$$n \sin\phi = \sin\phi_0 \quad (2)$$

$$\text{and } v_p = c/n \quad (3)$$

where, n is the refractive index of the ionosphere, ε (= ε_r) is the permittivity relative to free space, N is the number of electrons per cubic cm, f is the frequency in kHz, ϕ is the angle of refraction at P, ϕ_0 is the angle of incidence at the lower edge of ionosphere and c is the velocity of light.

To understand the relation given by (1), let us assume that a plane wave is traveling the positive Z-direction. Its electric field E has a component only along the x-axis (i.e., E_y and $E_z$are zero). Thus, E can be written as $E = E_x\mathbf{a}_x$, where $E_x = E \sin \omega t$. Also, the wave has only one component of H, i.e, $H = H_y\ \mathbf{a}_y$ (H_x and H_z are 0). This wave moves in a region containing free electrons. The electric field E will exert a force on each electron:

$$F_x = -eE_x \quad (4)$$

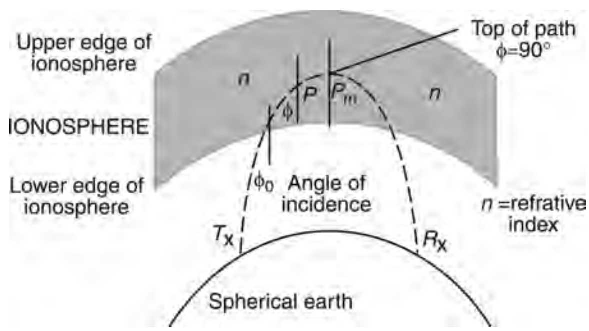


Figure 4–6 Bending of wave from an ionospheric layer.

This force results in acceleration of electrons in the x direction. From Newton's law,

$$\frac{md^2x}{dt^2} = -eE_x = -eE \sin \omega t \tag{5}$$

(5) with initial zero condition results in

$$\frac{dx}{dt} = -\frac{e}{m}\int E \sin \omega t \; dt = \frac{e}{m\omega} E \cos \omega t \tag{6}$$

If there are N electrons per cubic meter in the space, each carrying a charge $-e$ and having mass m, the current density J represented by this motion of electrons is

$$J = -Ne\frac{dx}{dt} = -\frac{Ne^2}{m\omega} E \cos \omega t \tag{7}$$

This current density must be included in Maxwell's equations, and in a particular case the term is generally represented by $J = \sigma E$

where $$\sigma = \frac{-Ne^2}{m\omega} \tag{8}$$

In view of Maxwell's equations,

$$\nabla \times H = J + \frac{\partial D}{\partial t} = \sigma E + \varepsilon \frac{\partial E}{\partial t} \text{ (a)} \quad \text{and} \quad \nabla \times E = -\frac{\partial B}{\partial t} = -\mu \frac{\partial H}{\partial t} \text{ (b)} \tag{9}$$

and the assumption that E has only the x component and H has only the y component. The following relations emerge.

$$J + \varepsilon_0 \frac{\partial E_x}{\partial t} = -\frac{\partial H_y}{\partial z} \tag{10a}$$

$$\mu_0 \frac{\partial H_y}{\partial t} = -\frac{\partial E_x}{\partial z} \tag{10b}$$

Substitution of Eqs (7) and (8) in Eq. (10a) gives

$$-\frac{Ne^2}{m\omega^2} E \cos \omega t + \varepsilon_0 \frac{\partial}{\partial t}(E \sin \omega t) = -\frac{\partial H_y}{\partial z} \tag{11}$$

$$\text{or } \left(\varepsilon_0 - \frac{Ne^2}{m\omega^2}\right) \omega E \cos \omega t = \varepsilon_0 \left(1 - \frac{Ne^2}{m\omega^2 \varepsilon_0}\right) \tag{12}$$

$$\omega E \cos \omega t = \varepsilon_0 \, \varepsilon_r \, \omega \, E \, \cos \omega t = -\frac{\partial Hy}{\partial z}$$

$$\text{where } \varepsilon_r = 1 - \frac{Ne^2}{m\omega^2 \varepsilon_0} \tag{13}$$

Since the refractive index $n = \sqrt{\in_r}$

$$n = \left(1 - \frac{Ne^2}{m\omega^2 \varepsilon_0}\right)^{1/2} = \left(1 - \frac{Ne^2}{m\varepsilon_0 (2\pi f)^2}\right)^{1/2} = \left(1 - \frac{Ne^2}{4\pi^2 \varepsilon_0 m f^2}\right)^{1/2} \tag{14}$$

For $e = 1.59 \times 10^{-19}$ c, $m = 9 \times 10^{-3}$ kg and f in Hz

$$n = \left[1 - \frac{N(1.59 \times 10^{-19})^2}{4\pi^2 \in_0 (9 \times 10^{-31}) f^2}\right]^{1/2} = \left(1 - \frac{81N}{f^2}\right)^{1/2} \tag{15}$$

From (15), it can be noted that n is a function of frequency so the velocity of the wave is also frequency dependent. This is the same phenomenon as observed in waveguides, giving rise to two velocities known as *phase velocity* and *group velocity*.
The phase velocity

$$v_p = \frac{c}{\sqrt{\mu_r \varepsilon_r}} = \frac{c}{\sqrt{\varepsilon_r}} = \frac{c}{(1 - \frac{81N}{f^2})^{1/2}} \text{ (for } \mu_r = 1) \tag{16a}$$

The group velocity

$$v_g = c(1 - \frac{81N}{f^2})^{1/2} \tag{16b}$$

From (16), it can be concluded that the phase velocity is directly proportional to the frequency whereas the group velocity is inversely proportional to the frequency. Lastly, (16a and b) lead to the well-known relation:

$$v_p v_g = c^2 \tag{17}$$

A critical study of (1, 2 and 3) reveals the following possibilities.

1. $n > 1$: This condition requires the term $81N\ /\ f^2$to be negative which is not possible in view of the nature of involved parameters. Thus, this condition does not exist.
2. $n < 1$: This condition requires that $81N\ /\ f^2 < 1$. This condition always exists. In view of (3) and this condition, v_p is always greater than c.
3. $n = 1$: This condition means that the term $81N\ /\ f^2 = 0$. In this case, $v_p = c$ and from (3), $\phi = \phi_0$.
4. $n = 0$: This condition requires that the term $81N\ /\ f^2 = 1$or $81N = f^2$. At this point, $f = f_c$ (where f_c is termed the *critical frequency*), and the inductive current i_L equals the capacitive current i_c. Also, in this case $v_p = \infty$ and from (3), $\phi_0 = 0$.
5. For $81N\ /\ f^2 > 1$ or $f^2 < 81N$, n is an imaginary quantity. In this case, the ionosphere shall not be able to transmit a wave at such a frequency, Instead, the wave will get attenuated.

When $v_p - c$ is large for $81N/f^2$, the wave front advances faster in the region where N is large than that where N is less. The wave gradually bends and follows the optical law given by (2). Smaller the ϕ_0, smaller the n, a higher N is required for the wave to return to the earth.

From the critical frequency relation $f_c^2 = 81N$, f_c corresponds to the maximum N of a layer. As N increases, the refractive index n decreases. For $f \leq f_c$, the wave will get reflected back from the layer irrespective of ϕ_0. For $f > f_c$, the wave will return only when ϕ_0 is sufficiently small or when ϕ_0 satisfies (2). The wave will penetrate the ionosphere otherwise.

The reflection $n \sin\phi = \sin\phi_0$ gives the path of a ray only when the change of n with height is small in a distance corresponding to λ in the medium, otherwise there is an appreciable reflection as well as refraction and the propagation can no longer be described in terms of a simple ray path. If change in n is very large in the space of λ, the wave has a true reflection from a well-defined boundary. For an intermediate situation, a mixture of reflection and refraction takes place.

The phase velocity v_p is related to c and n by the relation (3). Since $n < 1$ for an ionized medium, v_P is always greater than c. The difference $v_P - c$ is large for large N/f^2. As a result, when a wave enters the ionosphere, the edge of the wave front in the region of highest electron density will advance faster than the part of the wave front encountering region of lower electron density. The wave path in the ionosphere is accordingly bent. This bending of a wave follows optical law (i.e., $n \sin \phi = sin\phi_0$) shown in Fig. 4–6.

Here, n is the refractive index at the point P, ϕ is the angle of refraction at P, ϕ_0 is the angle of incidence at the lower edge of the ionosphere, and P_M is referred as the highest point of refraction from where the wave changes its direction downward. In view of this, smaller the ϕ_0, smaller the n, higher the N required to return the wave towards the earth. At $\phi_0 = 0$, $n = 0$, the wave penetrates the ionosphere such that $f_c^2 = 81N$.

The variation of electron density 'N' with height 'h' is illustrated in Fig. 4–7. The figure also indicates the relative locations of different ionospheric layers during day and night.

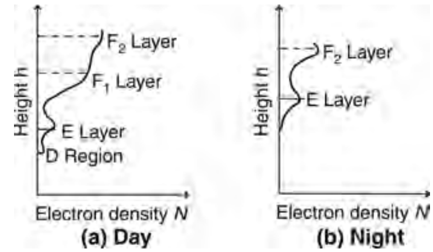


Figure 4–7 Variation of electron density 'N' with height 'h'.

4–5 Ray Path, Critical Frequency, MUF, LUF, OF, Virtual Height and Skip Distance

These terms are very commonly used in connection with sky wave propagation and thus all these terms require proper understanding for establishing ionospheric communication links. The definitions and detailed discussion related with these terms are given below.

Ray Path The path followed by a wave is termed *ray path*. Figure 4–8 illustrates six different paths followed by a wave under different conditions.

When $f > f_c$, the effect of the ionosphere depends on the angle of incidence ϕ_0. According to Fig. 4–6, we can infer the following:

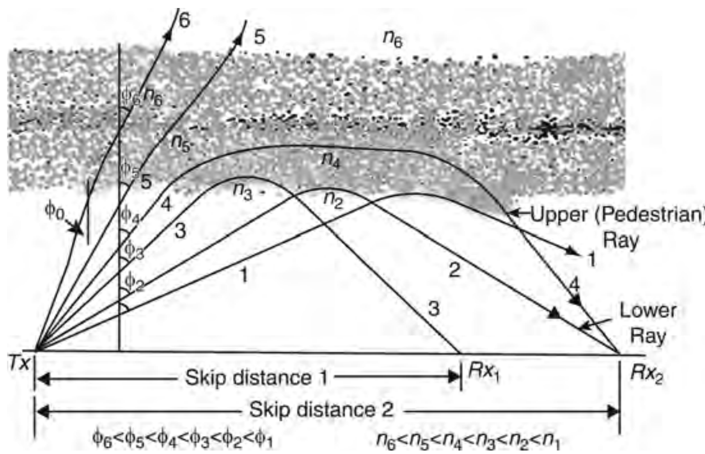


Figure 4–8 Illustration of paths followed by waves under different conditions.

1. When ϕ_0 is relatively large, the wave satisfies the relation $n = \sin\phi_0$. When n drops to less than 1, the wave returns after slight penetration (Ray-1).
2. When ϕ_0 decreases, n decreases, and penetration of the wave increases (Ray-2, 3 and 4).
3. When ϕ_0 further decreases, (2) of Sec. 4–4 cannot be satisfied even with the maximum electron density of the layer, the wave penetrates and crosses the layer (Ray-5 and 6).
4. In view of the point 2 and from Fig. 4–8, it can be seen that the distance at which the wave returns decreases until $\phi_0 = \phi_c$. The angle ϕ_c is called the *critical angle* and at this angle, the distance of return is minimum. This distance is called *skip distance* (Ray-2, 3 and 4).
5. When ϕ_0 further decreases and is less than ϕ_c, the distance of return first increases (Ray-4) and then penetrates the layer.

EXAMPLE 4–5.1 Calculate the skip distance for flat earth with MUF of 10 MHz if the wave is reflected from a height of 300 km where the maximum value of n is 0.9.

Solution

In view of (1),

$$
\begin{aligned}
n^2 &= 0.81 = (1 - 81N/f^2) \\
N_{\max} &= (1 - n^2)f^2/81 = [(1 - 0.81)\times 10^{14}]/81 = (19/81)\times 10^{12} \\
&= 23.45\times 10^{10} \\
f_c &= 9\sqrt{N_{\max}} = 9\sqrt{(23.45\times 10^{10})} = 9\times 4.8425\times 10^5 = 4.36\,\text{MHz} \\
\text{d}_{\text{skip}} &= 2h\sqrt{[(f_{\text{MUF}}/f_c)^2 - 1]} = 2\times 300\sqrt{[(10/4.36)^2 - 1]} = 600\times 6.527 \\
&= 3916.2\,\text{km}
\end{aligned}
$$

EXAMPLE 4–5.2 The critical frequencies at an instant observed for E, F_1 and F_2 layers were found to be 3, 5 and 9 MHz. Find the corresponding concentration of electrons in these layers.

Solution

$$
\begin{aligned}
&f_c = 9\sqrt{N_{\max}} \quad \text{or} && N_{\max} = f_c^2/81 \\
&\text{For E layer}, f_c = 3\text{MHz} && N_{\max} = f_c^2/81 = 9\times 10^{12}/81 = 0.111\times 10^{12} \\
&\text{For F}_1\text{ layer}, f_c = 5\text{MHz} && N_{\max} = f_c^2/81 = 25\times 10^{12}/81 = 0.3086\times 10^{12} \\
&\text{For F}_2\text{layer}, f_c = 9\text{MHz} && N_{\max} = f_c^2/81 = 81\times 10^{12}/81 = 10^{12}
\end{aligned}
$$

EXAMPLE 4–5.3 Calculate the critical frequencies for E, F_1 and F_2 layers if N_{max} for each corresponding layer reduces to 80% of the values obtained in Problem 4–5.1.

Solution

$$
\begin{aligned}
&\text{For E layer}, N_{\max} = 0.8\times 0.111\times 10^{12} && f_c = 9\sqrt{N_{\max}} = 9\sqrt{0.0888\times 10^{12}} = 2.68\,\text{MHz} \\
&\text{For F}_1\text{layer}, N_{\max} = 0.8\times 0.3086\times 10^{12} && f_c = 9\sqrt{N_{\max}} = 9\sqrt{0.24688\times 10^{12}} = 4.47\,\text{MHz} \\
&\text{For F}_2\text{layer}, N_{\max} = 0.8\times 10^{12} && f_c = 9\sqrt{N_{\max}} = 9\sqrt{0.8\times 10^{12}} = 8.05\,\text{MHz}
\end{aligned}
$$

Critical Frequency The highest frequency that returns from an ionospheric layer at a vertical incidence is called the *critical frequency* for that particular layer. For a regular layer, it is proportional to the square root of maximum electron density in the layer. Figure 4–9 shows the critical frequencies for different ionospheric layers at different instants of time in (a) winter, and (b) summer seasons.

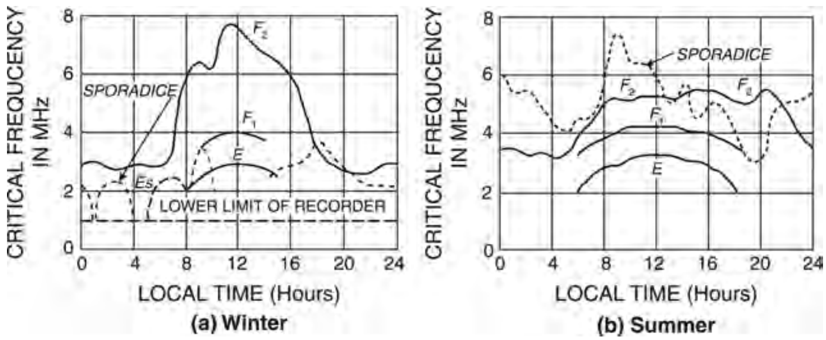


Figure 4–9 Critical frequencies for different ionospheric layers.

Maximum Usable Frequency Earlier, it was mentioned that the critical frequency f_c is the highest frequency that returns from an ionospheric layer at a vertical incidence. When the frequency exceeds f_c, the return will depend upon the angle of incidence at a particular ionospheric layer. Thus, for a specified angle of incidence, there will be a maximum frequency which will be reflected back. The maximum possible value of frequency for which reflection takes place for a given distance of propagation is termed as *maximum usable frequency (MUF)* for that distance and for the given ionospheric layer. Beyond MUF, the wave will not return. Figure 4–6 shows that at the point of reversal of path to return to the ground, the sky wave requires the angle of reflection to be 90°. Thus, if ϕ_0 is the incident angle and ϕ_r is the reflection angle, the refractive index n can be written as

$$n = \frac{\sin\phi_i}{\sin\phi_r} = \frac{\sin\phi_i}{\sin 90} = \sin\phi_i = \sqrt{1 - \frac{81N_{\max}}{f_{MUF}^2}} \tag{1}$$

$$\sin^2\phi_i = 1 - \frac{81N_{\max}}{f_{MUF}^2} \tag{2}$$

But as discussed earlier,

$$f_c^2 = 81N_{\max} \tag{3}$$

$$\text{Thus,} \quad \sin^2\phi_i = 1 - \frac{f_c^2}{f_{MUF}^2} \quad \text{or} \quad \frac{f_c^2}{f_{MUF}^2} = 1 - \sin^2\phi_i = \cos^2\phi_i \tag{4}$$

$$f_{MUF}^2 = \frac{f_c^2}{\cos^2\phi_i} = f_c^2 \sec^2\phi_i \tag{5}$$

Finally, we get

$$f_{MUF} = f_c \sec\phi_i \tag{6}$$

Equation (6) is known as *secant law*. It indicates that f_{MUF} is greater than f_c by a factor $\sec\phi_i$. It gives the maximum frequency which can be used for sky wave communication for a given angle of incidence between two locations.

Figure 4–10 illustrates the maximum usable frequencies at different times destined for coverage of various distances.

Lowest Usable Frequency The frequency below which the entire power gets absorbed is referred to as *lowest usable frequency* (LUF).

Optimum Frequency The frequency at which there is optimum return of wave energy is called the *optimum frequency* (OF).

Figure 4–11 illustrates the LUF, OF, MUF and the critical frequency f_c on a frequency scale. Limits of all these frequencies are different for different layers.

Virtual Height It may be defined as 'the height to which a short pulse of energy sent vertically upward and traveling with the speed of light would reach taking the same two-way travel time as does the actual pulse reflected from the ionospheric layer.'

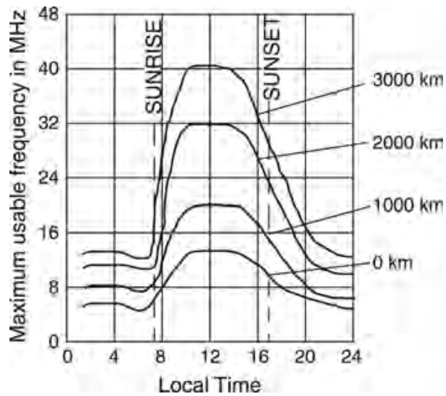


Figure 4–10 Maximum usable frequencies at different times of the day.

Figure 4–12 illustrates that there is no sharp change of the direction of wave and it starts bending down gradually (from the point E) through the process of refraction in the ionosphere. Just below the ionosphere (the point F), the incident and refracted rays follow exactly the same path as would have been followed by them if the reflection had taken place from a surface located at a greater height (the point B) which is often referred as the *virtual height*. If the virtual height of a layer is known, the angle of incidence required for the return of wave to the ground at a selected spot (the point C) can easily be calculated.

Figure 4–12 illustrates two different cases containing (a) flat earth, and (b) curved earth. The above discussion is true for both cases. On comparison of Fig. 4–12 (*a*) and (*b*), it can easily be concluded that both the actual height and the virtual height in case of curved earth are less than that for flat earth. The virtual height, however, is always greater than the actual height of

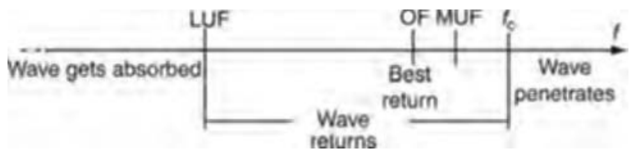


Figure 4–11 LUF, OF, MUF and f_c on a frequency scale.

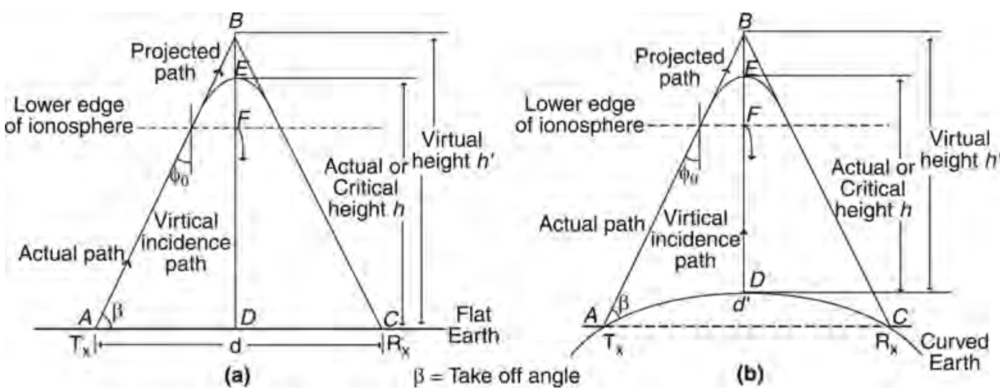


Figure 4–12 Actual and virtual height and the related parameters for (a) flat earth, and (b) spherical earth.

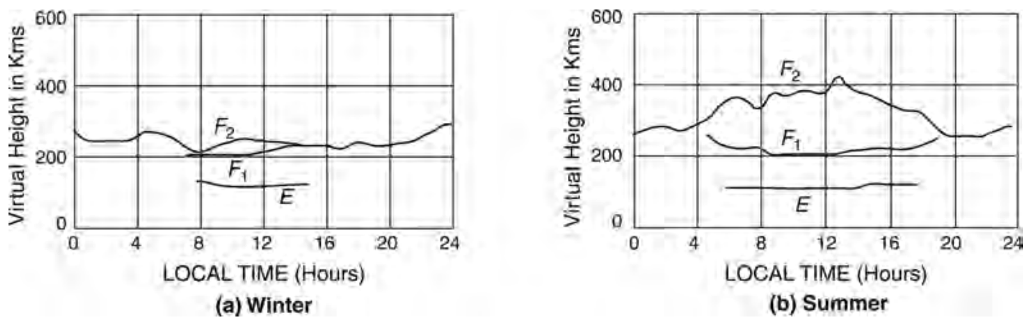


Figure 4–13 Virtual heights at different times of a day.

reflection because the exchange of energy that takes place between the wave and the electrons of the ionosphere causes the velocity of propagation to be reduced. The difference between virtual and true heights is influenced by the electron distribution in the regions below the level of reflection. It is usually quite small, but on occasions may be as large as 100 km or more. Figure 4–13 shows the virtual heights for different ionospheric layers at different instants of time in (a) winter, and (b) summer seasons.

Skip Distance The minimum distance at which the wave returns to the ground at a critical angle ϕ_c is termed the *skip distance*. Figure 4–8 illustrates two different skip distances which correspond to rays 2, 3 and 4. As mentioned earlier, the skip distance and the maximum usable frequency correspond to each other.

4–6 Relation Between MUF and the Skip Distance

Flat Earth Case Figure 4–14*a* illustrates the ionized layer which is assumed to be thin with sharp ionization density gradient so as to obtain mirrorlike reflections. For shorter distances, the earth can be assumed to be flat. In the figure, h is the height of the ionospheric layer, d is the skip distance, θ_i is the angle of incidence and θ_r is the angle of reflection. In view of the geometry of the configuration,

$$\cos\theta_i = \frac{OB}{AB} = \frac{h}{\sqrt{h^2 + d^2/4}} = \frac{2h}{\sqrt{4h^2 + d^2}} \tag{1}$$

In view of (4) of Sec. 4–5,

$$\frac{f_c^2}{f_{MUF}^2} = \cos^2\theta_i = \frac{4h^2}{4h^2 + d^2} \quad \text{or} \quad \frac{f_{MUF}^2}{f_c^2} = \frac{4h^2 + d^2}{4h^2} \tag{2}$$

$$\frac{f_{MUF}}{f_c} = \sqrt{\frac{4h^2 + d^2}{4h^2}} = \sqrt{1 + \frac{d^2}{4h^2}} \quad \text{or} \quad f_{MUF} = f_c\sqrt{1 + (\frac{d}{2h})^2} \tag{3}$$

Equation (3) gives MUF in terms of skip distance. Alternatively, from (1),

$$\frac{f_{MUF}^2}{f_c^2} = 1 + \frac{d^2}{4h^2} \quad \text{or} \quad \left(\frac{d}{2h}\right)^2 = \frac{f_{MUF}^2}{f_c^2} - 1 \quad \text{or} \quad d^2 = (2h)^2\left[\frac{f_{MUF}^2}{f_c^2} - 1\right]$$

$$d = (2h)\sqrt{[\frac{f_{MUF}^2}{f_c^2} - 1]} \tag{4}$$

Equation (4) gives skip distance with MUF

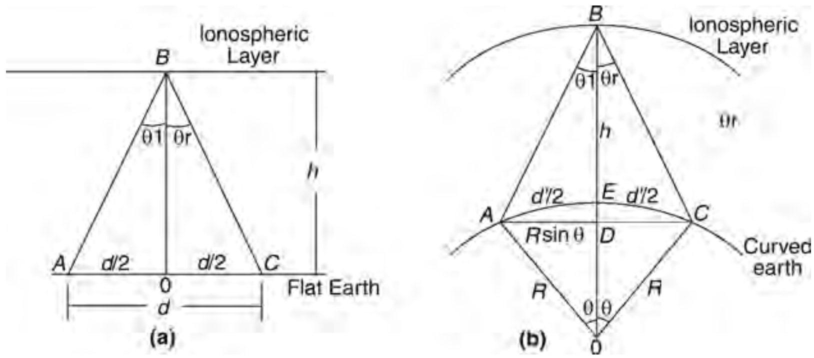


Figure 4–14 Skip distance and related geometrical parameters for (a) flat earth, and (b) spherical earth.

Curved earth case: Fig. 4–14*b* This shows the ionized layer and the curved earth. It is again assumed that the ionospheric layer is thin with sharp ionization density gradient so as to obtain mirror like reflections. In this figure, 2θ is the angle subtended by the skip distance d' at the center of the earth. From the geometry of Fig. 4–14*b*, the following relations are obtained:

$$\text{Arc}\, d' = 2R\theta \tag{5}$$

$$\text{Angle}\, 2\theta = d'/R \tag{6}$$

$$AD = R\sin\theta, \quad OD = R\cos\theta, \quad BD = OE + EB - OD$$

$$= R + h - R\cos\theta \tag{7}$$

$$AB = \sqrt{(AD)^2 + (BD)^2} = \sqrt{(R\sin\theta)^2 + (R + h - R\cos\theta)^2} \tag{8}$$

$$\cos\theta_i = \frac{BD}{AB} = \frac{R + h - R\cos\theta}{\sqrt{(R\sin\theta)^2 + (R + h - R\cos\theta)^2}} \text{ or}$$

$$(\cos\theta_i)^2 = \frac{(R + h - R\cos\theta)^2}{(R\sin\theta)^2 + (R + h - R\cos\theta)^2} \tag{9}$$

$$\text{Since } \frac{f_c^2}{f_{MUF}^2} = (\cos\theta_i)^2$$

the skip distance d' is maximum when θ is maximum. The curvature of the earth limits both the MUF and the skip distance. This limit is obtained when a wave leaves the transmitter at a grazing angle *OAB* = 90°. Under this condition,

$$\cos\theta = \frac{OA}{OB} = \frac{R}{R + h} \tag{10}$$

Since the actual value of θ is very small, this relation can be expanded as

$$\cos\theta = \frac{R}{R + h} = \frac{R}{R(1 + h/R)} = (1 + h/R)^{-1} \approx (1 - h/R), \text{ since } h/R << 1 \tag{11}$$

$$\cos\theta = \sqrt{1 - \sin^2\theta} \approx (1 - \theta^2)^{1/2} = 1 - \theta^2/2 \text{ for small } \theta \tag{12}$$

From (11) and (12),

$$1 - \frac{\theta^2}{2} = 1 - \frac{h}{R} \quad \text{or} \quad \theta^2 = \frac{2h}{R} \tag{13}$$

In view of (5) and (13),

$$d'^2 = 4R^2\theta^2 = 4R^2\frac{2h}{R} = 8hR \text{ or } d' = \sqrt{8hR} \tag{14}$$

$$\text{From (14), } h = \frac{d'^2}{8R} \tag{15}$$

In (14) and (15), d' is the maximum skip distance.
Equation (11) can now be rewritten in view of (15) as

$$\cos\theta = 1 - \frac{h}{R} = 1 - \frac{d'^2}{8R^2} \tag{16}$$

Also in view of (14) and (16)

$$\sin\theta \approx \theta = \sqrt{\frac{2h}{R}} = \sqrt{\frac{2d'^2/8R}{R}} = \sqrt{\frac{d'^2}{4R^2}} = \frac{d'}{2R} \tag{17}$$

Again in view of (4), of Sec. 4–5, and (9), (16), and (17)

$$\frac{f_c^2}{f_{MUF}^2} = \cos^2\theta_i = \frac{[R + h - R(1 - d'^2/8R^2)]^2}{(R^2\frac{d'^2}{4R^2}) + \{R + h - R(1 - \frac{d'^2}{8R^2})\}^2}$$

$$= \frac{(h + d'^2/8R)^2}{(d'^2/4) + (h + d'^2/8R)^2} \tag{18}$$

$$\frac{f_{MUF}^2}{f_c^2} = \frac{(d'^2/4) + (h + d'^2/8R)^2}{(h + d'^2/8R)^2} = 1 + \frac{d'^2/4}{(h + d'^2/8R)^2} \tag{19}$$

$$f_{MUF} = f_c[1 + \{\frac{d'^2/4}{h + (d'^2/8R)^2}\}]^{1/2} \tag{20}$$

Equation (20) gives maximum usable frequency in terms of skip distance. To get the expression of skip distance in terms of maximum usable frequency, (19) can be rewritten as

$$\frac{d'^2}{4} = (h + \frac{d'^2}{8R})^2[(\frac{f_{MUF}}{f_c})^2 - 1] \tag{21}$$

$$d' = 2(h + \frac{d'^2}{8R})\left[\left(\frac{f_{MUF}}{f_c}\right)^2 - 1\right]^{1/2} \tag{22}$$

Similarly, (22) is of quadratic form which will yield the value of the skip distance in terms of maximum usable frequency as given below.

$$d' = \frac{2R}{X} \pm 2\sqrt{(R/X)^2 - 2hR} \tag{23}$$

$$\text{where} \quad X = [(f_{MUF}/f_c)^2 - 1]^{1/2} \tag{24}$$

EXAMPLE 4–6.1 Calculate the maximum single hop distance for D, E, F_1 and F_2 layers if their heights are assumed to be 70, 130, 230 and 350 km respectively above the earth and the angle of incidence is 10° in all cases.

Solution

In view of (1),

$$\cos\theta_i = \frac{OB}{AB} = \frac{h}{\sqrt{h^2 + d^2/4}} = \frac{2h}{\sqrt{4h^2 + d^2}}$$

$d = 2h\sqrt{(\sec\theta_i)^2 - 1} = 2h\sqrt{(\sec 10)^2 - 1} = 2h \times 0.176 = 0.352\text{h}$

For D layer, $d = 0.352h = 0.352 \times 70 = 24.5$ km

For E layer, $d = 0.352h = 0.352 \times 130 = 45.76$ km

For F_1 layer, $d = 0.352h = 0.352 \times 230 = 80.96$ km

For F_2 layer, $d = 0.352h = 0.352 \times 350 = 123.2$ km

4–7 Impact of Solar Activity

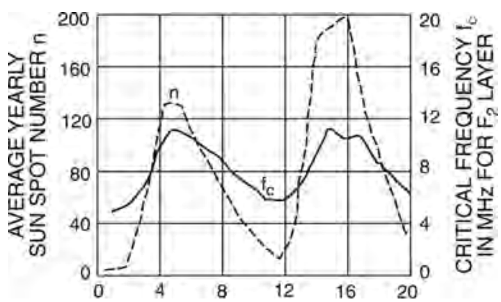


Figure 4–15 Recorded data of sunspot number and critical frequencyfor F_2 layer over a period of 20 years.

Like any other heavenly body, the sun also rotates on its axis and completes its rotation in 27.3 days. It is also known that certain areas of the sun are relatively more active than others in terms of flares, corona formation and ionic disturbances. The ionosphere and the magnetic field of the earth are bound to be affected when these areas are towards the earth. This orientation results in more ionospheric and magnetic disturbances and sometimes even in severe storms. Recurrence of such disturbances and storms greatly influence the effectiveness of ionospheric wave propagation. The studies have shown that decrease in the critical frequency results in more absorption in the D layer and increase in virtual height of the F_2 layer. The effects on E and F_1 layers are, however, less pronounced. The effect is observed to be more severe when transmission paths are nearer to the earth's magnetic poles. Besides, lesser effect has been noted when frequencies remain below 100 kHz. Thus, in LF range communication is better than at higher frequencies. Communication outage for 15–16 minutes has been reported due to more sun spots facing the earth. In order to understand the impact of sun status, Fig. 4–15 illustrates a variation in the number of sun spots and the corresponding critical frequencies.

To elaborate, the influence of solar activity can be summarized under different captions as given below.

Sunspots are the dark, irregularly shaped areas on the surface of the sun which keep on appearing and disappearing in two cycles, every 27 days and every 11 years. These are believed to be caused by violent eruptions on the sun and are characterized by strong magnetic fields. The occurrence of sunspots, their life span, shapes, size and location on the sun's surface are all variable and unpredictable. Sunspots cause variations in the ionization level of the ionosphere and hence affect the propagation characteristics of the waves.

Sudden Ionospheric Disturbances (SID) may occur any time and may last from minutes to several hours. The occurrence of SID is due to solar eruptions producing intense bursts of ultraviolet light which are not absorbed by upper ionospheric layers. These bursts mainly cause an immense increase of D-layer ionization density resulting in absorption of all frequencies at the upper edge of MF range. These may result in the total outage of HF communication.

Ionospheric storms are caused by disturbances in the earth's magnetic field and are related to solar eruptions and the 27-day cycle of the sun. The effect of these storms may lead to a turbulent ionosphere and erratic sky wave propagation. These storms mainly affect the F_2 layer, reducing its ion density and causing critical frequencies to be lower than the normal.

4–8 Multi-Hop Propagation

In Fig. 4–8, the distances between transmitter (T_x) and two receivers (R_{x1} and R_{x2}) were marked as skip distance-1 and skip distance-2. The wave originating from T_x arrives at R_{x1} and R_{x2} in one go, i.e., without touching the ground anywhere in between. These distances are termed as *one hop distances*. In Fig. 4–8, it was also shown that the energy may arrive at R_{x2} either through the ray 2 or the ray 4. These rays are termed as lower ray (LR) and upper ray (UR). Normally, it is the lower ray which is preferred for establishing the communication. The upper ray which is also called Pedersen ray is not very important. The upper ray is weaker than the lower ray in terms of its energy contents since over a given solid angle, it spreads more as compared to the lower ray. It becomes important only when the lower ray is prevented from reaching the receiver in one hop. This situation arises either when the earth's curvature prevents one hop lower ray or when the distance between the transmitter and receiver is greater than the skip distance. In such cases, a multi hop system is an alternative for establishing the communication. Also, if the frequency used falls between critical frequencies of E and F_1 layers and the receiver is beyond the skip distance for E layer, two or even three separate layers may contribute to the propagation of energy. The link between transmitter and receiver, in such cases, may be maintained in many ways. These propagation modes shown in Fig. 4–16 include (i) single hop single layer, (ii) single hop multi layer, (iii) multi hop single layer, and (iv) multi hop multi layer systems.

4–9 Take-Off Angle

We have seen earlier that at f = cutoff frequency f_c

$f_c^2 = 81N_{max}$

Also, $n \sin\phi = \sin\phi_0$

Since at $f = f_c$, $\phi = 90°$

$n = \sin\phi_0 = \sqrt{[1-(f_c/f)^2]}$, $1-\sin^2\phi_0 = (f_c/f)^2 = \cos^2\phi_0$, $f^2 = f_c^2\sec^2\phi_0$ or $f = f_c\sec\phi_0$

Thus, we get the secant law for flat ionosphere given earlier by (6) of Sec. 4–5.

From Fig. 4–17 for flat earth or for smaller distances:

$$\sec\phi_0 = \frac{\sqrt{[h'^2 + (d/2)^2]}}{h'} \tag{1}$$

In (1), d is the maximum distance from transmitter (located on earth) at which the ray returns or is the *maximum skip distance*.

For $d > 100\sqrt{h'}$, the following relation accounting for the earth radius R (6367 km) is used.

$$\tan\phi_0 = \frac{\sin(d/2R)}{1 + (h'/R) - \cos(d/2R)} \tag{2}$$

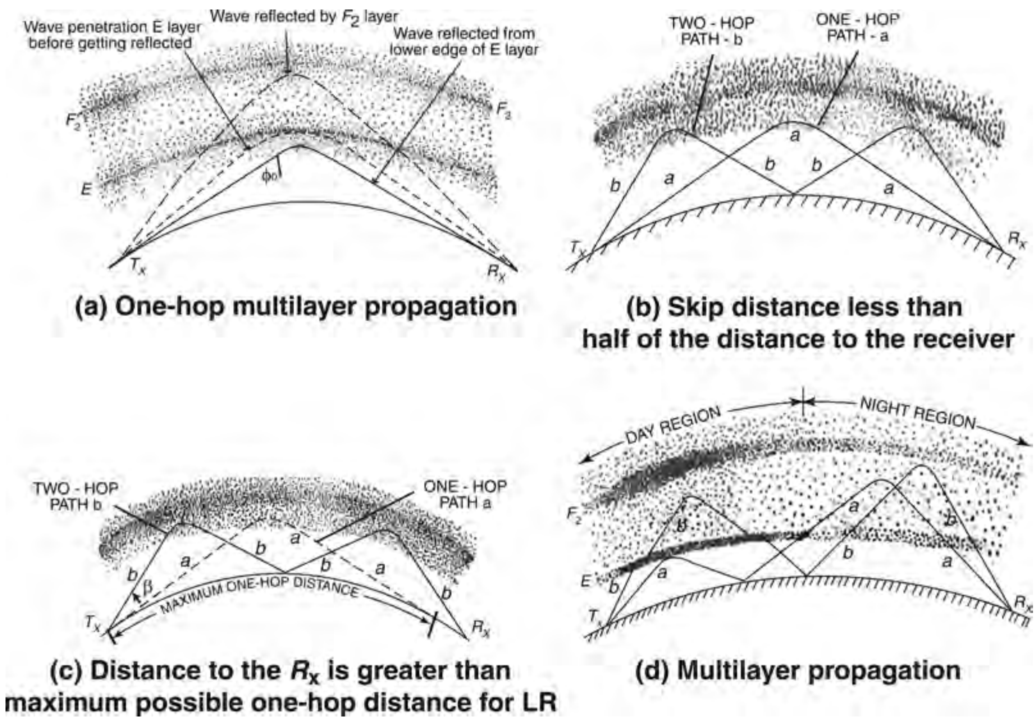


Figure 4–16 Multi-hop multilayer propagation.

The angle β(shown in Fig. 4–17) where $\beta = 90° - \phi_0$ is called the *take off angle* (for flat earth). For curved earth, β is given as

$$\beta = 90 - \phi_0 - 57.3d/2R \tag{3}$$

$$\sin\phi_0 = \frac{\cos\beta}{1 + h'/R} \quad \text{or} \quad \frac{h'}{R} = \frac{\cos\beta}{\sin\phi_0} - 1 \quad \text{or} \quad h' = (\frac{\cos\beta}{\sin\phi_0} - 1)R \tag{4}$$

The h' given above is the virtual height defined earlier. When $\beta = 0$, ϕ_0 is maximum, i.e., for flat earth $\phi = 90°$ and for curved earth:

$$\phi = 90° - 57.3d/2R \tag{5}$$

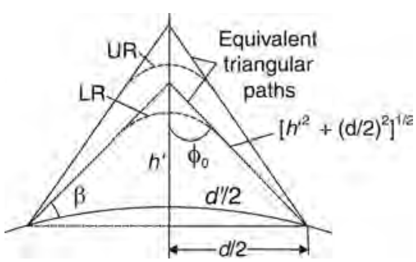


Figure 4–17 Take-off angle and secant law.

EXAMPLE 4–9–1 An ionospheric wave is reflected from a layer of height of 200 km. The takeoff angle is 20° and the earth's radius is 6370 km. Calculate the skip distance if the earth is considered as (a) flat surface, and (b) spherical.

Solution

Given $\beta = 20°$, $d = 200$ km, $R = 6370$ km

(a) For flat earth $\beta = 90° - \phi_0 \quad \phi_0 = 90° - \beta$ or $\phi_0 = 70°$

$$\cos\beta = \cos 20° = \sin\phi_0 = \sin 70° = 0.9397$$

In view of (1),

$$\sec\phi_0 = \frac{\sqrt{[h'^2 + (d/2)^2]}}{h'} \text{ or } h' = \frac{d/2}{\sqrt{\sec^2\phi_0 - 1}} = \frac{200/2}{\sqrt{(\sec 70)^2 - 1}} = 38.397$$

(b) For spherical earth

$$\beta = 90° - \varphi_0 - 57.3d/2R \quad \varphi_0 = 90° - \beta - 57.3d/2R$$

$$\varphi_0 = 90° - 20° - 57.3 \times 200/2 \times 6370 = 69.1$$

$$h' = \frac{d/2}{\sqrt{\sec^2\phi_0 - 1}} = \frac{200/2}{\sqrt{(\sec 69.1)^2 - 1}} = 38.18$$

4–10 Energy Loss in Ionosphere and Sky Wave Signal Strength

Even though gas pressure in the ionosphere is very low, the vibrating electrons collide with gas molecules from time to time. The kinetic energy acquired by electrons from the wave is lost. The amount of this loss depends on the gas pressure, velocity of vibration, likelihood of collision and frequency of collisions. Most of the absorption loss takes place at a lower edge of the ionized region, where the atmospheric pressure is greater (i.e., in the D layer and lower part of E layer). Other things being equal, the absorption is less at higher frequencies and maximum at gyro and lower frequencies. This absorption can be analyzed by assuming that the ionosphere has a conductivity 'σ' along with 'ε'. The curves shown in Fig. 4–18 illustrate these losses for different layers.

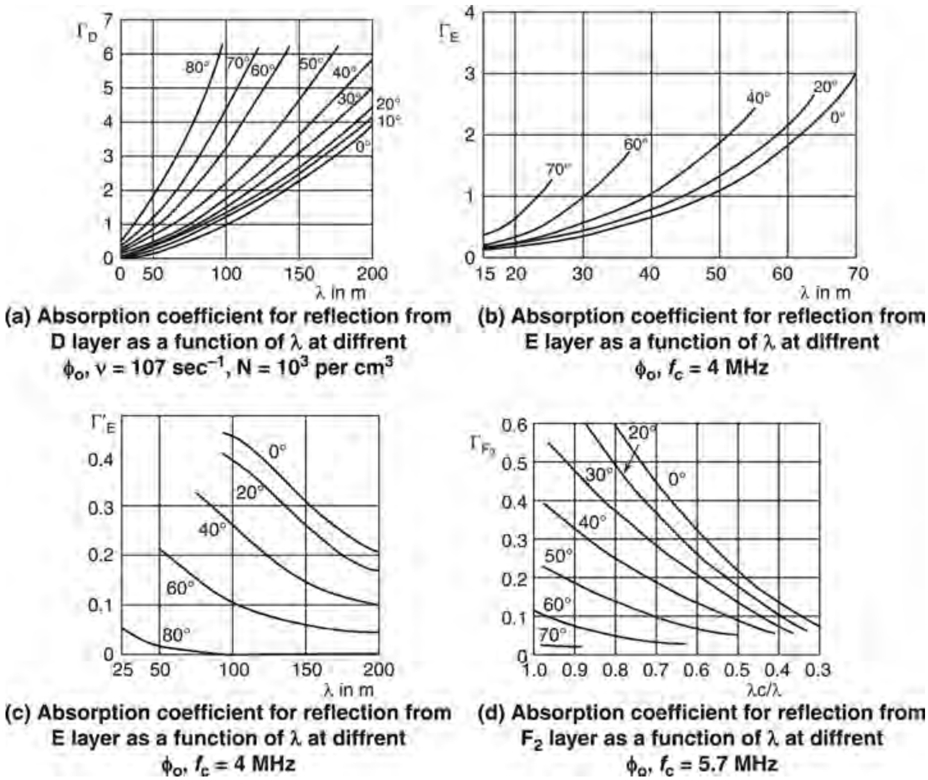
At high frequency, the energy loss due to collision occurs mainly just below the E layer (in the D layer) where product of collisional frequency and electron density is maximum. This type of loss is called *non-deviative absorption loss*.The attenuation constant for non-deviative absorption in E layer in dB/unit length of path is given by

$$\alpha = k(f_E/f)^2 \tag{1}$$

where $f_E = f_c$ for the E layer, f is the wave frequency and k is a constant which is a function of collisional frequency. Similarly, α can be obtained for a D layer.

4–11 Primary and Secondary Services

The region about a broadcast transmitting station in which the signal strength in the daytime is strong and adequate to override ordinary interference is termed as *daytime primary service area*. The coverage of this service area depends on the transmitted power, antenna directivity, ground wave attenuation factor and the frequency of broadcast. For high power transmission at lower broadcast frequencies and highly conducting



(a) Absorption coefficient for reflection from D layer as a function of λ at diffrent ϕ_o, ν = 107 sec^{-1}, N = 10^3 per cm^3

(b) Absorption coefficient for reflection from E layer as a function of λ at diffrent ϕ_o, f_c = 4 MHz

(c) Absorption coefficient for reflection from E layer as a function of λ at diffrent ϕ_o, f_c = 4 MHz

(d) Absorption coefficient for reflection from F_2 layer as a function of λ at diffrent ϕ_o, f_c = 5.7 MHz

Figure 4–18 Absorption coefficients for different regions.

earth, this coverage is normally between 50 to 100 miles. Outside this area where signal is still strong but not enough to override interference is called the daytime secondary coverage area. This region is also determined by the factors noted for primary area but extends to several hundred miles at receiving locations where the noise is low.

At night, sky waves of considerable strengths return to the earth. Near the transmitter, the sky wave is relatively weak compared to the ground wave and later predominates. As the distance from the transmitter increases, the ground wave attenuates and sky wave becomes stronger, thus both become approximately equal in strength. At still larger distances, the sky wave tends to become still stronger. It maintains a relatively high and constant signal up to a considerable distance. This phenomenon is illustrated in Fig. 4–19.

4–12 Wave Characteristics

Some of the characteristics exhibited by the waves in different modes of propagation and different frequency ranges are summarized below.

4–12a VLF Wave Propagation

- Range of VLF spreads over 3 kHz – 30 kHz.
- Low carrier frequency limits the bandwidth and hence the information contents and thus cannot be used for conventional communication.

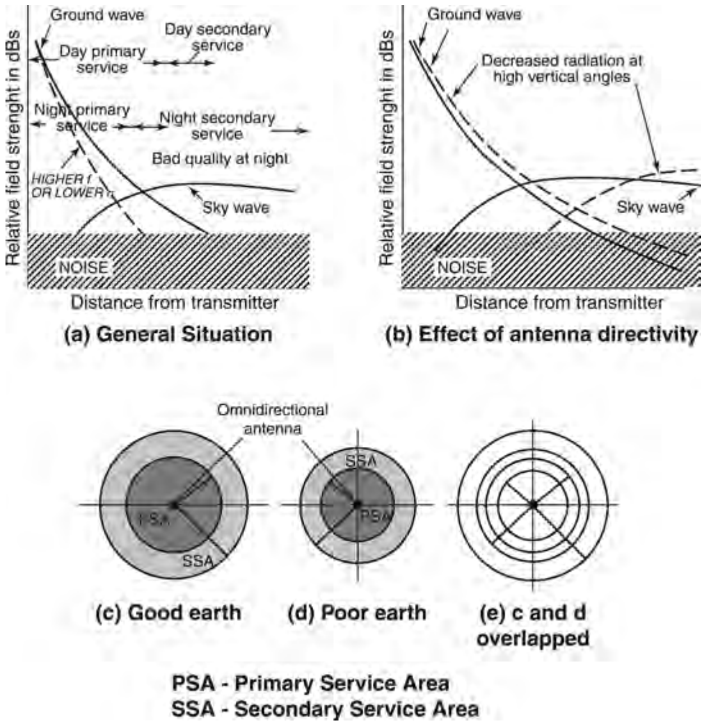


Figure 4–19 Primary and secondary service areas.

- These waves can penetrate deeper into sea as well as the earth, and therefore can be used for submarine and mine communication.
- Waves can travel thousands of kilometers along the earth's surface and have a very steady phase. Therefore, a VLF wave can be used for navigation and for time and frequency standards.
- These waves find extensive applications in magnetospheric probing. These waves travel from one hemisphere to the other in the earths' magnetic field lines in whistler mode. A study of these whistlers reveals information on magnetospheric electron and ion densities.
- In general, VLF has attenuation of about 3 dB/1000 km for propagation over seawater and about 6 dB/1000 km over land. Frequencies around 20 kHz show the least attenuation.
- An antenna has to be comparable to wavelength for meaningful radiation. Thus, VLF antennas have to be very large in length (i.e., several kilometers long). Horizontal antennas can be made quite long but their efficiency is less than 1%. Vertical antennas have efficiencies greater than 70% but need expensive ground plane and top hat structures.
- In VLF range, lightning discharges are the main source of noise. The level of noise at this range is considerably higher than that at higher frequencies.
- VLF waves are almost completely reflected both by the lower ionosphere and the earth. Thus they are guided in the region between ground and ionosphere much like waves in the waveguides. The height of the waveguide may be around 70–80 kilometers.

20 kHz – 100 kHz

- This range encompasses part of the VLF band and a part of LF band.
- In this range, ground waves have relatively low attenuation.

- Received ground wave signals show little diurnal, seasonal and yearly variation.
- Ground-wave mode is mostly used up to 1000 km.
- Sky waves are reflected back to the earth only after little absorption and slight penetration in the ionosphere.
- Received signal shows diurnal and seasonal variations.
- Signals are stronger at night than in day.
- Signals are stronger in winter than in summer.
- Although signals even after traveling great distances behave in a fairly regular manner, neither daily nor yearly cycles repeat exactly vis-à-vis signal strength.
- For distances greater than 1000 km, mostly the sky wave mode is used.
- Average yearly intensity correlates fairly well with 11-year sunspot cycle.
- Fading in the normal sense does not occur.

100 kHz – 535 kHz

- This range encompasses part of the LF band and a part of MF band.
- Ground waves attenuate more rapidly as the frequencies are raised above 100 kHz.
- Range of ground waves reduces as the frequency increases.
- Sky waves become the obvious choice for moderate distances.
- Ionospheric losses tend to be high in daytime but remain low at night.
- Due to relatively high ionospheric absorption in day time, long-distance communication in day time is not dependable.
- Night-time communications for long distances by sky wave are reliable.

535 kHz – 1600 kHz

- This range is a segment of MF band.
- This range encompasses frequencies primarily used for broadcast purposes.
- Daytime broadcast depends entirely on ground wave propagation.
- Daytime signal strength decreases more rapidly with distance for ground waves.
- Lower the earth's conductivity, the higher is the frequency of the signal.
- Sky waves in this range are completely absorbed in day.

1600 kHz – 30 MHz

- This range encompasses part of the MF band along with the entire HF band.
- Ground waves attenuate very rapidly. Thus, this mode of propagation is of no use except for very short distances.
- Almost all long-distance communications use ionospheric reflections.
- The range of frequencies to be used depends on the given set of conditions.
- The lower-frequency limit depends on the ionospheric absorption over the path, the radiated power and the noise level at the receiver.
- The maximum usable frequency (MUF) depends on the distance, height and electron density at the location of reflection in the ionosphere.
- The frequency which gives the best signal is the optimum frequency (OF), normally taken 15% below the maximum usable frequency. It allows short-term fluctuations in MUF.
- OF tends to be high (10 to 20 MHz) in the day for long paths and is low (5 to 10 MHz) at night for short paths and is normally greater in summer than winter.
- Optimum frequencies are susceptible to sunspot activity and tend to be higher for paths with lower altitude. For similar conditions, signals over north–south paths are stronger than over east–west paths.

This is mainly because of large variation in the quantum of sunlight and hence the ionization on east – west paths.

- For long-distance communication (beyond 1000 km), OF is determined mainly by the F_2 layer. OF may also be determined by E or F_1 layers under certain circumstances at noon.
- For medium distances (200 to1000 km) at lower heights, the E layer causes ϕ_0 to be glancing than for F_2 layer; E layer alone determines MUF.
- Sporadic E may cause increase in OF (maximum 80 to 100 MHz is reported and 20 to 40 MHz is common)
- Sporadic E is more prevalent in summer and may control ranges up to 2000 km at 15 MHz.
- OF increases with path distance for one hop transmission. On an average, it is 4000 km for F_2layer and 2000 km for E layer.
- For short distances, OF = f_c and for long distance MUF = $3f_c$ for F_2 layer.
- When $d \approx h$, β is large, when $d >> h$, β is small (5° to 15°) Fig. 4–20.
- For $\beta < 3.5°$, energy leaving the transmitter tends to be absorbed by the earth near the transmitter.
- Major variations of transmitting conditions (including diurnal, month to month and yearly variations) can be predicted at least 3 months in advance. Day-to-day variations cannot be predicted accurately.

Frequencies above 30 MHz, i.e., all bands above HF

- Rarely reflected back to earth by ionosphere except occasionally from sporadic E in the 30 to 60 MHz range.
- Usefulness above 30 MHz depends mainly upon space-wave propagation.
- Communication even with reasonable transmitted power is normally not appreciably possible beyond line-of-sight distance.
- Heights of transmitting and receiving antennas determine the distance.

4–12b VHF (metric) Waves

- All modes of propagation possible, i.e., as ground and tropospheric waves along the earth surface and also between 4 m to 10 m wavelength as ionospheric wave.
- Capable of passing through ionosphere as direct wave.

4–12c UHF (decimetric) and SHF (centimetric) Waves

- Can propagate as ground wave over short (LOS) distance.
- Communication for long distances through tropospheric waves (mainly due to scattering from irregularities and lees due to ducting).
- Diffraction in this range is negligible.

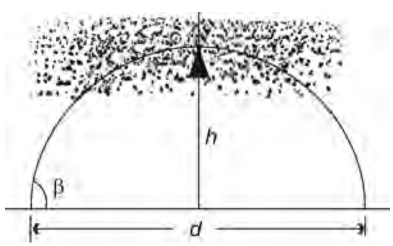


Figure 4–20 Takeoff angle β, height h and skip distance d.

- Practically, no molecular absorption or absorption in precipitation particles.
- Absorption due to rain, hail, snow at 3–5 cm and due to water vapours at 1.35 cm are significant.

4–12d EHF (millimetric) Waves

- No effect of ionosphere, troposphere causes bending due to atmospheric refraction.
- Rain, fog, hail, snow and other forms of precipitation particles responsible for marked absorption.
- Heavy rain and dense fog will completely stop propagation.
- Strong molecular absorption by tropospheric gases, especially water vapor and oxygen.

4–12e Sub-millimetric and Optical Waves

- Can propagate only as ground and direct wave.
- Atmospheric refraction causes bending of path.
- Heavy rain and dense fog will completely stop propagation.
- Well suited for space communication outside the troposphere.

References

Books

Sommerfeld, A.: "Partial Differential Equations in Physics" (English version), *Academic Press Inc.,* New York 1949, Chapter 6 - "Problems of Radio".

Terman, F. E.: "Electronics and Radio Engineering", McGraw Hill Book Co., Tokyo, 1955.

Budden, K. G.: "Radio waves in the ionosphere; the mathematical theory of the reflection of radio waves from stratified ionised layers". Cambridge, Eng., University Press, 1961.

Budden, K. G.: "The wave-guide mode theory of wave propagation". London, Logos Press; Englewood Cliffs, N.J., Prentice-Hall, 1961.

Barlow, H.M., and Brown, J.: "Radio Surface Waves", Oxford University Press, 1962.

J. R. Wait: Electromagnetic Waves in Stratified Media, pp. 107–137, 341–363, Pergamon Press, New York, 1962.

Wait, J. R.: "Electromagnetic surface waves", *Advances in Radio Research*, 1, New York, Academic Press, pp. 157–219, 1964.

Fock, V. A.: Electromagnetic Diffraction and Propagation Problems, pp. 254–275, Pergamon Press, New York, 1965.

Waldron, Richard Arthur: "Theory of guided electromagnetic waves". London, New York, Van Nostrand Reinhold, 1970.

Dolukhanov, M.: Propagation of Radio Waves", Mir Publishers, Moscow, 1971.

Zucker, F. J.: "Surface wave antennas and surface wave excited arrays", *Antenna Engineering Handbook*, 2nd ed., R. C. Johnson and H. Jasik, Eds. New York: McGraw-Hill, 1984.

Budden, K. G.: " The propagation of radio waves: the theory of radio waves of low power in the ionosphere and magnetosphere". Cambridge (Cambridge shire); New York: Cambridge University Press, 1985.

Wait, J. R.: "Electromagnetic Wave Theory", New York, Harper andRow, 1985.

Jordon, E. C., Balmain, K. G.: "Electromagnetic Waves and Radiating Systems', Prentice Hall Ltd, New Delhi, 1987.

Collin, R. E.: "Field Theory of Guided Waves". New York: Wiley-IEEE Press, 1990.

Felsen, L. B. and Marcuirtz, N. eds.: Radiation and Scattering of Waves, chap.4, *IEEE Press*, (Classic Reissue), New Jersey, 1994.

Kennedy Georg,: "Electronic Communication Systems", III ed. McGraw Hill, New Delhi, 1996.

Ito, Y: Chap.14, in Radio wave Propagation Handbook, ed. Y. Hosoya, pp. 171–199, *Realize Inc.*, Japan, 1999.

Soundara Rajan, V.: "Antenna Theory and Wave Propagation", *Scitech Publications (India) Pvt.* Ltd, Chennai, 2001

Dhar, P. C.: "Electromagnetic Field Theory, Antenna and Wave Propagation", Dhanpat Rai Publishing Co. Pvt. Ltd, New Delhi, 2001.

Sevgi, L.: Complex Electromagnetic Problems and Numerical Simulation Approaches, pp. 63–125, IEEE Press, New Jersey, 2003.

Gautam, A. K.: "Antenna and Wave Propagation", S. K. Kataria and Sons, Delhi, II Edn. 2004.

Journals and papers

Sommerfeld, A.: "Fortpffanzung elektrodynamischer Wellen an einem zylindnschen Leiter", Ann. der Physik und Chemie, **Vol. 67**, pp. 233–290, Dec 1899. (Tr. Reproduction of electro-dynamic waves at a cylinder)

Zenneck, J.: "Über die Fortpflanzung ebener elektromagnetischer Wellen Mngs einer ebenen Leiterflache und ihre Beziehung zur drahtlosen Telegraphie", Ann. der Phwk, **Vol. 23**, pp. 846-866, Sept. 1907. (Tr. "Over the reproduction of even electromagnetic waves of an even leader-flat and their relationship with the wireless telegraphy")

Sommerfeld, A.: "Über die Ausbreitlung der Wellen in der drahtlosen Telegraphie", Annalen der Physik, **Vol. 28**, March, 1909, pp. 665-736. (Tr. Over the Propagation of the waves in the wireless telegraphy)

Zenneck, J.: (translators: P. Blanchin, G. Guérard, É. Picot), "Précis de télégraphie sans fil : complément de l'ouvrage : Les oscillations électromagnétiques et la télégraphie sans fil", Paris : Gauthier-Villars, 1911. viii, 385 p. : ill. ; 26 cm. (Tr. Precisions of wireless telegraphy: complement of the work: Electromagnetic oscillations and wireless telegraphy)

Zenneck, J.: (translator: A.E. Seelig) "Wireless telegraphy,", New York [etc.] McGraw-Hill Book Company, inc., 1st ed. 1915. xx, 443 p. illus., diagrs. 24 cm. (ed. "Bibliography and notes on theory" p. 408-428.)

Zenneck, J.: "Elektromagnetische Schwingungen und drahtlose Telegraphie", gart, F. Enke, 1905. xxvii, 1019 p. : ill. ; 24 cm. (Tr. "Electromagnetic oscillations and wireless telegraphy.")

Sommerfeld, A.: "Propagation of waves in wireless telegraphy", Ann. Phys., **Vol. 81**, pp. 1367–1153, 1926.

Norton, K. A.: "The propagation of radio waves over the surface of the earth and in the upper atmosphere", Proc. IRE, **Vol. 24**, pp. 1367–1387, 1936.

Norton, K. A.: "The calculations of ground wave field intensity over a finitely conducting spherical earth", Proc. IRE, **Vol. 29**, pp. 623–639, 1941.

Kahan, T. and Eckart, G,: "On the Electromagnetic Surface Wave of Sommerfeld", Phys. Rev. 76, pp. 406–410 (1949).

Georg Goubau: "Surface waves and their application to transmission lines", J. Appl. Phys., **Vol. 21**, pp. 1119-1128; November,1950.

Furutsu, K: "Propagation of electromagnetic wave over the spherical earth across boundaries separating different earth media," Journal of the Radio Research Laboratories, **Vol. 2**, No. 10, pp. 345–398, Oct. 1955.

Wait, J. R.: "Mixed path ground wave propagation: 1 short distances," Journal of Research of the National Bureau of Standards, **Vol. 57**, No. 1, pp. 1–15, July 1956.

Bremmer, H: "Applications of operational calculus to ground-wave propagation, particularly for long waves," *IRE Trans. Antennas Propag.*, **AP-6**, No. 3, pp. 267–272, 1958.

King, M. J. and Wiltse, J. C.: "Surface-Wave Propagation on a Dielectric Rod of Electric Cross-Section." Electronic Communications, Inc., Tirnonium: kld. Sci. Rept.'No. 1, AFCKL Contract No. AF 19(601)-5475; August, 1960.

Wait, J. R.: "A note on surface waves and ground waves", IEEE Transactions on Antennas and Propagation, Nov 1965. **Vol. 13**, Issue 6, pp. 996–997 ISSN 0096–1973.

King, R. J. and Schlak, G.A.: "Groundwave attenuation function for propagation over a highly inductive earth," Radio Science, **Vol. 2**, No. 7, pp. 687–693, July 1967.

Wait, J. R.,: "Appendix C: On the theory of ground wave propagation over a slightly roughned curved earth", Electromagnetic Probing in Geophysics. Boulder, CO., Golem, 1971, 37–381.

Wait, J. R.: "Recent analytical investigation of electromagnetic ground wave propagation over inhomogeneous earth models," Proc. IEEE, **Vol. 62**, No. 8, pp.1061–1072, Aug. 1974.

Wait, J. R., and Hill, D. A.: "Excitation of the Zenneck surface by a vertical aperture", Radio Science, 13, 1978, pp. 967-977.

Hill, D. and Wait, J. R: "Excitation of the Zenneck Surface Wave by a Vertical Aperture", Radio Science, **Vol. 13**, No. 6, November-December, pp. 969–977, 1978.

Causebrook, J. H.: "Medium-wave propagation in build-up areas," *Proc. IEE*, **Vol. 125**, No. 9, pp. 804–808, Sept. 1978.

Wait, J. R.,: and Hill, D. A.: "Excitation of the HF surface wave by vertical and horizontal apertures". Radio Science, 14, pp. 767-780, 1979.

Hill, D. A. and Wait, J.R.: "Ground wave attenuation function for a spherical earth with arbitrary surface impedance," Radio Science, **Vol. 15**, No. 3, pp. 637–643, May–June 1980.

Hitney, H. V. Richter, J.H. Pappert, R.A. Anderson, K.D. and Baumgartner, G.B. Jr.: "Tropospheric radio propagation assessment," *Proc. IEEE*, **Vol. 73**, No. 2, pp. 265–283, Feb. 1985.

Kistovich, Yu. V.: "Possibility of Observing Zenneck Surface Waves in Radiation from a Source with a Small Vertical Aperture", Soviet Physics Technical Physics, **Vol. 34**, No. 4, pp. 391–394, April, 1989.

Baibakov, V. I. Datsko, V. N. Kistovich, Yu. V.: "Experimental discovery of Zenneck's surface electromagnetic waves", Sov Phys Uspekhi, 1989, 32, pp. 378–379.

Corum, K. L. and Corum, J. F.: "The Zenneck Surface Wave", *Nikola Tesla, Lightning Observations, and Stationary Waves*, Appendix II. 1994.

Ishihara, T. and Mukai, Y. "Analysis of radio wave propagation over mixed-path including tropospheric ducting effect," *Proc. Int. Symp. on Antennas & Propag.*, pp. 297–300, Chiba, Japan, Sept. 1996.

Wait, J. R.: "The ancient and modern history of EM ground-wave propagation," *IEEE Antennas Propag. Mag.*, **Vol. 40**, No. 5, pp. 7–24, Oct. 1998.

Sevgi, L. and Felsen, L. B.: "A new algorithm for ground wave propagation based on a hybrid ray-mode approach," Int. Journal of Numer. Model.: Electronic Networks, Devices and Fields, **Vol. 11**, 87–103, Nov. 1998.

Wait, J. R., "The ancient and modern history of EM ground-wave propagation". IEEE Antennas Propagat. Mag., **Vol. 40**, pp. 7–24, Oct. 1998.

Ostrovsky (ed.), L. A.: "Laboratory modeling and theoretical studies of surface wave modulation by a moving sphere", m, *Oceanic and Atmospheric Research Laboratories*, 2002.

Collin, R. E.: "Hertzian Dipole Radiating Over a Lossy Earth or Sea: Some Early and Late 20th-Century Controversies", *Antennas and Propagation Magazine*, 46, 2004, pp. 64–79.

Kawano, T. and Ishihara, T.: "Theoretical and experimental studies on ground wave propagation over mixed-path with inhomogeneous impedance surface," *Technical Report, IEE Japan*, EMT-04-66, pp. 85–89, Sept. 2004.

Kawano, T. and Ishihara, T.: "Ground wave propagation over land-to-sea and urban-to-suburban mixed-paths with inhomogeneous impedance," *IEEE AP-S Int*. Symp. Digest, **Vol. 1A**, pp. 375–378, Washington D.C., USA, July 2005.

Kawano, T. and Ishihara, T.: "Ground wave propagation over three-section mixed-path consisting of urban, suburban, and sea paths," *The Papers of Technical Meeting on Electromagnetic Theory*, IEE Japan, EMT-05-32, pp. 1–6, Nov. 2005.

Kawano, T. and Ishihara, T.: "Ground wave propagation over a homogeneous impedance surface and a mixed-path with inhomogeneous impedance surfaces including tropospheric ducting effect," *IEEE AP-S Int*. Symp. Digest, **Vol. 5**, pp. 4735–4738, Albuquerque, USA, July 2006.

Problems

4–6–1 **Skip distance.** Calculate the skip distance for flat earth with MUF of 20 MHz if the wave is reflected from a height of 200 km where the maximum value of n is 0.95.

4–6–2 **Concentration of electrons.** The critical frequencies at an instant observed for E, F_1 and F_2 layers were found to be 4, 6 and 10 MHz. Find the corresponding concentration of electrons in these layers.

4–6–3 **Critical frequency.** Calculate the critical frequencies for E, F_1 and F_2 layers if N_{max} for each corresponding layer reduces to 90% of the values obtained in Problem 4-1

4–6–4 **Skip distance.** An ionospheric wave is reflected from a layer of height of 300 km. The takeoff angle is 10° and the earth's radius is 6370 km. Calculate the skip distance if the earth is considered as (a) flat surface (b) spherical.

4–6–5 **Maximum single hop distance.** Calculate the maximum single hop distance for D, E, F_1 and F_2 layers if their heights are assumed to be 50, 110, 200 and 300 km respectively above the earth and the angle of incidence is 20° in all cases.