CHAPTER

3

Wave Propagation-II

Ionospheric Wave Propagation

Extra Read.

3.1 INTRODUCTION

In this chapter, we will discuss the propagation of radio waves through ionosphere. The sky wave propagation or ionospheric wave propagation plays an important role in the long distance radio communication. This sky wave propagation is effective for 2–30 MHz radio waves. This mode is also defined as *short wave communication* because the wavelengths of radio waves become smaller for high frequency (3–30 MHz) band.

The ionosphere is sub-divided into four important layers namely D, E, F1 and F2 layer. Each layer has its own characteristics and specific role in sky wave propagation. Other phenomena like refraction and reflection are important in the understanding of sky wave propagation.

3.2 EARTH'S ATMOSPHERE

The earth's atmosphere is up to 400 km in height from the equator. The earth's atmosphere is divided into three separate regions. The names of these regions are the troposphere, the stratosphere and the ionosphere. These regions are shown in Figure 3.1.

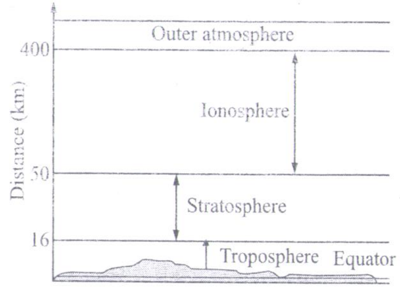

FIGURE 3.1 Earth's atmosphere.

3.2.1 Troposphere

The troposphere region is extended up to 18 km from the surface of the earth (from equator). At poles the height of troposphere is 6 km. The average height of troposphere is 16 km. All weather phenomena take place in troposphere. There may be much turbulence in this region because of the variations in temperature, density and pressure. The temperature in this region decreases rapidly with altitude.

3.2.2 Stratosphere

The stratosphere is the middle layer of the atmosphere ranging from 16 to 50 km above the earth's surface. It is located between troposphere and ionosphere. The ozone layer is found in this region which absorbs the UV rays coming from the sun. Due to little water vapour and almost no cloud, the temperature remains almost constant throughout this region hence this region has almost no effect on radio wave propagation. This layer is considered as the best layer for aircraft movements.

3.2.3 Ionosphere

It is the uppermost layer of the atmosphere ranging from 50 to 400 km above the earth's surface. This layer consists of charged ions hence it is named as ionosphere. This layer is further divided into many sub-layers which help the EM wave to travel great distances around the earth. The molecules in this region are charged by radiations from the sun like α, β and UV rays. This region is important for the propagation of 3–30 MHz radio propagation. Due to the radiations from the sun, the molecules in this region get charged, i.e., the molecule emits electron. This free electron in the ionosphere causes the radio waves to refract and then reflect back to earth. The greater density of free electrons reflects back the higher frequencies. The ionosphere is divided into sub-layers which are as follows:

(a) D-Layer
(b) E-Layer
(c) F1-Layer
(d) F2-Layer

The sub-layers of the ionosphere during day and night times are shown in Figures 3.2(a) and (b) respectively.

Note: The density of ions/electrons reduces from top to bottom layer, i.e., the D-layer has minimum ion density as compared to the F2-layer. This happens so because the top layer (F2-layer) receives maximum solar radiation as compared to the bottom layer (D-layer).

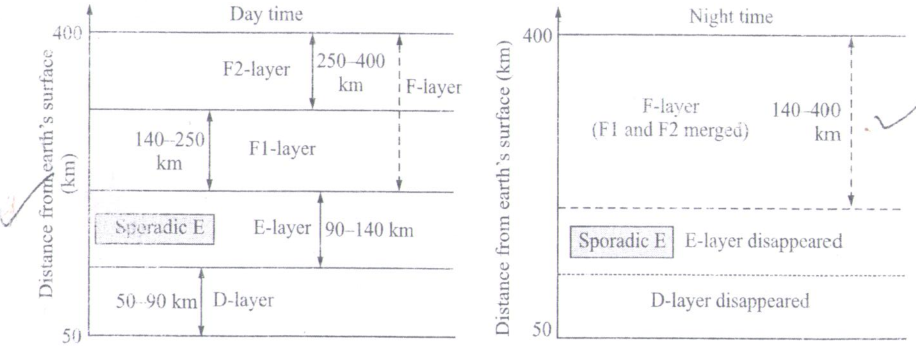

FIGURE 3.2 (a) Structure of ionosphere during day time (b) Structure of ionosphere during night time.

(a) D-Layer

The D-layer is the lowest layer of ionosphere and it exists from 50 to 90 km above the earth's surface. It remains present during the day time only. At night it disappears due to the recombination of ions and absence of ionising radiations. The ionisation of D-layer is low because UV rays cannot reach up to this region without getting absorbed in the upper layers. The amount of ionisation in D-layer is proportional to the elevation angle of the sun, so ionisation density reaches maximum at mid-day. The D-layer can refract signals of VLF and LF band hence supports long range communication for VLF and LF waves only. While for HF band signals, the D-layer acts as an absorbing layer and hence restrict the long-range communications during daytime. The absorption in D-layer reduces significantly in night because D-layer disappears completely in night.

(b) E-Layer

This layer was first proposed by A.K. Kennelly and Oliver Heaviside. E-layer ranges from 90 to 140 km above the earth's surface. The characteristics of E-layer are similar to D-layer as E-layer also acts as an absorbing layer and does not reflect signals. During day time, E-layer acts as an effective radio wave reflector but after sunset, the rate of recombination of ions is rapid in this layer hence its ability to reflect HF signals reduces greatly during night. This layer is responsible for the reflection and higher frequency signals (above 20 MHz) and provides long-range communication up to 2500 km.

(c) Sporadic E-Layer

It is a highly ionised region which exists in the E-layer. The high ionisation is caused due to the solar flare and the ionised area can be small or large depends upon the intensity of solar radiation. The ion density in this region is comparable with F2-layer hence it is useful for HF communications. Sometimes, the sporadic E-layer acts as a transparent layer and allows the radio wave to pass up to F-layer while for other instances it stops the radio waves completely. The stopping of radio waves is known as *sporadic E-blanketing*.

The sporadic E-layer tends to form at night at high altitudes while in low and mid-altitudes it tends to form during the day time and early evening.

Sporadic E-layer causes fading (loss in signal strength) if it is partially transparent because in this case the radio wave is likely to be refracted many times from both F and sporadic E-layer as shown in Figure 3.3 hence attenuation occurs.

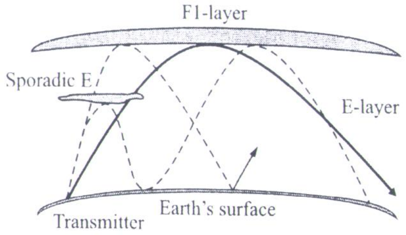

FIGURE 3.3 Fading due to sporadic E-layer.

(d) F-Layers

The F-layers (both F1 and F2) range from 140 to 400 km above the earth's surface. Based on the ionisation levels during the day time, the F-layer is sub-divided into F1 and F2 layers in which F1 ranges from 140 to 250 km and F2 exists from 250 to 400 km.

At specific solar cycles, the F1 and F2 layers merge to form F-layer. During night the F1-layer is completely depleted because of the ion recombination hence only F2-layer is available for communications during this period. Due to the proximity with sun, the maximum ionisation takes place in both F1 and F2 layers and especially during afternoon. The lifetime of electrons is maximum in F2-layer hence this layer is present whole night. The F2-layer becomes important for high frequency propagation because:

- It exists for 24 hours of the day.
- Its high altitude allows the longest communication paths.
- The high electron density refracts and eventually reflects back the high frequencies in the HF range.

It can be noted that the F-layer is responsible for high frequency, long-distance communications because of its high altitude and high ionisation density. For horizontally polarised radio wave, the single reflection from F-layer can help the wave to propagate over 4800 km (single hop distance). Radio wave covers more distance by multi-hopping.

The maximum reflected frequency depends upon the sunspot activity and during maximum sunspot activity; the reflected frequency can go up to 100 MHz while minimum sunspot frequency, the reflected frequency can go up to 10 MHz only.

Some important characteristics of ionospheric layers are concluded in Table. 3.1.

TABLE 3.1 Characteristics of ionospheric layers

Layer name	*Altitude*	*Maximum electron density (electrons/cm^3)*	*Occurrence*	*Mean life time of electrons*	*Critical frequency*	*Formation*	*Importance*
D	70 km	400	Day time	< 20 seconds	100 kHz	Photo-ionisation	VLF and LF long range communication
E	100 km	5×10^5	Day time	20 seconds	3 to 5 MHz	Ionisation of all gases by soft X-rays	Suitable for long distance communication
Sporadic E	>110 km	~ 10^6	Whole day	–	–	Meteoric ionisation, solar flare and turbulent motion of air molecules	Not suitable for long range communication of HF waves
F1	180 km	5×10^5	Day time (merges with F2 at night)	1 minute	5 to 7 MHz	By ionisation of O_2	Not suitable for HF wave propagation
F2	325 km	2×10^6	Whole day	20 minutes	5 to 12 MHz	Ionisation by UV and X-rays	Acts as radio mirror for HF waves

3.3 SKY WAVE OR IONOSPHERIC WAVE PROPAGATION

For radio waves 3–30 MHz, ground and space wave propagation do not help in covering large distances. For long range communication where the distance involved is greater than 1000 km, ionospheric or sky wave propagation is used. As discussed in earlier sections, radio waves are refracted towards the earth's surface by the layers present in the ionosphere. The frequency range is 3–30 MHz for such propagation. The radio wave from transmitter to receiver can reach in a single hop or in multiple hops as shown in Figure 3.4. Multiple hops allow the radio waves to propagate distances more than 4000 km.

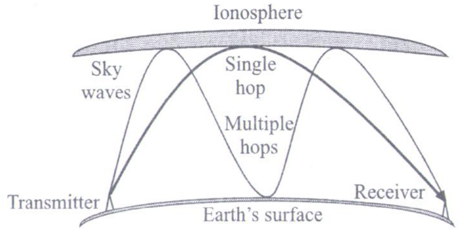

FIGURE 3.4 Sky wave propagation.

Sky wave propagation involves the reflection of the HF waves from the ionosphere through refraction of waves. As we have studied earlier, the electron density increases with the increase in altitude. The refractive index of the ionosphere decreases with increase in altitude hence the radio wave entering into the ionosphere encounters rarer medium. As a result radio waves bend away from the normal as shown in Figure 3.5.

Radio wave suffers repeated refractions due to many layers in the ionosphere. In this way, the waves eventually reflect back to the earth at an angle equal to the incident angle. The refractive index plays the important role in bending the wave back to the earth.

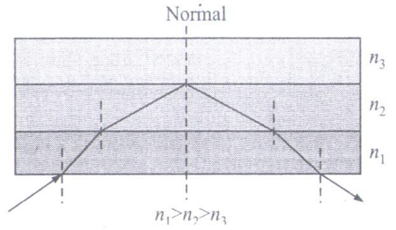

FIGURE 3.5 Refraction of radio wave by ionosphere.

3.3.1 Refractive Index of Ionosphere

When radio wave enters into the ionosphere, it encounters the mixture (or cloud) of electrons, positive and negative ions which is known as *plasma*. The electric field of the radio wave exerts a force on the charged particles namely electrons and ions. The exerted force causes the displacement of charged particles and as a result current flows. As the mass of the ions is much greater than electrons hence there displacement is small and current is almost negligible. The electrons start oscillating in response to the force exerted by radio wave.

If the electric field of the radio wave is E, then

$$E = E_0 \sin \omega t \qquad \text{...(3.1)}$$

Coulomb's force exerted on each electron is given as:

$$F = -eE = -eE_0 \sin \omega t \qquad \text{...(3.2)}$$

The acceleration of the electron can be written as:

$$m\frac{dv}{dt} = -eE_0 \sin \omega t \qquad \text{...(3.3)}$$

By integrating Eq. (3.3), the velocity of electron comes out as:

$$v = -\int \frac{eE_0 \sin \omega t}{m}\, dt \qquad \text{...(3.4)}$$

or

$$v = \frac{e}{m\omega} E_0 \cos \omega t \qquad \text{...(3.5)}$$

If we assume that N is the electron density, the conduction current density (J_e) in the ionosphere can be given as:

$$J_e = -Nev = -\frac{Ne^2}{m\omega} E_0 \cos \omega t \qquad \text{...(3.6)}$$

Equation (3.6) indicates that the conduction current density lags behind the electric field by 90°.

The displacement current density (J_d) due to the time varying electric field is given as:

$$J_d = \frac{\partial D}{\partial t} = \varepsilon_0 \frac{\partial E}{\partial t} = \varepsilon_0 \omega E_0 \cos \omega t \qquad \text{...(3.7)}$$

The resultant current density in the ionosphere is given as:

$$J = J_e + J_d = \omega \left[\varepsilon_0 - \frac{Ne^2}{m\omega^2} \right] E_0 \cos \omega t \qquad \text{...(3.8)}$$

or

$$J = \omega \varepsilon E_0 \cos \omega t \qquad \text{...(3.9)}$$

where,

$$\varepsilon = \left[\varepsilon_0 - \frac{Ne^2}{m\omega^2} \right] \qquad \text{...(3.10)}$$

The relative permittivity of the ionosphere can be written as:

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} = \left[1 - \frac{Ne^2}{m\omega^2 \varepsilon_0} \right] \qquad \text{...(3.11)}$$

The refractive index of any medium is defined as the ratio of velocity of EM wave in vacuum to the velocity in that medium, hence for ionosphere the refractive index can be given as:

$$n = \frac{c}{v} = \frac{\frac{1}{\sqrt{\mu_0 \varepsilon_0}}}{\frac{1}{\sqrt{\mu\varepsilon}}} = \sqrt{\mu_r \varepsilon_r} \qquad \text{...(3.12)}$$

If the ionosphere is assumed as non-magnetic medium then $\mu_r = 1$, hence Eq. (3.12) comes out as:

$$n = \sqrt{\varepsilon_r} \qquad \text{...(3.13)}$$

Equation (3.13) suggests that the refractive index of the ionosphere is the square root of the relative permittivity of ionosphere, hence by substituting value in Eq. (3.13) from Eq. (3.11), we get

$$n = \sqrt{\left[1 - \frac{Ne^2}{m\omega^2 \varepsilon_0}\right]} \qquad \text{...(3.14)}$$

where,

e = Charge on electron = 1.6×10^{-19} C
m = Mass of electron = 9.1×10^{-31} kg
ε_0 = Permittivity of free space = 8.854×10^{-12} F/m
$\omega = 2\pi f$ = Frequency in radians

Hence, by substituting values in Eq. (3.14), the refractive index (n) of ionosphere comes out as:

$n \propto \frac{1}{f}$

$$n = \sqrt{\left[1 - \frac{81N}{f^2}\right]} \qquad \text{...(3.15)}$$

Equation (3.15) suggests that the refractive index of ionosphere is less than unity. Moreover, with the increase in altitude, the electron density in ionosphere increases which further reduces the refractive index of ionosphere.

3.3.2 Plasma and Plasma Frequency (f_p)

A completely ionised gas consisting charged ions and electrons at very high temperature is defined as plasma. Plasma is considered as the fourth state of matter.

Plasma frequency is the natural frequency at which the charged particles oscillate in plasma region. At Plasma frequency ($\omega = \omega_p$), the relative permittivity (ε_r) is zero, hence by substituting it in Eq. (3.11), plasma frequency comes out as:

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} = \left[1 - \frac{Ne^2}{m\omega_p^2 \varepsilon_0}\right] = 0 \qquad \text{...(3.16)}$$

or

$$\omega_p^2 = \frac{Ne^2}{m\varepsilon_0} \qquad \text{...(3.17)}$$

By substituting the values of constants in Eq. (3.17), the simplified equation comes out as:

$$f_p = 9\sqrt{N} \qquad \text{...(3.18)}$$

Equation (3.18) suggests that the plasma frequency is proportional to the square root of the electron density in the ionosphere.

The refractive index (n) of the ionosphere in terms of plasma frequency can be obtained by substituting the value of electron density (N) in Eq. (3.15) from Eq. (3.18). The refractive index (n) comes out as:

$$n = \sqrt{\left[1 - \frac{f_p^2}{f^2}\right]} \qquad \text{...(3.19)}$$

3.3.3 Critical Frequency (f_c)

As we have discussed earlier, when high frequency radio wave enters into the ionosphere, it gets reflected back due to the refraction of wave from several layers.

As per the Snell's law, the refractive index of a medium is given as:

$$n = \frac{\sin i}{\sin r} \qquad \text{...(3.20)}$$

Fig. 3.5

where,

i = Angle of incidence relative to normal
r = Angle of refraction relative to normal

The refractive index of ionosphere is always less than unity ($n < 1$), hence the angle of refraction, r is always greater than incidence angle, i. It means the radio wave bends more away from the normal.

At a certain angle of incidence, i, the refracted angle, r becomes 90°. If the angle of incidence just exceeds this value, the wave is totally internally reflected. In this case, the refractive index is defined as:

$$n = \frac{\sin i}{\sin 90^\circ} = \sin i \qquad \text{...(3.21)}$$

By substituting value of n from Eq. (3.15) into Eq. (3.21), we get

$$n = \sqrt{\left[1 - \frac{81N}{f^2}\right]} = \sin i \qquad \text{...(3.22)}$$

For vertical incident radio wave, the angle of incidence, i is equal to zero, which in turn makes the refractive index zero.

Hence, the *critical frequency* is the highest frequency which can be reflected back to the earth by a particular layer of ionosphere at *vertical incidence*. Hence, from Eq. (3.22), we get

$$n = \sqrt{\left[1 - \frac{81N_{\max}}{f_c^2}\right]} = \sin i = 0 \qquad \text{...(3.23)}$$

or

$$f_c = 9\sqrt{N_{\max}}$$

or
$$f_c^2 = 81 N_{\max} \qquad \text{...(3.24)}$$

where,

$N_{\max}$ = Electron density (per cubic metre)

f_c = Critical frequency (in Hz).

As Eq. (3.24) suggests that the critical frequency is proportional to the square root of maximum electron density and it is different for different layers of ionosphere.

PROBLEM 1: What is the maximum density of free electrons in the ionospheric layer for which the corresponding critical frequency is 1.6 MHz?

Solution: The relationship between critical frequency (f_c) and maximum electron density ($N_{\max}$) is given by Eq. (3.24) as:

$$f_c = 9\sqrt{N_{\max}}$$

Given:

$$f_c = 1.6 \text{ MHz}$$

Hence,

$$N_{\max} = \frac{f_c^2}{81} = \frac{(1.6 \times 10^6)^2}{81}$$

$$N_{\max} = 3.16 \times 10^{10} \text{ electrons/m}^3$$

PROBLEM 2: Find the critical frequency of an ionospheric layer which has maximum electron density of 500 electrons/cm^3.

Solution: The relationship between critical frequency (f_c) and maximum electron density ($N_{\max}$) is given by Eq. (3.24) as:

$$f_c = 9\sqrt{N_{\max}}$$

Given:

$$N_{\max} = 500 \text{ electrons/cm}^3 = 500 \times 10^6 \text{ electrons/m}^3$$

Hence,

$$f_c = 9\sqrt{(500 \times 10)^6}$$

$$f_c = 201.24 \text{ kHz}$$

The layer must be D-layer as it has critical frequency less than 2 MHz.

3.3.4 Maximum Usable Frequency (MUF)

As we have discussed earlier that the critical frequency is the maximum frequency that can be reflected back to earth by the ionosphere for the vertical incidence.

But for the angle of incidence other than vertical incidence, there may be a frequency higher than critical frequency which is reflected back towards the earth's surface. Such frequency is known as *maximum usable frequency* (MUF).

MUF is also defined as the maximum frequency which can be used for sky wave propagation for specific distance between two points on the earth's surface. Hence, it can be concluded that MUF is distance dependent and varies with the variation in distance.

For the radio wave to return back to the earth, the angle of refraction must be equal to 90°. In such case, the electron density (N) becomes maximum electron density ($N_{\max}$) and frequency (f) becomes maximum usable frequency (f_{MUF}). Hence, for ionosphere:

$$n = \frac{\sin i}{\sin 90^\circ} = \sqrt{\left[1 - \frac{81N}{f^2}\right]} \qquad \text{...(3.25)}$$

or
$$\sin i = \sqrt{\left[1 - \frac{81N_{\max}}{f_{\text{MUF}}^2}\right]} \qquad \text{...(3.26)}$$

or
$$\sin^2 i = \left[1 - \frac{81N_{\max}}{f_{\text{MUF}}^2}\right] \qquad \text{...(3.27)}$$

or
$$\frac{81N_{\max}}{f_{\text{MUF}}^2} = 1 - \sin^2 i \qquad \text{...(3.28)}$$

or
$$\frac{81N_{\max}}{f_{\text{MUF}}^2} = \cos^2 i \qquad \text{...(3.29)}$$

By substituting the value of 81 $N_{\max}$ from Eq. (3.24) to Eq. (3.29), we get

$$\frac{f_c^2}{f_{\text{MUF}}^2} = \cos^2 i \qquad \text{...(3.30)}$$

or
$$f_{\text{MUF}} = (\sec i) f_c \qquad \text{...(3.31)}$$

Equation (3.31) is also known as *secant law*. Secant law explains that the maximum usable frequency is always greater than critical frequency by the factor sec i. It also concludes that maximum frequency has to be used for sky wave propagation between the two points for a given angle of incidence.

As we know that the earth's surface is curved and the maximum angle for the reflection from the top most layer of ionosphere (from F-layer) is found to be approximately equal to 74°. Thus for this limiting angle, the maximum f_{MUF} can be given as:

$$f_{\text{MUF}}\,(\text{max.}) = (\sec 74^\circ) f_c = 3.6 f_c \qquad \text{...(3.32)}$$

Equation (3.32) gives the maximum frequency in MHz which can be reflected back to the earth from the ionosphere. Any other radio wave having greater frequency than this frequency penetrates through the ionosphere and will never come back to earth's surface.

Some important points about MUF are:

- The secant law is applicable to the distance of 1000 km between transmitter and receiver. This limitation is due to the curvature of earth's surface.
- MUF depends upon the latitude, time (longitude), distance, incidence angle, season and solar activity.

- MUF ranges from 8 MHz to 30 MHz. It may go up to 50 MHz during peak solar activity.
- As shown in Figure 3.6, if the radio wave is transmitted from the transmitter (at point A) to the receiver (at point B) at θ_i angle of incidence, then the maximum angle of incidence for curved earth's surface is defined from the geometry as:

$$\theta_i\,(\max) = \sin^{-1}\left(\frac{R}{R+h}\right) \qquad \text{...(3.33a)}$$

where,

R = Radius of earth = 6370 km
h = Height of reflecting layer of ionosphere from earth's surface = 400 km

Substituting these values in Eq. (3.33a), θ_i (max) comes out as:

$$\theta_i\,(\max) = \sin^{-1}\left(\frac{6370}{6370+400}\right) \approx 74^\circ \qquad \text{...(3.33b)}$$

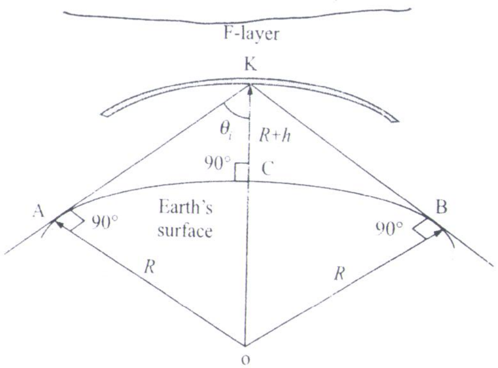

FIGURE 3.6 Depiction of sky wave propagation.

3.3.5 Maximum Usable Frequency (f_{MUF}) for Short Distance Communication

When the distance between transmitter and receiver is less than 1000 km, it is considered as short distance communication. For short distance, the earth's surface is considered as *flat surface*. Let us assume that the ionising layer acts as a perfect reflector and the distance between transmitter and receiver is D. The flat earth is shown in Figure 3.7(a) and in this case, the secant of incidence angle can be given as:

$$\sec i = \frac{\sqrt{h^2 + \dfrac{D^2}{4}}}{h} \qquad \text{...(3.34)}$$

By substituting value of sec i from Eq. (3.34) to Eq. (3.31), we get

$$f_{\text{MUF}} = \frac{\sqrt{h^2 + \dfrac{D^2}{4}}}{h} f_c \qquad \text{...(3.35)}$$

$$f_{\text{MUF}} = f_c\sqrt{1 + \frac{D^2}{4h^2}} \qquad \text{...(3.36)}$$

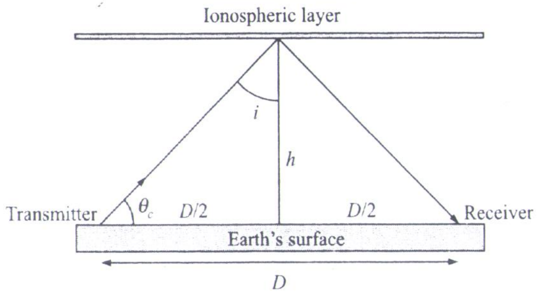

FIGURE 3.7(a) Depiction of flat earth's surface.

3.3.6 Maximum Usable Frequency (f_{MUF}) for Long Distance Communication

When the distance between transmitter and receiver is greater than 1000 km, it is considered as long distance communication. For long distance, the earth's surface is considered as *curved surface*. Let us assume that the ionising layer is concentric with earth's surface. The height of the ionising layer is h and it acts as a perfect reflector. The distance between transmitter and receiver is D. The curved earth is shown in Figure 3.7(b) and in this case, the transmitted wave leaves the transmitter tangentially to the earth's surface and the angle of incident at ionospheric layer is i. It is assumed that the distance D (shown by curve PM) subtends an angle 2θ at the centre of the Earth shown by point O. Hence, from Figure 3.7(b), we get

$$2\theta = \frac{D}{R} \qquad \text{...(3.37)}$$

or

$$D = 2R\theta \qquad \text{...(3.38)}$$

From ΔQTP, we have

$$\text{PT} = R\sin\theta \text{ and } \text{OT} = R\cos\theta \qquad \text{...(3.39)}$$

$$\text{QT} = \text{OQ} - \text{OT} = h + R - R\cos\theta \qquad \text{...(3.40)}$$

$$\text{PQ} = \sqrt{(\text{PT}^2 + \text{QT}^2)} = \sqrt{\{(R\sin\theta)^2 + (h + R - R\cos\theta)^2\}} \qquad \text{...(3.41)}$$

Hence,

$$\cos^2 i = \left(\frac{\text{QT}}{\text{PQ}}\right)^2 = \frac{(h + R - R\cos\theta)^2}{(R\sin\theta)^2 + (h + R - R\cos\theta)^2} = \frac{f_c^2}{f_{\text{MUF}}^2} \qquad \text{...(3.42)}$$

As assumed earlier, ∠OPQ should be 90° and when D is maximum, θ is maximum, therefore from ΔOPQ

$$\cos\theta = \frac{OP}{OQ} = \frac{R}{R+h} = \frac{1}{\left(1+\dfrac{h}{R}\right)} \quad \text{...(3.43)}$$

$D << R$ hence θ is so small that,

$$\sin\theta \approx \theta \quad \text{...(3.44)}$$

This makes,

$$\cos\theta = \sqrt{(1-\sin^2\theta)} = (1-\theta^2)^{\frac{1}{2}} = 1 - \frac{\theta^2}{2} \text{ (by binomial expansion)} \quad \text{...(3.45)}$$

By substituting the value of $\cos\theta$ from Eq. (3.45) to Eq. (3.43), we get

$$(1-\theta^2)^{\frac{1}{2}} = \left(1+\frac{h}{R}\right)^{-1} \quad \text{...(3.46)}$$

Because $h << R$ and θ is very small hence by using Binomial theorem and expanding Eq. (3.46), we get,

$$1 - \frac{\theta^2}{2} = 1 - \frac{h}{R} \quad \text{[by neglecting higher order terms]}$$

or

$$\theta^2 = \frac{2h}{R} \quad \text{...(3.47)}$$

By squaring Eq. (3.38) and substituting the value of θ^2 from Eq. (3.47), we get

$$h = \frac{D^2}{8R} \quad \text{...(3.48)}$$

Hence, θ can be obtained by substituting value of h in Eq. (3.47). Now, Eqs. (3.44) and (3.45) can be rewritten as

$$\cos\theta = \left(1 - \frac{D^2}{8R^2}\right) \text{ and } \sin\theta \approx \theta = \frac{D}{2R} \quad \text{...(3.49)}$$

By substituting these values in Eq. (3.42), the MUF comes out as:

$$\frac{f_c^2}{f_{\text{MUF}}^2} = \frac{(h+R-R\cos\theta)^2}{(R\sin\theta)^2 + (h+R-R\cos\theta)^2} = \frac{\left(h+\dfrac{D^2}{8R}\right)^2}{\dfrac{D^2}{4} + \left(h+\dfrac{D^2}{8R}\right)^2} \quad \text{...(3.50)}$$

Hence,

$$\boxed{f_{\text{MUF}} = f_c \frac{\left[\dfrac{D^2}{4} + \left(h+\dfrac{D^2}{8R}\right)^2\right]^{\frac{1}{2}}}{\left(h+\dfrac{D^2}{8R}\right)}} \quad \text{...(3.51)}$$

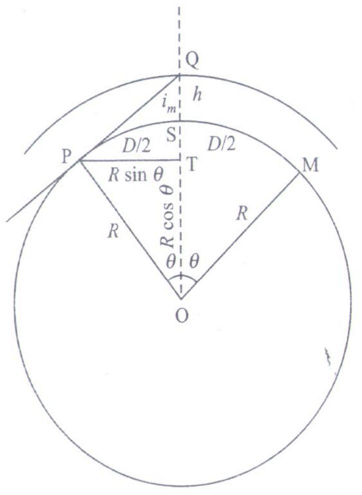

FIGURE 3.7(b) Depiction of curved earth's surface.

PROBLEM 3: The refractive index of an ionospheric layer is 0.9 and the MUF is 9 MHz. If the height of the ionospheric layer is 400 km above the earth's surface then find out the maximum electron density, critical frequency and the distance between transmitter and receiver assuming that earth's surface is flat.

Solution: Given:

$n = 0.9$; $f_{\text{MUF}} = 9$ MHz; $h = 400$ km

- The refractive index is given by Eq. (3.25) as:

$$n = \sqrt{\left[1 - \frac{81N_{\max}}{f_{\text{MUF}}^2}\right]}$$

By substituting values, we get

$$0.9 = \sqrt{\left[1 - \frac{81N_{\max}}{(9\times10^6)^2}\right]}$$

$$N_{\max} = [1-(0.9)^2] \times \frac{(9\times10^6)^2}{81}$$

$$N_{\max} = 1.9 \times 10^{11} \text{ electrons/m}^3$$

- The critical frequency is given by Eq. (3.24) as:

$$f_c = 9\sqrt{N_{\max}}$$

$$f_c = 9\sqrt{(1.9\times10^{11})}$$

$$f_c = 3.92 \text{ MHz}$$

- The distance between transmitter and receiver can be obtained by using Eq. (3.36) as:

$$f_{MUF} = f_c\sqrt{1+\frac{D^2}{4h^2}}$$

$$\left(\frac{9}{3.92}\right)^2 = 1+\frac{D^2}{4\times(400\times10^3)^2}$$

or $$D = 1653.35 \text{ km.}$$

PROBLEM 4: In a communication link, the distance between transmitter and receiver is 500 km. The communication is established via sky wave propagation and the height of ionospheric layer is 300 km above the earth's surface. If the critical frequency is 10 MHz, find the maximum transmission frequency beyond which the signal strength becomes negligible at receiver. Assume that earth's surface is flat.

Solution: Maximum usable frequencyis the frequency beyond which the signal strength becomes negligible at receiver.

Given:

$D = 500$ km, $h = 300$ km, $f_c = 10$ MHz

From Eq. (3.36), we have

$$f_{MUF} = f_c\sqrt{1+\frac{D^2}{4h^2}}$$

or $$f_{MUF} = (10\times10^6)\times\sqrt{1+\frac{500^2}{4\times300^2}}$$

or $$f_{MUF} = 13.01 \text{ MHz}$$

PROBLEM 5: The change in the maximum electron density in E-layer from day time to night time is 2.3×10^{11} electrons/m^3. If the critical frequency during day time is 4.5 MHz then find out the critical frequency during night time.

Solution: Maximum electron density is more during day time as compared to night time, hence, the critical frequency is more for day time as compared to night time.

The relationship between critical frequency (f_c) and maximum electron density (N_{max}) is given by Eq. (3.24) as:

$$f_c = 9\sqrt{N_{max}}$$

Given:

$f_{c1} = 4.5$ MHz, $\Delta N_{max} = 2.3 \times 10^{11}$ electrons/m^3

Hence, corresponding maximum electron density for day time critical frequency is:

$$N_{max1} = \frac{f_{c1}^2}{81} = \frac{(4.5\times10^6)^2}{81}$$

$$N_{max1} = 2.5\times10^{11} \text{ electrons/m}^3$$

The change in maximum electron density is given as:

$$\Delta N_{max} = N_{max1} - N_{max2}$$

or $$N_{max2} = N_{max1} - \Delta N_{max}$$

or $$N_{max2} = (2.5\times10^{11}) - (2.3\times10^{11})$$

or $$N_{max2} = 0.2\times10^{11} \text{ electrons/m}^3$$

Hence, the critical frequency during night time is given as:

$$f_{c2} = 9\sqrt{N_{max2}}$$

or $$f_c = 9\sqrt{(0.2\times10^{11})}$$

or $$f_c = 1.27 \text{ MHz}$$

PROBLEM 6: For the different layers of ionosphere the electron densities are given as:

- For D-layer = 500 electrons/cm^3
- For E-layer = 5×10^5 electrons/cm^3
- For F-layer = 3×10^6 electrons/cm^3

If the frequency of the propagating radio wave is 50 MHz, find out the relative permittivity of each layer.

Solution: The refractive index of each layer is equal to the square root of the relative permittivity of that layer, hence,

$$n = \sqrt{\varepsilon_r} = \sqrt{\left(1-\frac{81N}{f^2}\right)}$$

or $$\varepsilon_r = \left(1-\frac{81N}{f^2}\right)$$

For the simplification of calculation, readers can remember that if electron density is given in electrons/cm^3 then the frequency can be written in kHz. Hence.

- *For D-layer,* $N = 500$ electrons/cm^3 = 500×10^6 electrons/m^3

$$\varepsilon_r = \left[1-\frac{81\times500\times10^6}{(50\times10^6)^2}\right]$$

or $$\varepsilon_r \approx 1$$

The permittivity remains same for D-layer.

- *For E-layer,* $N = 5 \times 10^5$ electrons/cm^3 = 5×10^{11} electrons/m^3

$$\varepsilon_r = \left[1-\frac{81\times5\times10^{11}}{(50\times10^6)^2}\right]$$

or $$\varepsilon_r \approx 0.9838$$

- *For F-layer,* $N = 3 \times 10^6$ electrons/cm^3 = 3×10^{12} electrons/m^3

$$\varepsilon_r = \left[1 - \frac{81 \times 3 \times 10^{12}}{(50 \times 10^6)^2}\right]$$

or $$\varepsilon_r \approx 0.9028$$

PROBLEM 7: A sky wave of frequency 20 MHz is incident on E-layer at an angle of 30°. Find out the angle of refraction if the electron density in E-layer is 5×10^5 electrons/cm^3.

Solution: For E-layer, $N = 5 \times 10^5$ electrons/cm^3 = 5×10^{11} electrons/m^3

Angle of incidence, $i = 30°$

We know that,

$$\varepsilon_r = \left(1 - \frac{81N}{f^2}\right)$$

or $$\varepsilon_r = \left[1 - \frac{81 \times (5 \times 10^{11})}{(20 \times 10^6)^2}\right]$$

or $$\varepsilon_r = 0.8987$$

The relationship between relative permittivity and refractive index is given as:

$$n = \sqrt{\varepsilon_r}$$

or $$n = \sqrt{0.8987}$$

or $$n = 0.95$$

By Snell's law,

$$n = \frac{\sin i}{\sin r}$$

or $$r = \sin^{-1}\left[\frac{\sin i}{n}\right]$$

or $$r = \sin^{-1}\left[\frac{\sin 30°}{0.95}\right]$$

or $$r = 75°$$

Hence, the sky wave will be refracted at an angle of 31.75° from E-layer.

PROBLEM 8: Find out the critical angle of propagation and angle of incident for E-layer if the distance between transmitter and receiver is 600 km. Assume that the height of E-layer is 100 km.

Solution: Refer Figure 3.7(a), the critical angle (θ_c) is given as:

$$\tan \theta_c = \left[\frac{2h}{D}\right] \qquad \text{...(i)}$$

3.3.7 Optimum Working Frequency (OWF)

For sky wave propagation, it is necessary to use maximum possible frequency wave. It means the radio wave should be of MUF. But as we have studied earlier that MUF depends upon many factors like distance between transmitter and receiver and the state of ionosphere (the level of ionisation). The MUF varies about 15% of its maximum value due to the regular changes and irregularities in the ionosphere. Hence, practically the value of radio wave should be less than 15 % to the maximum value of MUF in order to have efficient sky wave propagation. This frequency is termed as *optimum working frequency* (OWF). OWF is used for ionospheric propagation instead of MUF. For a given pair of transmitter and receiver, OWF can be selected between 50–85% of the predicted MUF.

As we know that MUF depends upon the time of the day, season and month hence OWF also varies in the same manner with these factors. Practically it is not possible to change OWF continuously hence two OWF frequencies are defined for sky wave propagation. The higher frequency is selected for day time (because electron density is more during day time) and lower frequency is selected for night. During night, the altitude of the ionised layer increases hence distance covered by the reflected wave (skip distance) increases as shown in Figure 3.8.

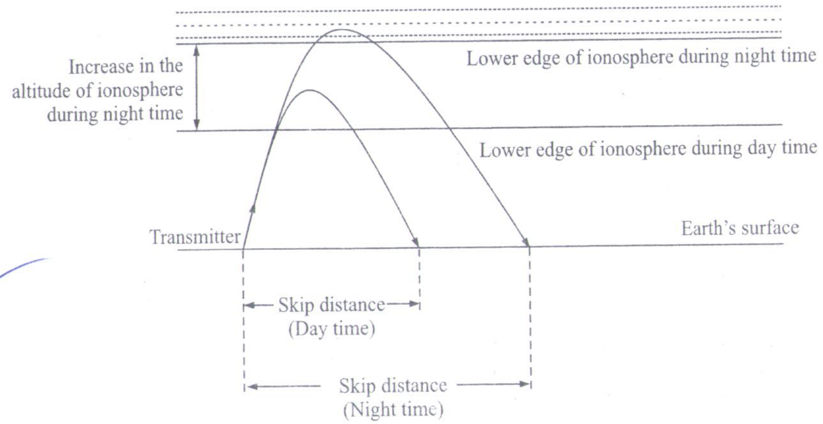

FIGURE 3.8 Increase in skip distance with increase in ionosphere altitude.

Note:

- The lower frequency radio waves are bent more towards the earth by ionosphere, hence, to compensate the increase in skip distance, 'lower frequency radio wave is used as OWF' at night.
- OWF is also abbreviated as "FOT" which is derived from the French words "frequency optimum de travail" used for OWF.

3.3.8 Lowest Usable Frequency (LUF)

The *lowest usable frequency* is defined as the minimum frequency in the high frequency band (3–30 MHz) which gives satisfactory reception for the given transmission power and distance. It defines the lower limit of the OWF and OWF should lie between MUF and LUF.

The D-layer of the ionosphere absorbs the lower frequencies of HF band. The magnitude of absorption is inversely proportional to the square of frequency, hence, high frequencies of HF band are selected as OWF. But for the high frequencies near MUF, the radio waves suffer abnormal retardation and considerable amount of absorption takes place. Hence, the signal strength received at receiver is quite low.

That is why the OWF ranges between 50% and 85 % of the predicted MUF.

The LUF is quite less at night because the D-layer completely disappears at night and even lower frequencies of HF band can be communicated using sky wave propagation.

The LUF depends upon the following factors:

- The effective radiated power, i.e., product of power transmitted (P_t) and gain of transmitting antenna (G_t).

- The S/N ratio at the receiver.
- The ionospheric characteristics between transmission distance.
- Polarisation changes in the wave due to the presence of earth's magnetic field.
- Scattering of the waves.

3.3.9 Skip Distance

The *skip distance* is the shortest distance from the transmitter at which the sky wave of particular frequency will return back to the earth. This distance is always measured along the earth's surface.

The angle of incidence, for which the skip distance is minimum, defined as *angle of critical incidence* and denoted by θ_c. The angle of critical incidence depends upon the frequency of the radio wave transmitted. For higher frequency radio waves, angle of critical incidence is smaller.

To understand the importance of angle of critical incidence, let us assume a situation as shown in Figure 3.9.

From Figure 3.9 it is clear that a transmitter is located at point X and the receiver is placed at point Z. Between points X and Z, there exists a point Y up to which ground waves from transmitter can reach. The distance between X and Y is termed as *ground wave range*.

The radio wave from point X can reach up to point Z if the angle of incidence is critical incidence angle. Hence the distance between point X and point Z is called *skip distance*.

If the angle of incidence is smaller than critical incidence angle, the radio wave will go beyond point Z through sky wave propagation and if the angle of incidence is greater than the critical angle of incidence then the wave escapes in the space.

The distance between point Y and point Z is termed as *skip zone* because neither ground wave nor sky wave reaches in this region.

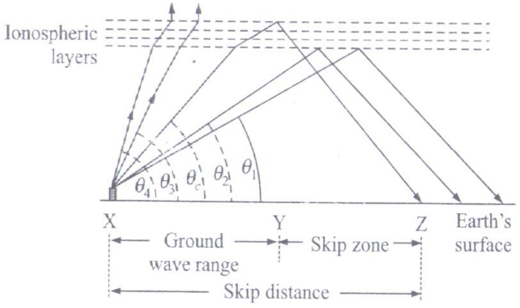

FIGURE 3.9 Depiction of critical incidence angle and skip distance.

Skip distance (D_{skip}) can be calculated by substituting D_{skip} in Eq. (3.36); hence, Eq. (3.36) can be written as:

$$f_{\text{MUF}} = f_c\sqrt{1+\frac{D_{\text{skip}}^2}{4h^2}} \qquad \text{...(3.52)}$$

By squaring both sides of Eq. (3.52) and rearranging the terms, we get

$$\frac{f_{\mathrm{MUF}}^2}{f_c^2} - 1 = \frac{D_{\mathrm{skip}}^2}{4h^2} \qquad \ldots(3.53)$$

or

$$D_{\mathrm{skip}} = 2h\sqrt{\left[\left(\frac{f_{\mathrm{MUF}}}{f_c}\right)^2 - 1\right]} \qquad \ldots(3.54)$$

By substituting value of $\frac{f_{\mathrm{MUF}}}{f_c}$ from Eq. (3.31) to Eq. (3.54), we get

$$D_{\mathrm{skip}} = 2h\sqrt{[\sec^2 i - 1]} \qquad \ldots(3.55)$$

or

$$D_{\mathrm{skip}} = 2h \tan i \qquad \ldots(3.56)$$

Here,

i = angle of incidence on ionospheric layer with respect to normal

θ = angle of transmitted wave with respect to earth's surface

Hence,

$$i = 90° - \theta \quad \ldots(3.57) \quad \text{[Refer Figure 3.7(a)]}$$

By substituting the value of incidence angle in Eq. (3.56), we get

$$D_{\mathrm{skip}} = 2h \tan (90° - \theta) \qquad \ldots(3.58)$$

or

$$D_{\mathrm{skip}} = 2h \cot \theta \qquad \ldots(3.59)$$

or

$$D_{\mathrm{skip}} = \frac{2h}{\tan \theta} \qquad \ldots(3.60)$$

Hence, it can be concluded that if the angle of incidence, i increases for a given frequency, the skip distance also increases.

PROBLEM 10: The sky wave reflects from an ionospheric layer which has an altitude of 400 km and refractive index as 0.9 at 10 MHz. Find out the skip distance for which MUF is 10 MHz. Neglect earth's curvature.

Solution: The relationship between refractive index and maximum electron density is given as:

$$n = \sqrt{\left(1 - \frac{81 \times N_{\max}}{f_{\mathrm{MUF}}^2}\right)}$$

Given: $n = 0.9$; $f_{\mathrm{MUF}} = 10$ MHz; $h = 400$ km.

Hence,

$$0.9 = \sqrt{\left(1 - \frac{81 \times N_{\max}}{(10 \times 10^6)^2}\right)}$$

or

$$0.81 = \left(1 - \frac{81 \times N_{\max}}{(10 \times 10^6)^2}\right)$$

or

$$N_{\max} = 2.34 \times 10^{11} \text{ electrons/m}^3$$

The critical frequency is given as:

$$f_c = 9\sqrt{N_{\max}}$$

or

$$f_c = 9\sqrt{(2.34 \times 10^{11})}$$

or

$$f_c = 4.35 \text{ MHz}$$

The skip distance is defined in Eq. (3.54) as:

$$D_{\mathrm{skip}} = 2h\sqrt{\left[\left(\frac{f_{\mathrm{MUF}}}{f_c}\right)^2 - 1\right]}$$

or

$$D_{\mathrm{skip}} = (2 \times 400)\sqrt{\left[\left(\frac{10}{4.35}\right)^2 - 1\right]}$$

or

$$D_{\mathrm{skip}} = 1656 \text{ km}$$

3.3.10 Skip Zone (Dead Zone)

The ground wave propagation is also associated with sky wave propagation. Skip zone appears when both the sky waves and ground waves are transmitted from the same transmitter. The range of ground waves for HF band is quite small as compared to sky waves.

In the previous section, it was discussed that the sky wave cannot be received at a distance smaller than skip distance. Hence, there exists a *skip zone (dead zone)* between the points where the strength of ground wave is too small for reception and where the sky wave is first returns to the earth (as shown in Figure 3.9).

The region of skip zone depends upon the operating frequency, direction of transmission, time of day, solar activity and season of the year.

For any sky wave propagation, if no skip zone exists and the signal strength of both sky wave and ground wave is equal then the ground and sky wave cancel out each other. This phenomenon occurs because the sky wave travels more distance as compared to the ground wave hence the phase difference between the sky and ground wave is almost 180° which causes the cancellation of signal received. This causes fading of the signal received at the receiver.

3.3.11 Actual and Virtual Height

In sky wave propagation, the ionosphere acts as a radio mirror and reflects the radio waves of HF band back to the earth. The reflection is caused due to the successive refractions at different layers of the ionosphere. The amount of refraction caused to radio wave in sky wave propagation depends upon the angle of incidence, frequency of radio wave and ionisation density of the layer.

The high ionisation density is found in the upper layers of ionosphere and high ionisation density reduces the relative permittivity of the medium. The reduction in relative permittivity causes the refractive index to decrease. Hence, when a radio wave enters in any of these layers, it experiences rarer medium and moves away from the normal (as shown in Figure 3.5). Successive refraction causes the radio wave to bend towards the earth as shown in Figure 3.10. When the wave bends away from the normal, at some specific point it becomes almost parallel to the ionospheric layer and then bends further downwards. In such case the angle of incidence is almost equal to the angle of refraction.

The height at a point above the earth's surface at which the transmitted radio wave bends down to the earth is called *actual* or *true height (h)* (distance DB as shown in Figure 3.10).

The refraction of radio wave is similar to the reflection of radio wave because the paths of transmitted and refracted wave follow the same paths in case of reflection takes place. Hence, the height from the earth's surface to the virtual point where the reflection of radio wave takes place is defined as *virtual height (h′)* (distance DO as shown in Figure 3.10).

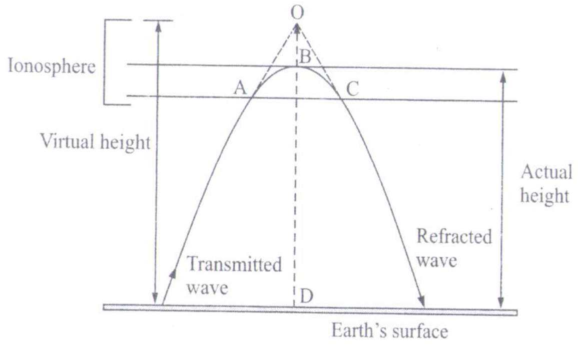

FIGURE 3.10 Actual and virtual heights.

The actual and virtual heights are defined for ionospheric layers and the virtual height is measured by using an instrument known as *ionosonde* (or *chirpsounder*). Ionosonde is a short pulse transmitter which works on the echo principle and it measures the virtual height by transmitting RF pulses of short duration (pulse width = 150 μs) vertically towards the layer. The radio wave travels at the speed of light hence the instrument sends RF pulse which goes to the ionosphere and comes back to the earth as shown in Figure 3.11. The instrument receives the pulse and finds out the virtual height by following relation:

$$h' = c\left(\frac{T}{2}\right) \qquad \text{...(3.61)}$$

where,

T = Total time taken by the pulse in travelling from earth to ionosphere and coming back

c = Velocity of light = 3×10^8 m/s

Ionosonde repeats this measurement from 1 MHz to 25 MHz and plots the corresponding virtual heights. These plots are termed as *ionogram*. For critical frequency, the value of virtual height comes out very high.

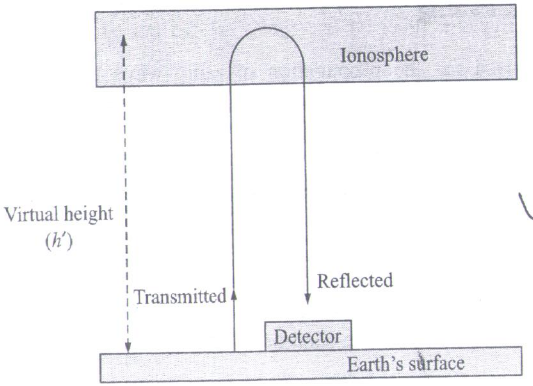

FIGURE 3.11 Virtual height measurement.

PROBLEM 11: A pulse of a given frequency is transmitted upwards and it is received back after a period of 1ms. Find the virtual height of the reflecting layer.

Solution: Given:

$T = 1$ ms

The virtual height can be calculated using Eq. (3.61),

$$h' = c\left(\frac{T}{2}\right)$$

or

$$h' = (3\times10^8)\left(\frac{1\times10^{-3}}{2}\right)$$

or

$$h' = 150 \text{ km}$$

3.4 FADING

Fading is defined as the undesirable variation or fluctuations in the intensity of the signal received at receiver. The fluctuations in the signal strength are caused due to the variations in the characteristics of ionospheric layer. Fading is a common characteristic of sky wave propagation of HF radio waves. Various types of fading are:

- Multipath fading
- Selective fading
- Interference fading
- Absorption fading
- Polarisation fading
- Skip fading

3.4.1 Multipath Fading

Multipath term is used for the propagation of radio wave through different paths. The propagation includes sky wave propagation, ground wave propagation, reflection from earth's surface and re-radiation by the ionospheric layers as shown in Figure 3.12.

The multiple versions of radio wave reach at the receiver with different distances travelled hence the phase of each version is different from another. The receiver receives the vector sum of all the versions of waves hence when the received waves are out of phase, very weak signal is received at receiver and inversely when the received waves are in phase, strong signal appears at receiver. The phase of the received waves change continuously hence they cause fading.

Because this type of fading depends upon the phase of the received signal which in turn depends upon the path or distance travelled hence this type of fading is termed as *multipath fading*.

The multipath fading can be overcome by using *space diversity* or *frequency diversity* technique which will be discussed in the later section.

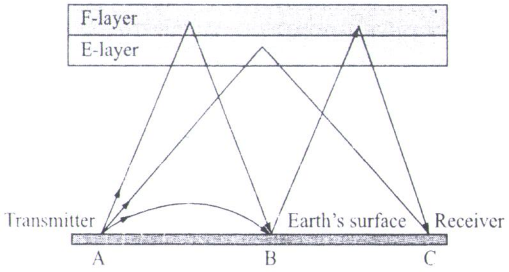

FIGURE 3.12 Different version of radio wave.

3.4.2 Selective Fading

When the fading is frequency selective, i.e., fading is more for any specific frequency, such type of fading is termed as *selective fading*. It is dominant for high frequencies used in sky wave propagation. Modulated signals get distorted due to the selective fading. The amplitude modulated signals are distorted more by selective fading. Hence, in order to reduce distortion by selective fading single-side band (SSB) systems are employed for amplitude modulated communications.

3.4.3 Interference Fading

The interference of radio waves reflected by upper and lower ionospheric layers causes fading and this type of fading is termed as *interference fading*. It is also caused because of the interference of ground wave and sky wave. As we know that the ionisation density of the ionosphere is subjected to continuous small variations hence the path of the reflected wave also undergoes small variations. The interference of these reflected waves cause fading at receiver.

This is the most serious fading and can be minimised by using *space diversity* or *frequency diversity* scheme.

3.4.4 Absorption Fading

The change in the characteristics of ionospheric layers changes the absorption property of ionosphere. Hence at different times, radio waves of different frequencies are absorbed with different rates which further cause the variation in the signal strength. This type of fading is termed as *absorption fading*.

3.4.5 Polarisation Fading

The polarisation of sky wave changes continuously when it propagates through ionosphere and finally at the receiver it reaches with different polarisation as compared to the polarisation of the transmitted wave. It means the polarisation of the transmitted radio wave and the polarisation of the received radio wave (reaching after reflection from ionosphere) are different. Hence in this case, the polarisation mismatch occurs between the antenna and the received wave. This causes the fall in signal strength at receiver. This type of fading is known as *polarisation fading* and can be overcome by using *polarisation diversity* technique.

3.4.6 Skip Fading

This type of fading occurs near the skip distance due to the variations in the height and density of ionospheric layers. The variation in height and density of ionospheric layers causes the reflected radio wave to move out of the sky wave communication range hence the signal strength received by the receiver falls down. This type of fading is called *Skip fading* and can be minimised by using *automatic gain control* (AGC) or *Automatic volume control* (AVC) method. This method becomes ineffective if the signal strength falls below the noise level because such signal cannot be used further even after amplification. In this case, diversity reception system is used to minimise such kind of fading.

3.5 DIVERSITY SCHEMES

In diversity scheme, two or more communication channels with different characteristics are employed to improve the reliability of signal carrying information. It is based on the fact that each channel experiences different level of interference and fading. Hence, by employing different communication channels, many versions of the information signal are obtained and fed to the receiver to obtain a reliable signal.

Diversity schemes are extremely useful in avoiding error bursts and combating with fading and co-channel interference. The various types of diversity techniques are:

- Time diversity
- Frequency diversity

- Space diversity
- Polarisation diversity

3.5.1 Time Diversity

In time diversity scheme multiple versions of the same signal are transmitted at different time instants. As we know that fading is time-dependent, some signals may be strong and fading is less. The error bursts are avoided by adding error correction code with the message before transmitting it.

3.5.2 Frequency Diversity

This is used to avoid selective fading. In frequency diversity scheme, the information signal is transferred using several frequency channels. As the fading is more for a specific frequency hence the other versions will remain less affected by the fading.

3.5.3 Space Diversity

This is used to overcome multipath fading. In space diversity technique, different receiving antennas are used and kept at different locations. The combination of received signal from all the receiving antennas gives signal with good strength.

3.5.4 Polarisation Diversity

This is used to overcome polarisation fading. In polarisation diversity technique, different receiving antennas having different polarisations are used for receiving the signal. In such arrangement, at least one antenna will receive the signal with matched polarisation.

3.6 TRANSMISSION LOSSES

All radio waves propagate over ionospheric paths and suffer energy losses (or attenuated) before reaching at the receiver. A large part of energy loss occurs due to the absorption of radio wave at the lower layers of the ionosphere. The other factors like ground reflection loss and free space loss also contribute to the overall energy loss of radio wave during sky wave propagation. Some of the factors contributing for energy loss of radio wave are:

- ***Free space loss:*** The wavefront of radio wave spreads out while propagating in free space as shown in Figure 3.13. With the increase in the distance travelled, the wavefront spreads out and the energy contained in the wavefront also spreads out and power per unit area decreases. Hence, the power received at the receiver is only a fraction of the total power which is supposed to be received. The spreading out of wavefront causes the free space loss.

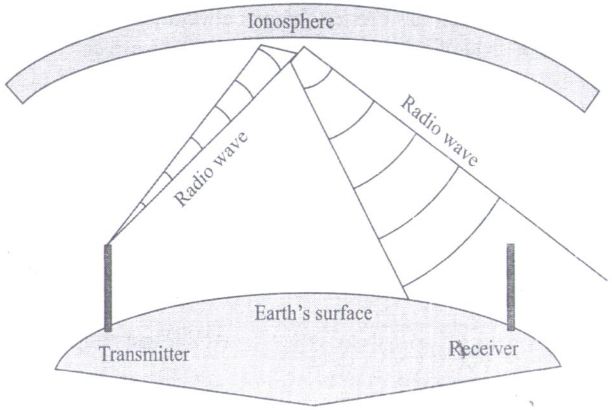

FIGURE 3.13 Wavefront spreading of radio wave.

- ***Ground reflection loss:*** Multi-hop refraction which is used in the sky wave propagation to achieve higher communication distance is one of the reasons for propagation loss. Each time the radio wave is reflected from the earth, RF energy is lost. The amount of RF energy lost depends upon the angle of incidence, frequency of the wave, surface irregularities and electrical characteristics of earth.
- ***Electromagnetic interference (EMI):*** Electromagnetic interference affects the communication systems by creating disturbances due to either electromagnetic induction or electromagnetic radiation emitted from an external source. EMI may interrupt, obstruct, degrade or limit the performance of a radio communication system. The effect of EMI ranges from simple degradation of information signal to complete loss of information signal. The sources of EMI are natural and man-made (or artificial). Some of the natural sources of EMI are the sun, thunderstorms, cosmic sources and the northern lights. Artificial sources of EMI include radio communication systems which are intentionally designed for jamming like mobile jammer and electronic warfare jammers. Spurious emissions from some of the artificial sources affect the AM broadcast, cellular telephony and television reception. EMI can be reduced or eliminated by controlling the spurious emission of radio frequencies and for that narrow band electromagnetic circuits, limited bandwidth and high directive transmitting/receiving antennas, filtering networks and metallic shielding are employed.

3.7 EFFECT OF EARTH'S MAGNETIC FIELD

The sky wave propagation is also affected by the earth's magnetic field. The average magnetic flux density of earth is 5×10^{-5} Wb/m^2. The earth's magnetic field (B_0) exerts a deflecting force on the oscillating free electrons and the magnitude of this force on each electron is given as:

$$F_m = -e(v \times B_0) \qquad \text{...(3.62)}$$