CHAPTER 4: PROPAGATION AND RADIO FREQUENCY SPECTRUM

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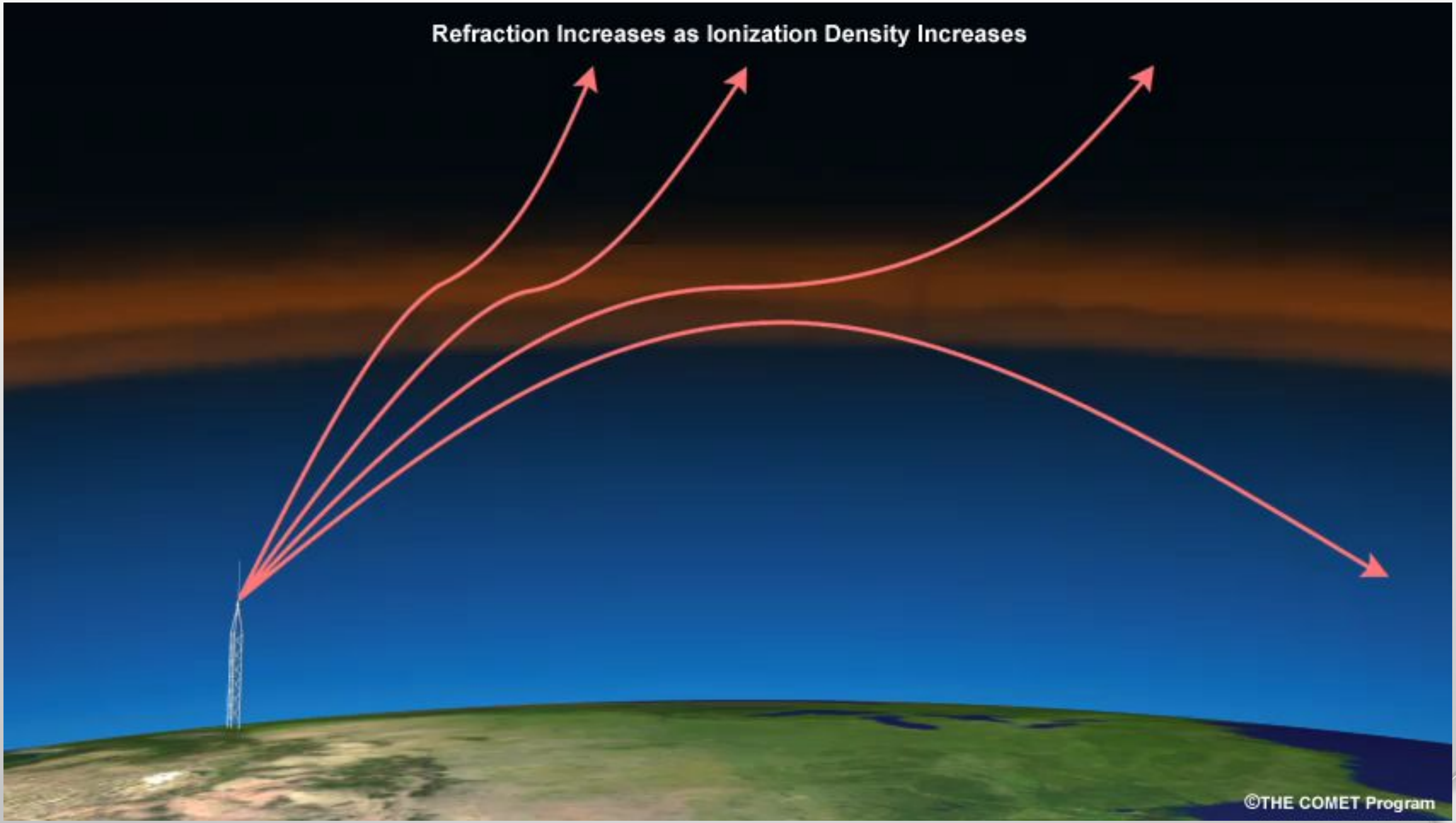
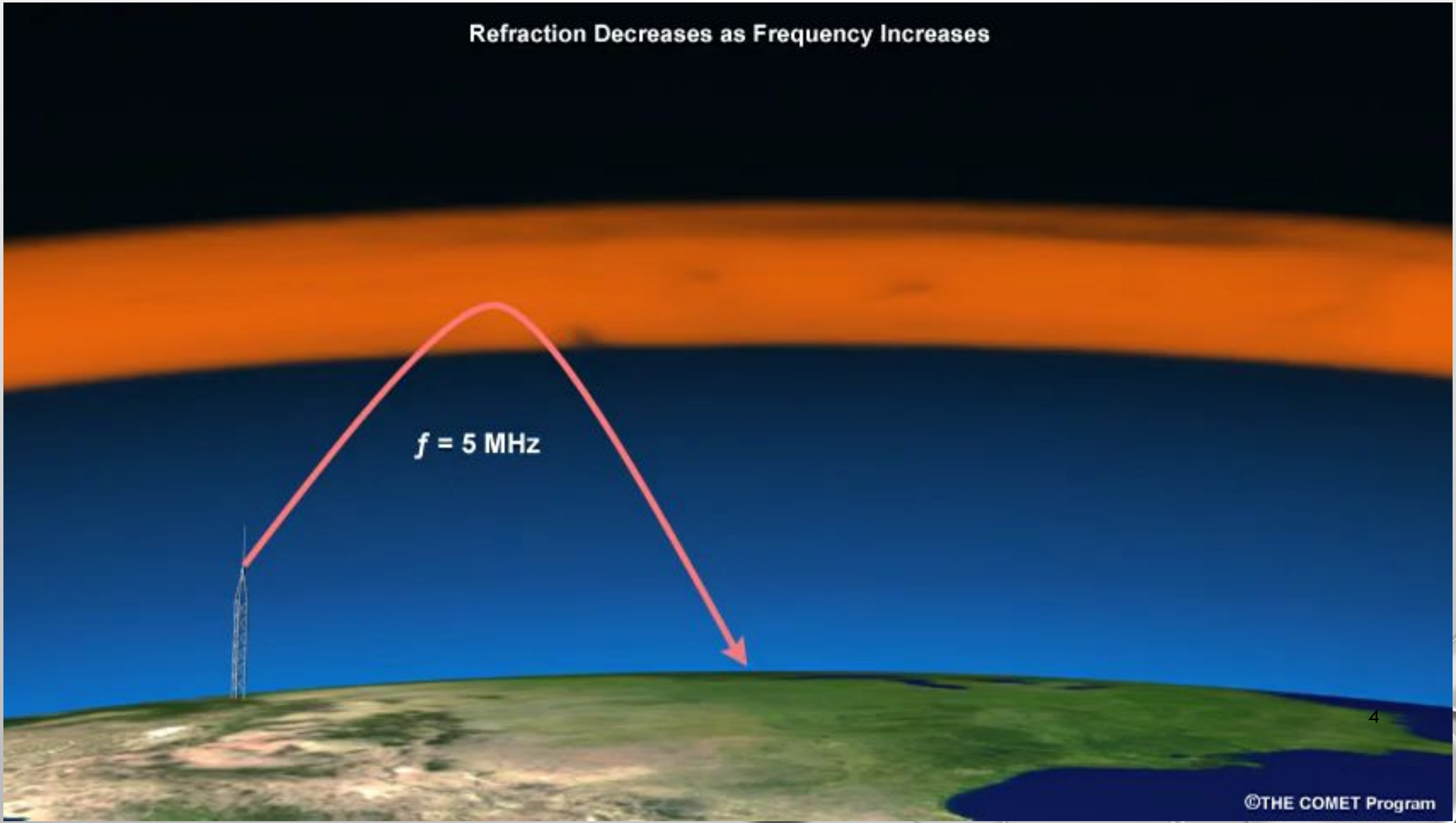
COURSE STRUCTURE

- GROUND OR SURFACE WAVE
- SPACE WAVE; DIRECT AND GROUND REFLECTED WAVE, DUCT PROPAGATION
- IONOSPHERIC OR SKY WAVE; CRITICAL FREQUENCY, MUF, SKIP DISTANCE
- TROPOSPHERIC WAVE
- RADIO FREQUENCY SPECTRUM AND ITS PROPAGATION CHARACTERISTICS

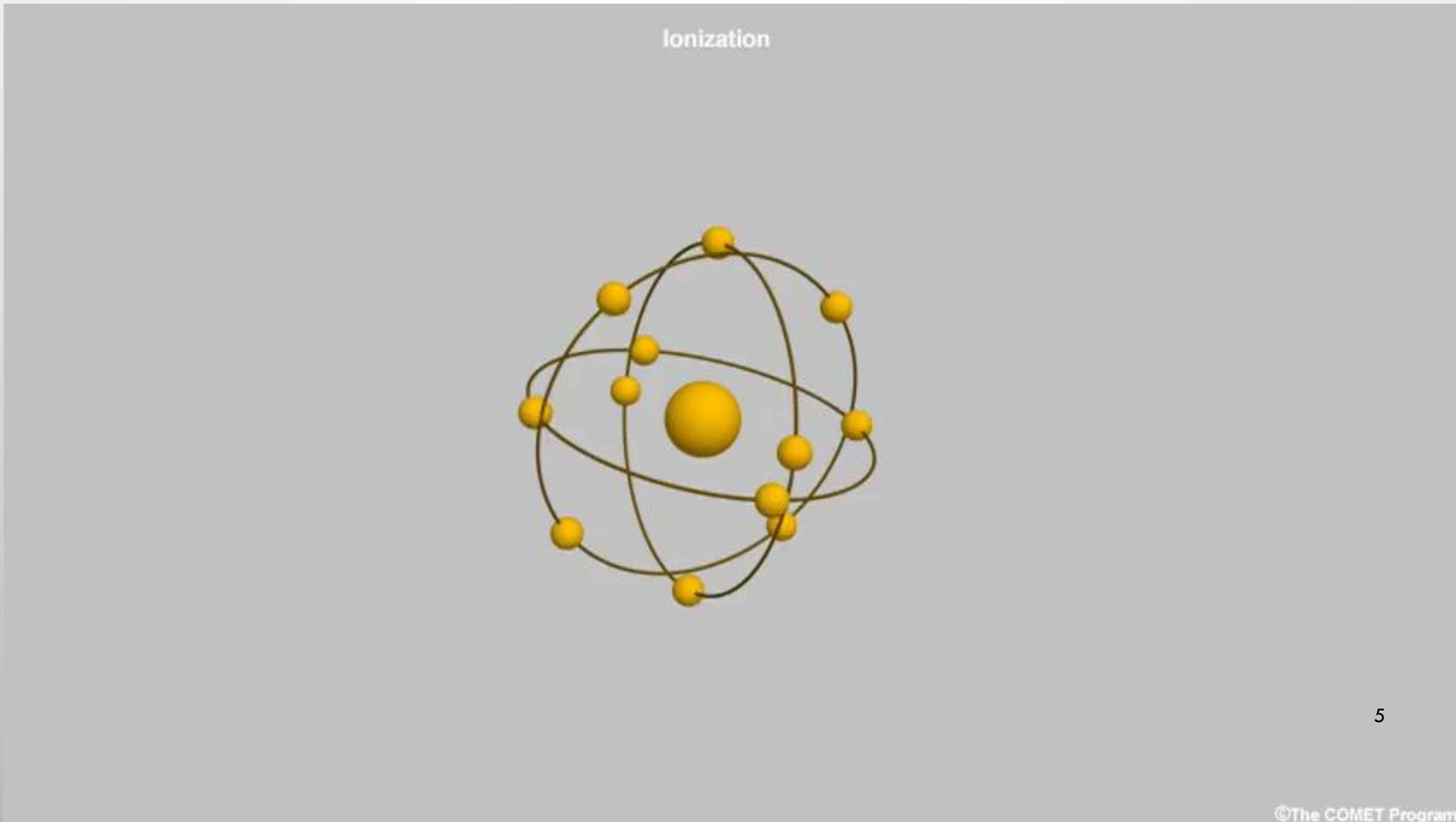
Refraction_density



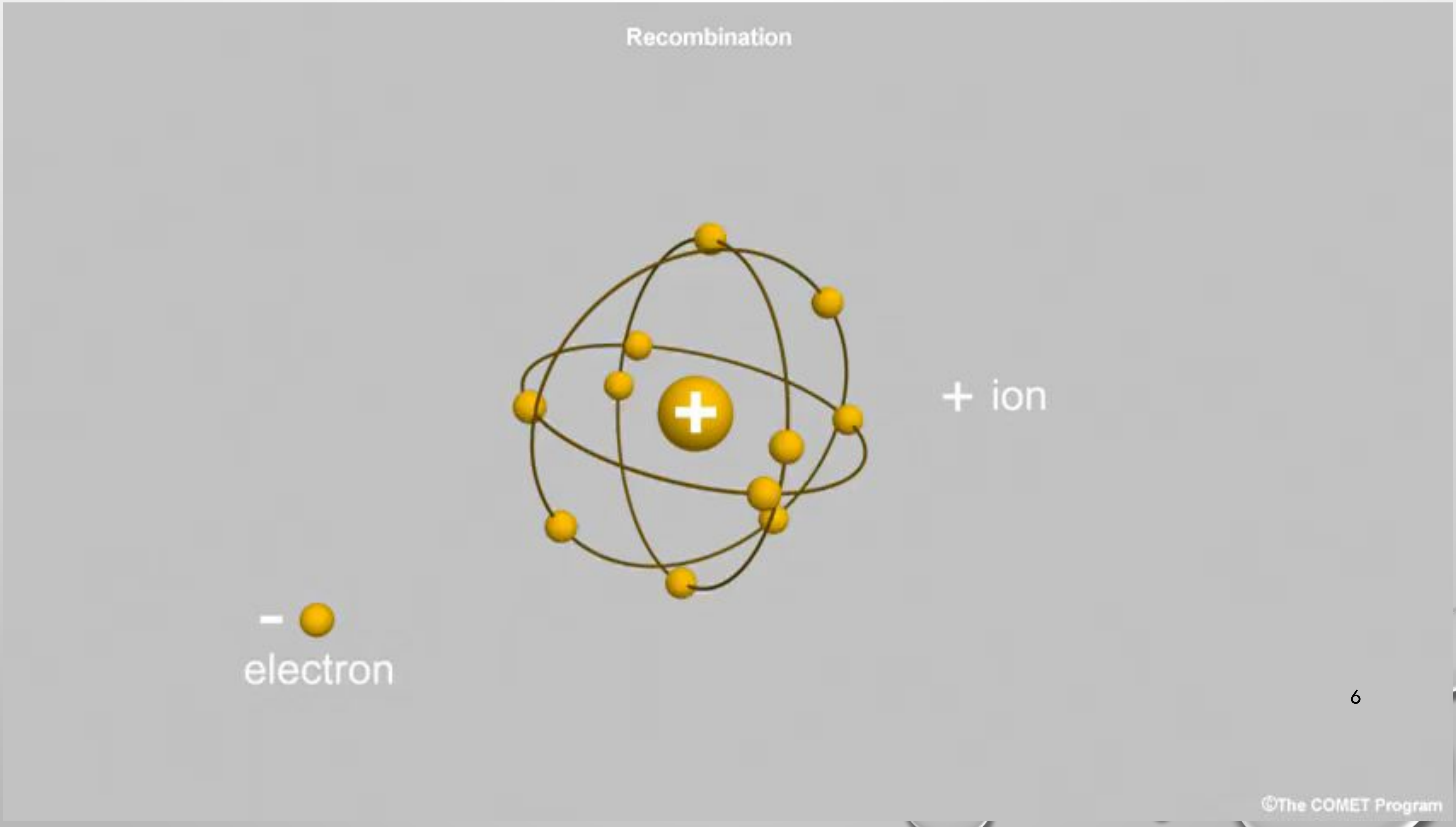
REFRACTION FREQUENCY



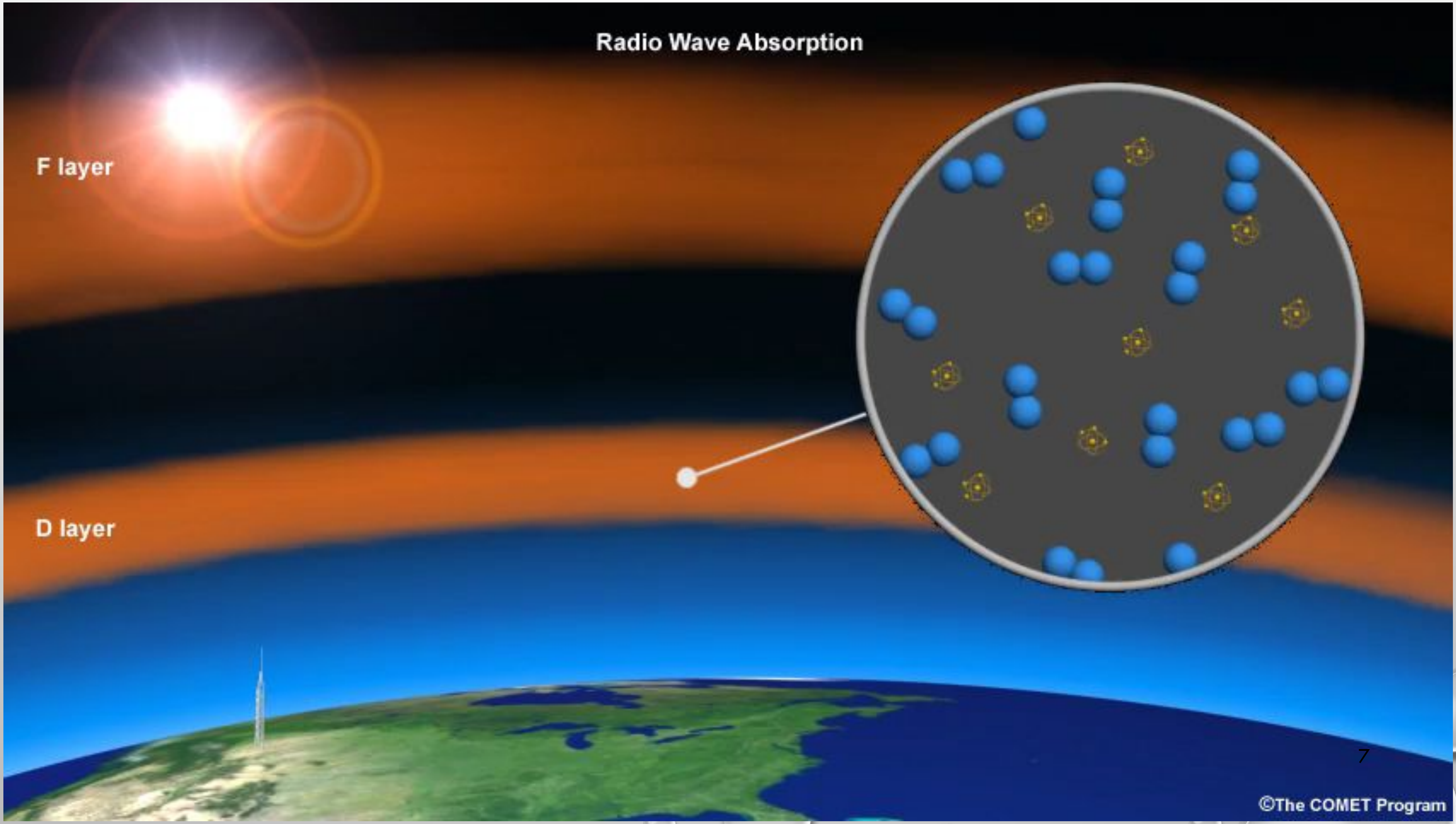
IONISATION



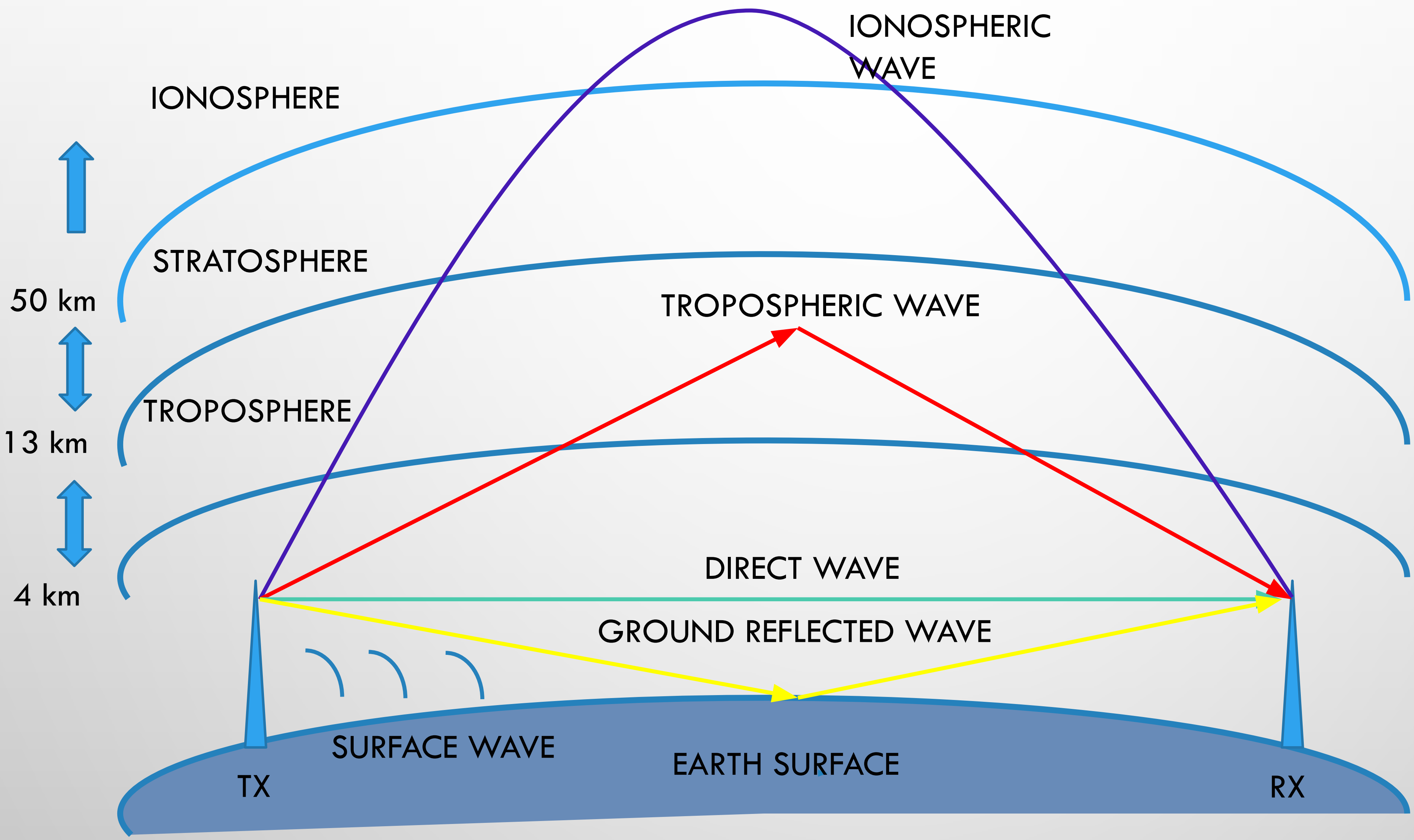
RECOMBINATION



ABSORPTION



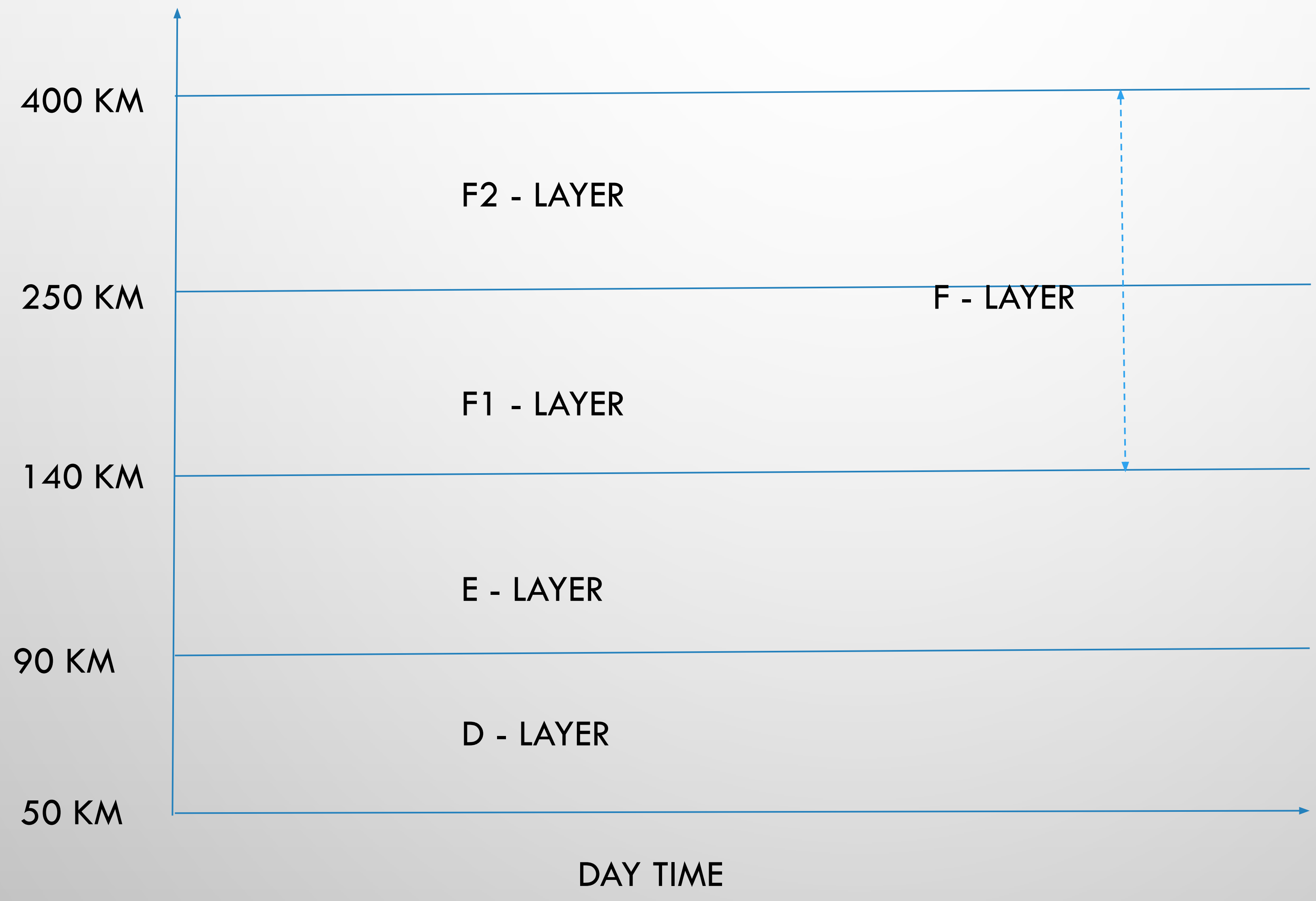
COMMUNICATION LAYER

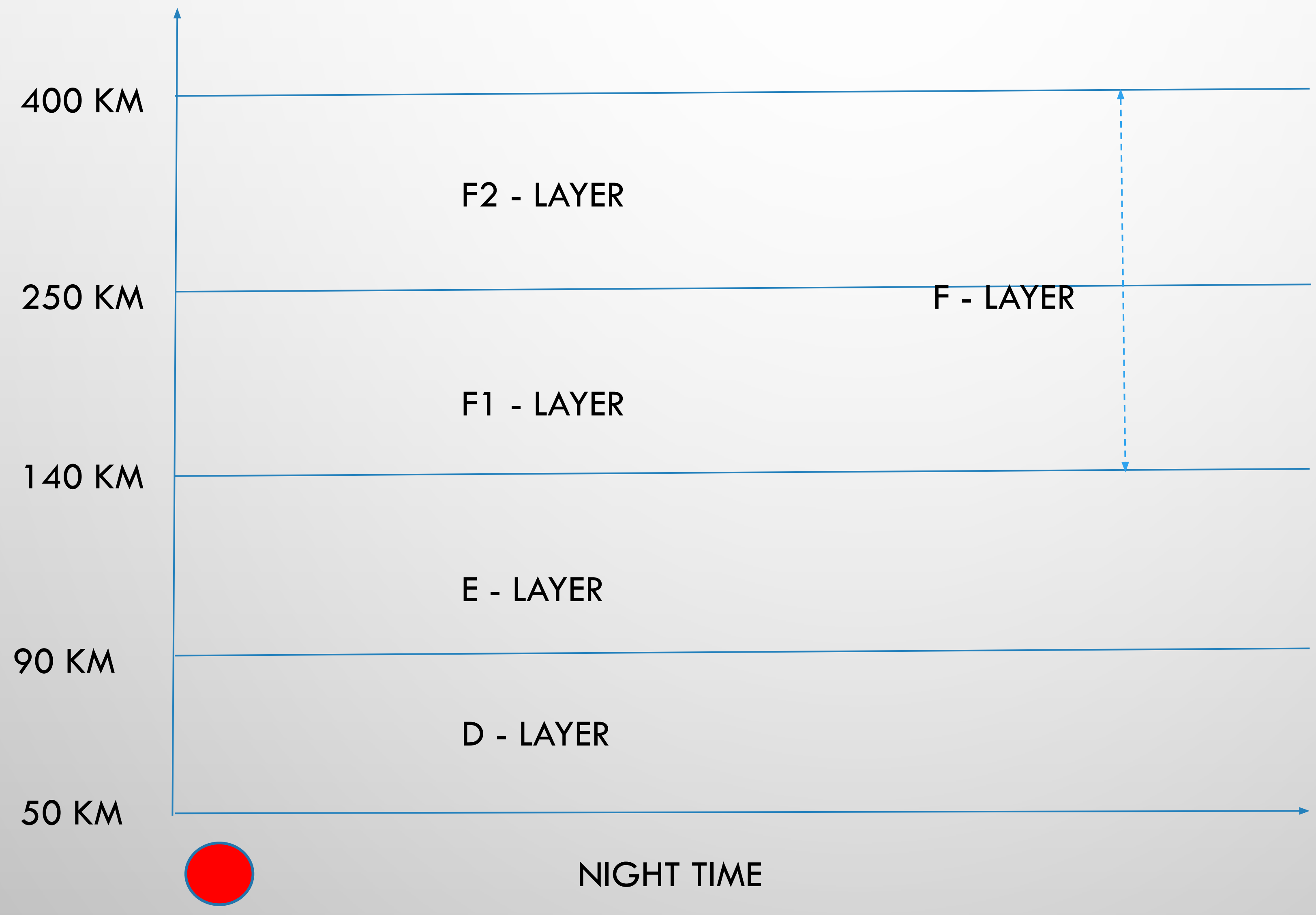


DIRECT WAVE +GROUND REFECTED WAVE = SPACE WAVE

SPACE WAVE + SURFACE WAVE = GROUND WAVE

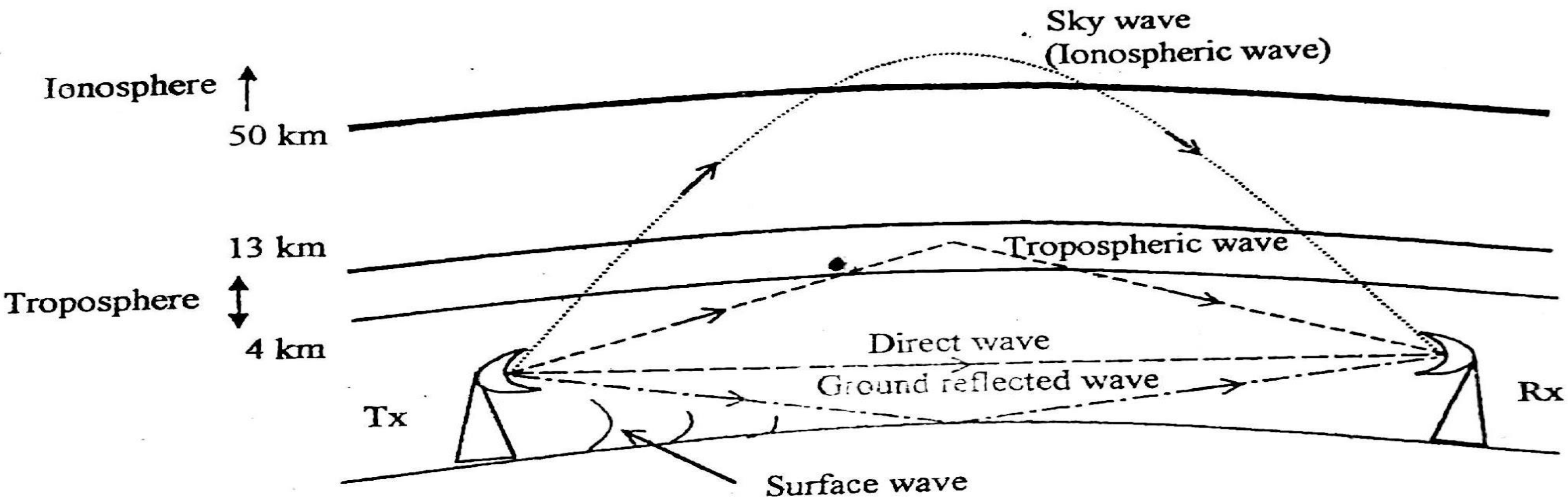
DIFFERENT LAYERS IN IONOSPHERE




400 KM
F2 - LAYER
250 KM
F - LAYER
F1 - LAYER
140 KM
E - LAYER
90 KM
D - LAYER
50 KM
NIGHT TIME

5.1 Radio Waves

The range of frequency between 10^4 Hz and 10^{10}Hz is generally referred to the radio frequency. The types of waves that the radio frequency can take during its propagation are shown in Figure 5.1.



Direct wave + Ground reflected wave = Space wave
Space wave + Surface wave = Ground wave

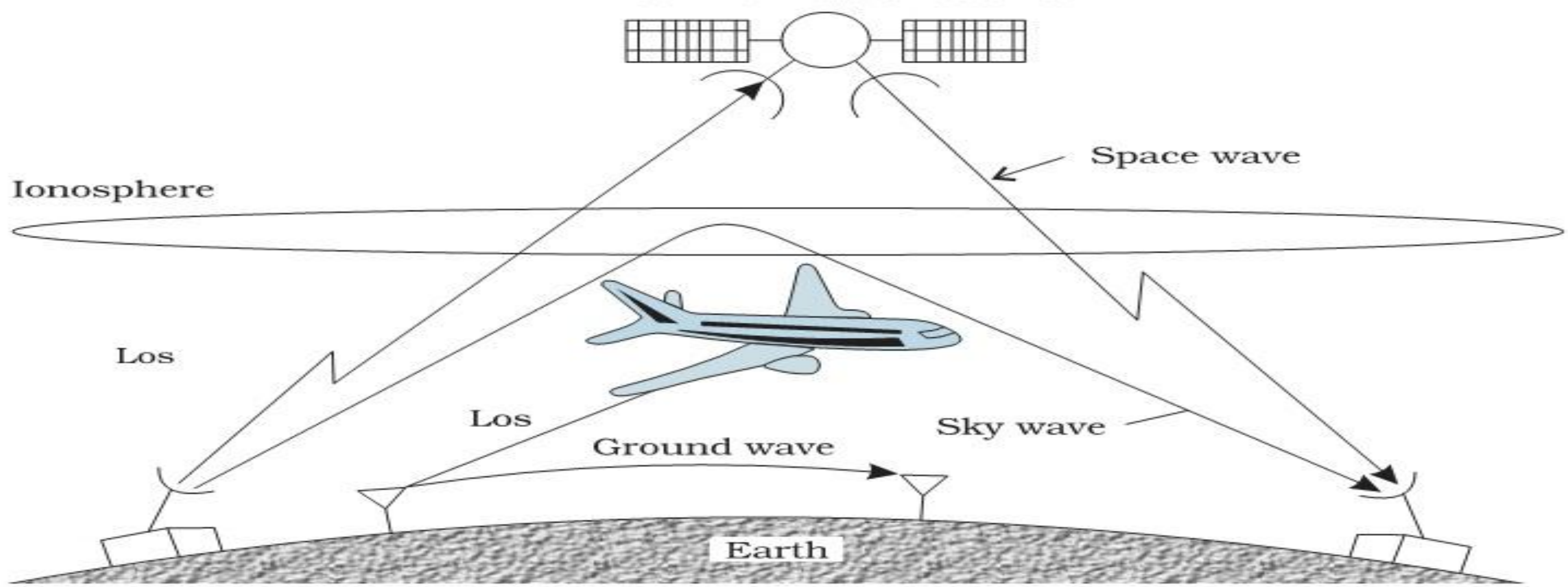
Figure 5.1 Designation of radio waves according to the path they have taken during propagation.

WHAT IS SPACE WAVE PROPAGATION?

- THESE WAVES OCCUR WITHIN THE LOWER 20 KM OF THE ATMOSPHERE, AND ARE COMPRISED OF A DIRECT AND REFLECTED WAVE.
- THE RADIO WAVES HAVING HIGH FREQUENCIES ARE BASICALLY CALLED AS SPACE WAVES. THESE WAVES HAVE THE ABILITY TO PROPAGATE THROUGH ATMOSPHERE, FROM TRANSMITTER ANTENNA TO RECEIVER ANTENNA.
- THESE WAVES CAN TRAVEL DIRECTLY OR CAN TRAVEL AFTER REFLECTING FROM EARTH'S SURFACE TO THE TROPOSPHERE SURFACE OF EARTH. SO, IT IS ALSO CALLED AS TROPOSPHERICAL PROPAGATION.

- BASICALLY THE TECHNIQUE OF SPACE WAVE PROPAGATION IS USED IN BANDS HAVING VERY HIGH FREQUENCIES. E.G. V.H.F. BAND, U.H.F BAND ETC. AT SUCH HIGHER FREQUENCIES THE OTHER WAVE PROPAGATION TECHNIQUES LIKE SKY WAVE PROPAGATION, GROUND WAVE PROPAGATION CAN’T WORK. ONLY SPACE WAVE PROPAGATION IS LEFT WHICH CAN HANDLE FREQUENCY WAVES OF HIGHER FREQUENCIES. THE OTHER NAME OF SPACE WAVE PROPAGATION IS LINE OF SIGHT PROPAGATION.

PRINCIPLE USED IN SPACE WAVE PROPAGATION



Various propagation modes for em waves.

Sky wave propagation.

- ALTHOUGH SPACE WAVES SUFFER LITTLE GROUND ATTENUATION, THEY NEVERTHELESS ARE SUSCEPTIBLE TO FADING. THIS IS BECAUSE SPACE WAVES ACTUALLY FOLLOW TWO PATHS OF DIFFERENT LENGTHS (DIRECT PATH AND GROUND REFLECTED PATH) TO THE RECEIVING SITE AND, THEREFORE, MAY ARRIVE IN OR OUT OF PHASE.
- IF THESE TWO COMPONENT WAVES ARE RECEIVED IN PHASE, THE RESULT IS A REINFORCED OR STRONGER SIGNAL. LIKEWISE, IF THEY ARE RECEIVED OUT OF PHASE, THEY TEND TO CANCEL ONE ANOTHER, WHICH RESULTS IN A WEAK OR FADING SIGNAL.

2.8 FACTORS AFFECTING SPACE WAVE PROPAGATION

The field strength due to the space wave is affected by following factors:

(a) Curvature of the earth
(b) Earth's surface imperfection and roughness
(c) Obstacles like hills, tall buildings, etc.
(d) Height of propagation above earth's surface
(e) Polarisation of the waves
(f) Transition between ground and space wave

2.8.1 Effect of the Curvature of Earth's Surface

The expression for the field strength due to space wave is given by Eq. (2.63a) and can be written as:

$$|E| = \left(\frac{4\pi h_t h_r}{\lambda d^2}\right) E_0$$

This expression is derived assuming that the earth's surface is flat but as we know that the earth's surface is not flat and its curved structure creates *shadow zones* or *diffraction zones*. In shadow zone, there is almost zero or very small signal strength hence a receiving antenna lying in this zone cannot receive signals from the transmitting antenna as shown in Figure 2.14.

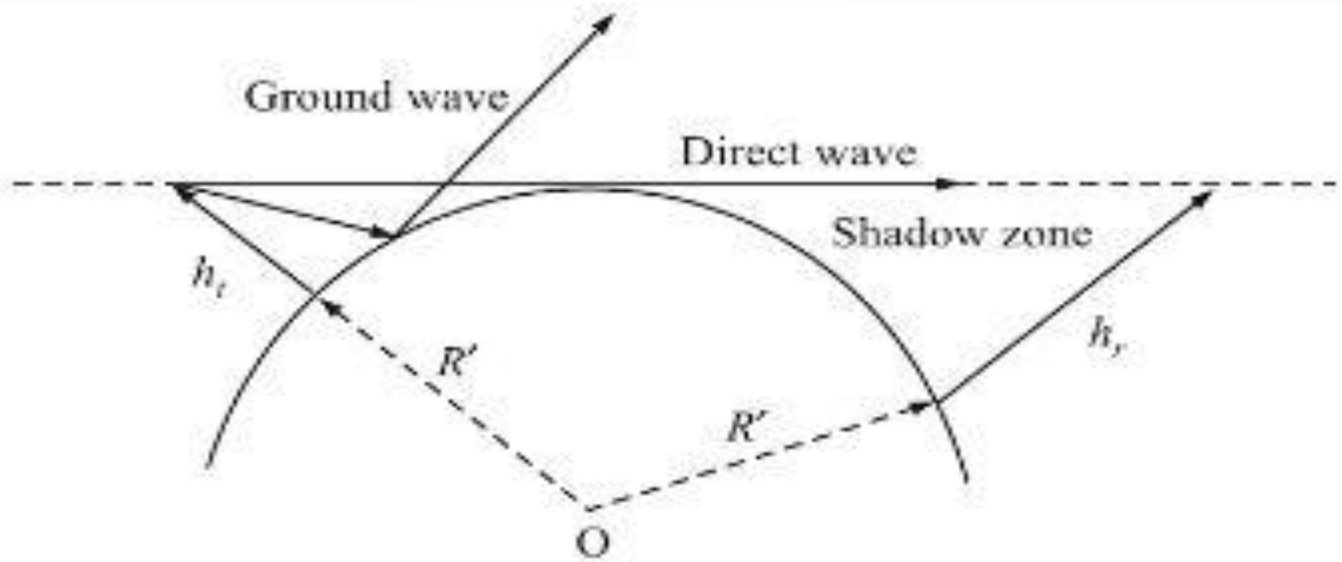


FIGURE 2.14 Shadow zone due to earth's curvature.

This reduces the possible distance of transmission. The field strength due to curved earth's surface is given as:

$$|E| = \left(\frac{4\pi\, h_t' h_r'}{\lambda d^2}\right) E_0 \qquad \ldots(2.101)$$

where,

h_t' = Effective height of transmitting antenna

h_r' = Effective height of receiving antenna

The effective height of an antenna is the height taken from the assumed flat earth's surface as shown in Figure 2.15.

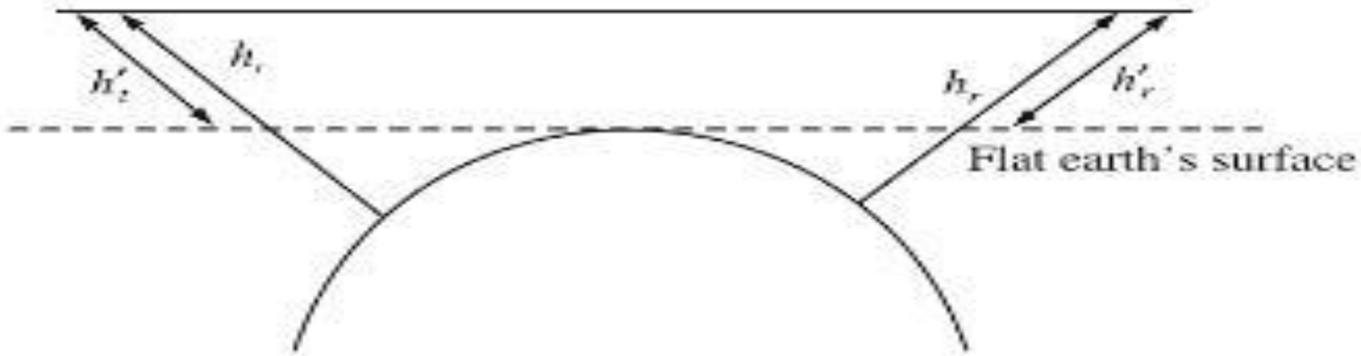


FIGURE 2.15 Effective height of antennas.

2.8.2 Effect of Earth's Imperfections and Roughness

Earth's surface is electrically rough which means the earth's reflection coefficient is not unity and in general it is always less than one. This means that whenever radio wave incidents on earth, some portion of this wave is absorbed and some part is reflected. Moreover for a perfectly reflecting surface, the phase of reflected wave is 180° more than the phase of the incident wave but in case of earth's surface the phase difference between incident and reflected wave is different from 180°. Due to the earth's surface imperfections, the amplitude of the reflected wave is always lesser than the incident wave. The field strength at the receiver is always less than what would be expected because of the imperfections of earth's surface.

2.8.3 Effect of Hills, Buildings and Other Obstacles

Hills, buildings and other obstacles in the path of space wave propagation create "shadow or diffraction zones". As a result, the possible distance of space wave propagation reduces significantly as shown in Figure 2.16.

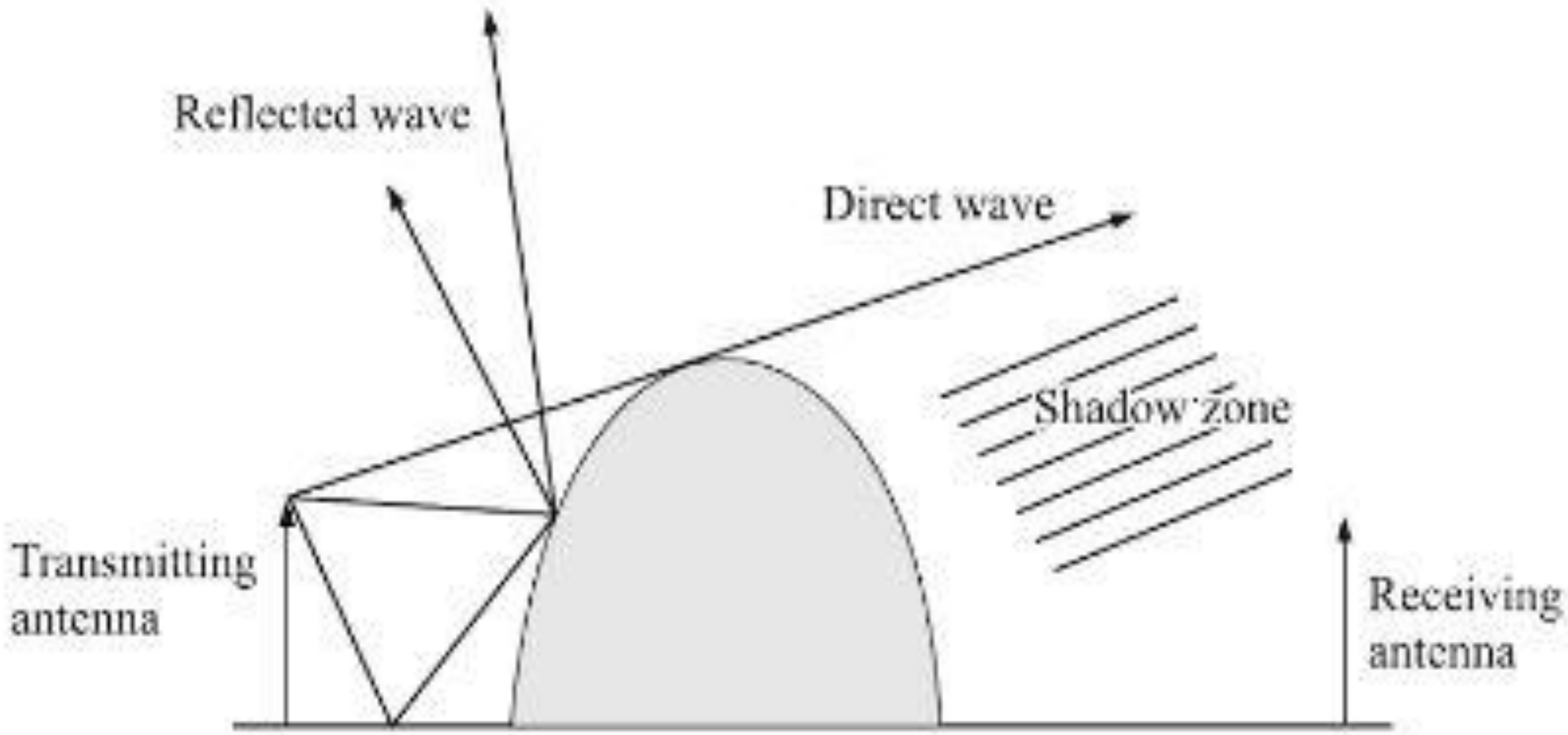
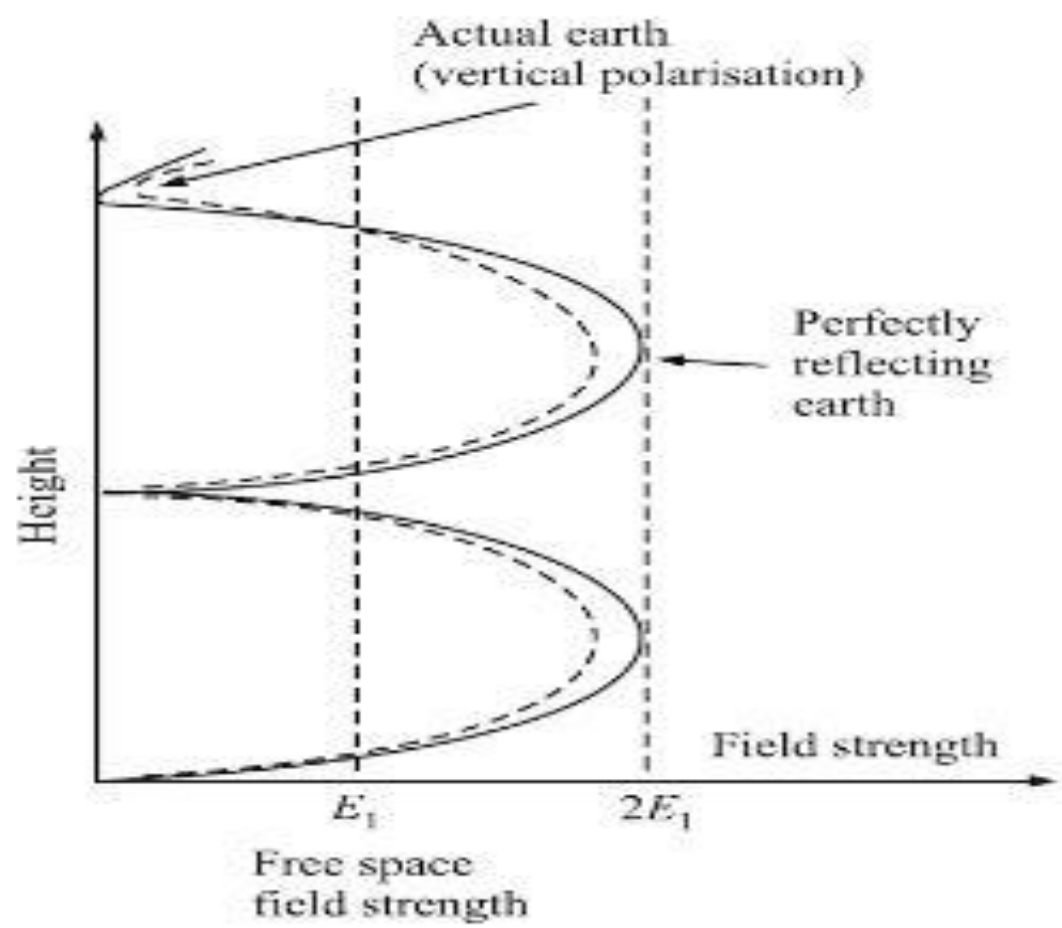


FIGURE 2.16 Shadow zone due to obstacles.

2.8.4 Field Strength Variation with Height

It is found that the field strength varies with height as shown in Figure 2.17. The field strength has minima and maxima points with the variation in height. If the earth's surface is assumed as perfectly reflecting surface, the maxima points are equal to the twice of the field strength in free space and minima points are zero. In case of practical earth's surface, the maxima points are slightly lesser than twice the field strength in free space and minima points are above zero. To avoid such nulls, vertical polarised waves are used instead of horizontal waves as horizontal waves offer deep nulls.

The position of such maxima and minima depends upon the height of transmitting antenna, frequency and the distance involved.



2.8.5 Effect of Polarisation of Space Wave

It is found that for any angle of incidence other than $\theta = 0°$ or $90°$, the amplitude of vertically polarised wave is always lesser than the horizontal polarised wave. Due to this, the amplitude of ground reflected wave is always reduced.

The antenna height below which ground wave takes action is always smaller for horizontal wave instead of vertically polarised wave. This is important for broadcast at lower frequencies.

Most of the electromagnetic interferences created by ignition systems, domestic and consumer electronics and communication systems are vertically polarised. Hence, horizontal polarisation is useful to avoid such disturbances in TV and FM broadcasting.

2.8.6 Effect of Transition between Ground Wave and Space Wave

When the transmitting antenna is closer to earth, ground wave dominates and the total field strength is independent of antenna height.

The antenna height affects the field strength if it is more direct and ground reflected wave dominates over ground wave. The antenna height effects also depend upon the frequency, polarisation and the nature of surface (conductivity and permittivity).

For vertically polarised wave, the ground wave does not dominate if the antenna heights are of the order of one to two wavelengths. In such cases, space wave dominates over ground waves. The antenna height is far greater if the wave propagation takes place over ocean as compared to the earth's region with low conductivity.

For horizontally polarised wave, transition between the ground and space wave takes place if antenna height is lesser than one-tenth of the wavelength. If the wave propagates over sea or good earth, the height will be further less.

2.9 ATMOSPHERIC EFFECTS IN SPACE WAVE PROPAGATION

The atmosphere through which space wave propagation takes place, affects the propagation in several ways. The atmosphere consists of gas molecules or water vapour molecules which in turn changes the relative dielectric constant of atmosphere. The dielectric constant becomes slightly greater than unity. The density of water vapour molecules is not uniform and varies with height. This also causes variation in the refractive index of the air with height and in turn a variety of phenomena takes place like refraction, reflection, scattering, duct propagation and fading.

2.9.1 Refractive Index of Air

The refractive index of any medium defines the nature of wave propagation through that medium. The refractive index n of air is defined as the square root of the dielectric constant. In practical, the refractive index of air is defined in terms of modified refractive index (M). This is so done to see the variation in refractive index with respect to the height above the earth's surface. The modified refractive index is given as:

$$N = n + h/R \qquad \text{...(2.102a)}$$

To observe the change in refractive index with respect to height above the earth's surface, another important parameter is defined which is known as excess *modified index of refractive modulus* (M). It is given as:

$$M = \left(n - 1 + \frac{h}{R}\right) \times 10^6 \qquad \text{...(2.102b)}$$

where,

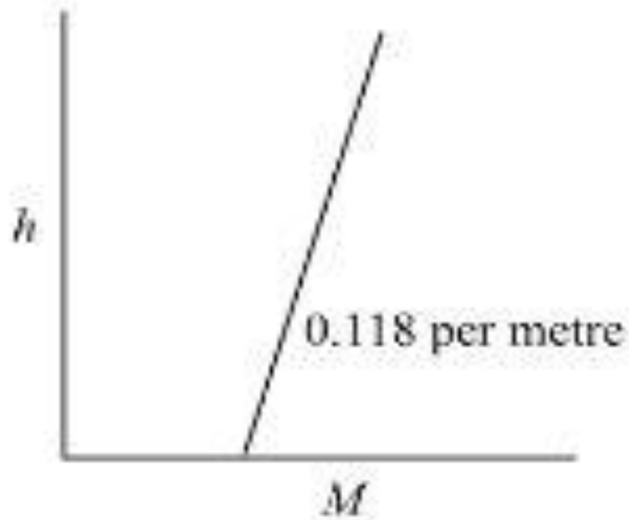
n = Refractive index
h = Height above the earth's surface
R = Earth's radius = 6370 km

The variation of M with height, i.e., dM/dh is very important in radio propagation as it defines the nature of atmosphere.

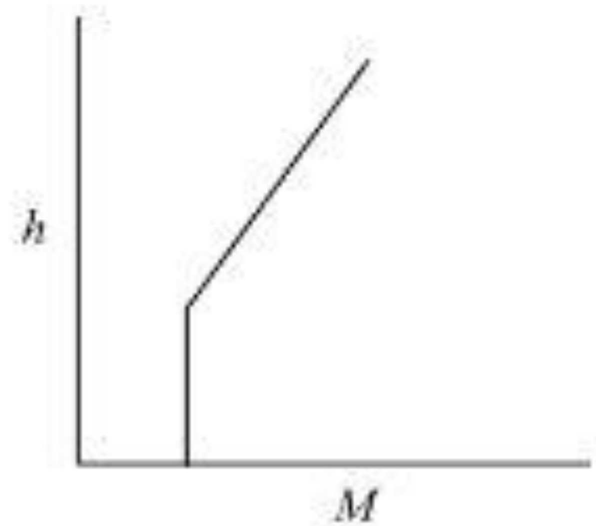
For *standard atmosphere*, dM/dh corresponds to 0.118 M-units/metre (or 0.036 M-units/foot) as shown in Figure 2.18(a).

For high altitudes, dM/dh increases at the rate of 0.158 M-units/metre (or 0.048 M-units/foot) while near earth's surface dM/dh increases linearly at a constant rate lesser than 0.158 M-units per metre as shown in Figure 2.18(b).

The variation of M with respect to different heights is shown in Figure 2.18. With increase in height, the air masses that differ in temperature and moisture content overlay each other. This gives rise to the temperature inversion regions (where the slope dM/dh is negative) as shown in Figures 2.18(c) and (d). The temperature inversion region is known as *duct* which plays an important role in the UHF and microwave propagation beyond radio horizon.



(a)



(b)

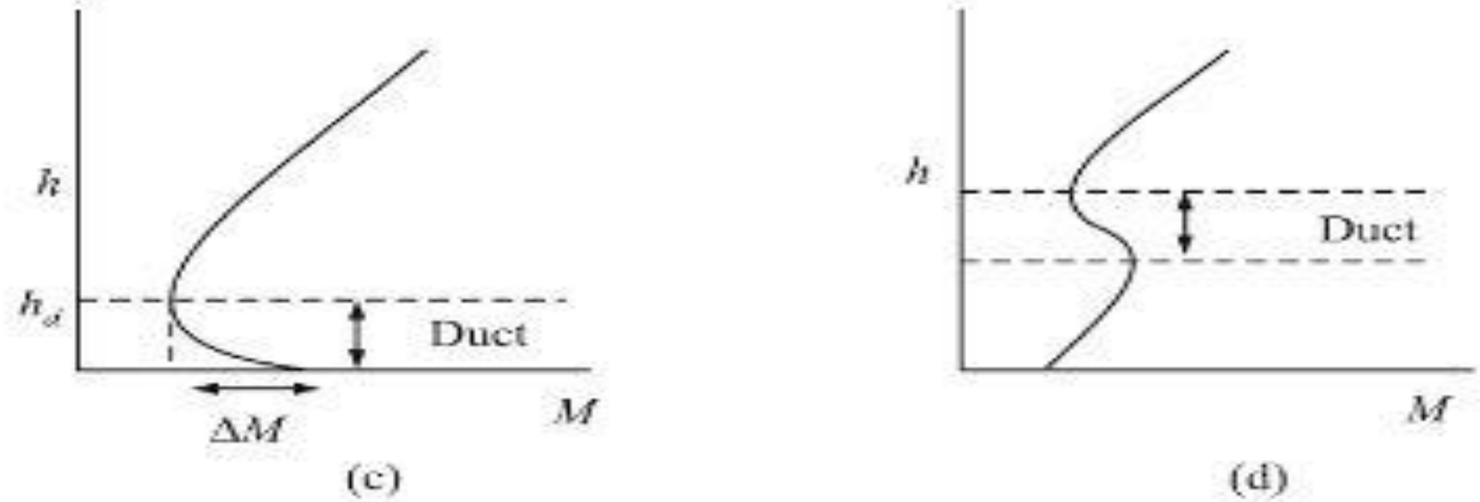


FIGURE 2.18 Variation in M with respect to height.

The *effective earth's radius factor* (k) can also obtained by using the following relation:

$$k = \frac{R'}{R} = \frac{0.048}{\left(\frac{dM}{dh}\right)} \qquad \ldots(2.103)$$

The standard dM/dh is 0.036 M-units/foot and it increases at 0.048 M-units/foot [which is already written in Eq. (2.103)] hence by substituting the value of standard dM/dh in Eq. (2.103), we get the effective earth's radius factor (k) as:

$$k = \frac{0.048}{0.036} = \frac{4}{3}$$

The factor k comes out same as derived earlier in Section 2.7.4.

2.9.2 Duct Propagation

It is observed that with the increase in height, the temperature and the moisture content of the air changes in the atmosphere. There exists a region near the earth surface where the moisture content of the air is high but decreases rapidly with the increase in height. For such region, the slope of the curve of excess modified index of refractive modulus (M) vs. height (h) from earth's surface curvature, i.e., dM/dh is negative. This region traps the energy originated from the earth's surface and forces the energy to travel along the earth's curvature in multi hops because of scattering, refraction and reflection as shown in Figure 2.19. This phenomenon is termed as *super refraction* or *duct propagation*. The region in which duct propagation takes place is defined as *duct region*.

Duct region lies near the earth's surface mostly within the 50 m of the troposphere. Due to the duct propagation, the wave can propagate beyond the LOS distance along the curvature without much attenuation.

The duct can form either near to the earth's surface as shown in Figure 2.18(c) or it can form above the earth's surface up to certain height as shown in Figure 2.18(d). These types of duct formations are defined as *simple surface duct* and *elevated duct* respectively.

Under certain meteorological conditions, elevated duct takes place as shown in Figure 2.19. If the transmitting antenna is placed in this elevated duct region, the transmitted wave can travel beyond the radio horizon and if the receiving antenna is placed in the elevated duct, good signal strength can be received with low attenuation.

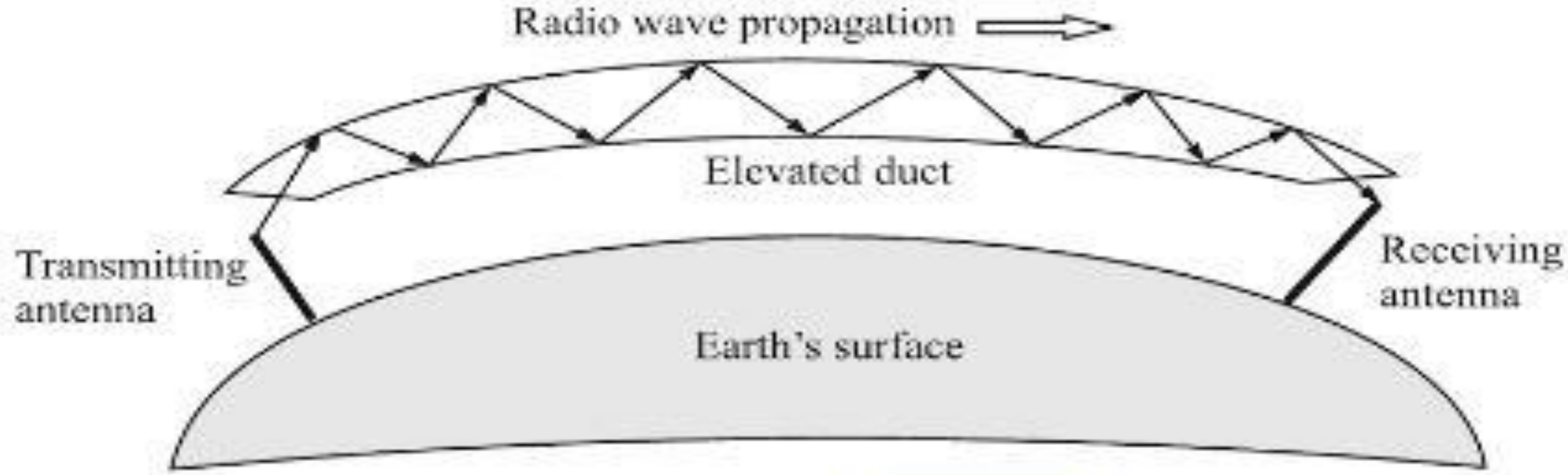


FIGURE 2.19 Duct propagation.

The duct acts as a waveguide with some cut-off frequency. The wave having wavelength more than the certain value [as shown in Eq. (2.104)] leaks out from the duct as shown in Figure 2.20. The maximum wavelength for which the duct propagation can take place is defined as:

$$\lambda_{max} = 2.5\, h_d \sqrt{\Delta M \times 10^{-6}} \qquad \ldots(2.104)$$

where,

ΔM = Total decrease in M across the duct height

h_d = Duct height

λ_{max} = Maximum wavelength

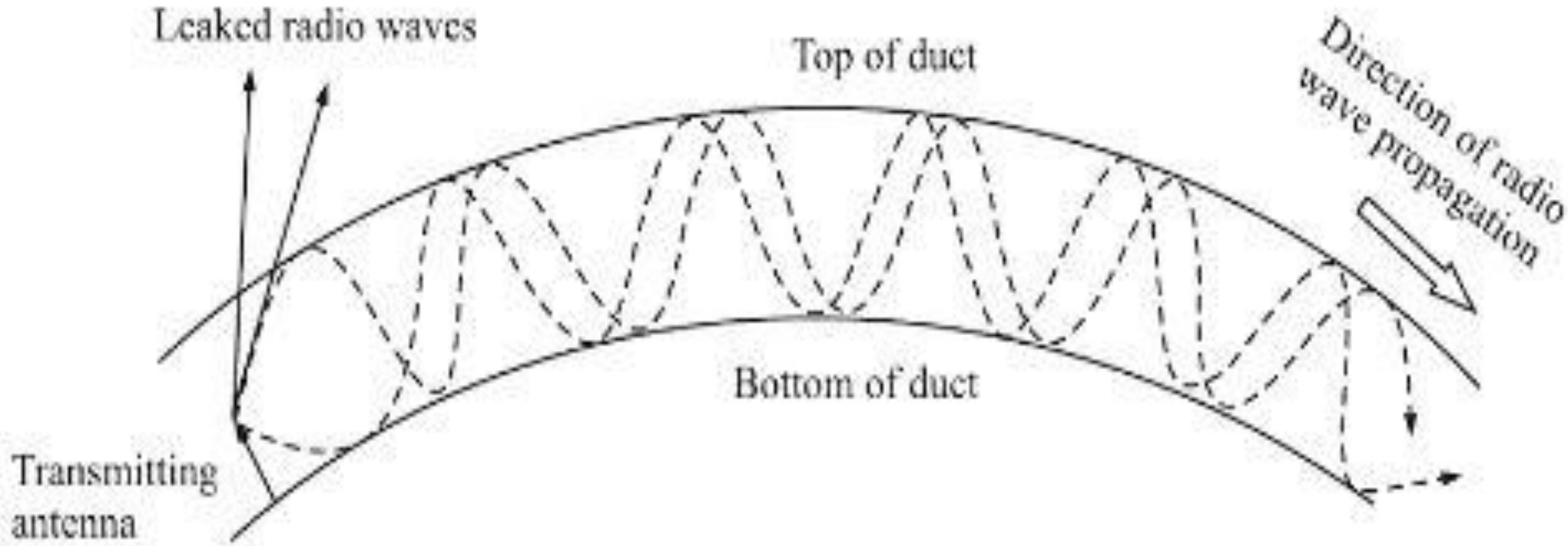


FIGURE 2.20 Leaked radio waves from duct.

The duct propagation exists if the transmitting antenna height is smaller than duct height. The duct propagation is limited up to UHF and microwaves. The duct is mostly found over the ocean region and is less frequent and temporary over land areas.

PROBLEM 18: Find the maximum wavelength at which ground based duct supports propagation if the duct height is 20 m and total decrease in modified refractive index (M) is 30.

Solution: Given:

$$\Delta M = 30;\ h_d = 20\ \text{m}$$

The maximum wavelength at which duct propagation is possible is given as:

$$\lambda_{max} = 2.5\, h_d \sqrt{\Delta M \times 10^{-6}}$$

$$\lambda_{max} = 2.5 \times 20 \times \sqrt{30 \times 10^{-6}}$$

$$\lambda_{max} = 50 \times 5.48 \times 10^{-3}$$

$$\lambda_{max} = 0.274\ \text{m}$$

Hence, the maximum wavelength that can propagate through ground based duct is 0.274 m.

2.9.3 Tropospheric Scattering

Tropospheric scattering propagation is extremely important at VHF, UHF and microwave frequencies. This is also known as *forward scattering propagation*. Tropospheric scattering is a phenomenon in which the transmitted radio wave reaches beyond the radio horizon. This type of propagation takes place due to the scattering and reflection of transmitted radio waves from a specific region of troposphere which lies in the receiving range of receiving antenna. Hence, the field strength at the receiving antenna which lies in the shadow region is found greater than what would be expected. The angle at which the receiving antenna must be kept to intercept the scattered energy is known as *scatter angle* and the specific region which is responsible for troposphere scattering is defined as *scatter volume*.

There are three possible reasons for higher signal strength in shadow regions due to Tropospheric scattering. These are:

(a) Due to the roughness of earth, the diffracted fields have more strength as it would be expected in case of smooth earth.

(b) Due to eddies or blobs in the atmosphere, the irregularities happens in the refractive index of tropospheric regions and this causes the wave energy to be scattered in the shadow zone above the intersection of the horizon lines as shown in Figure 2.21.

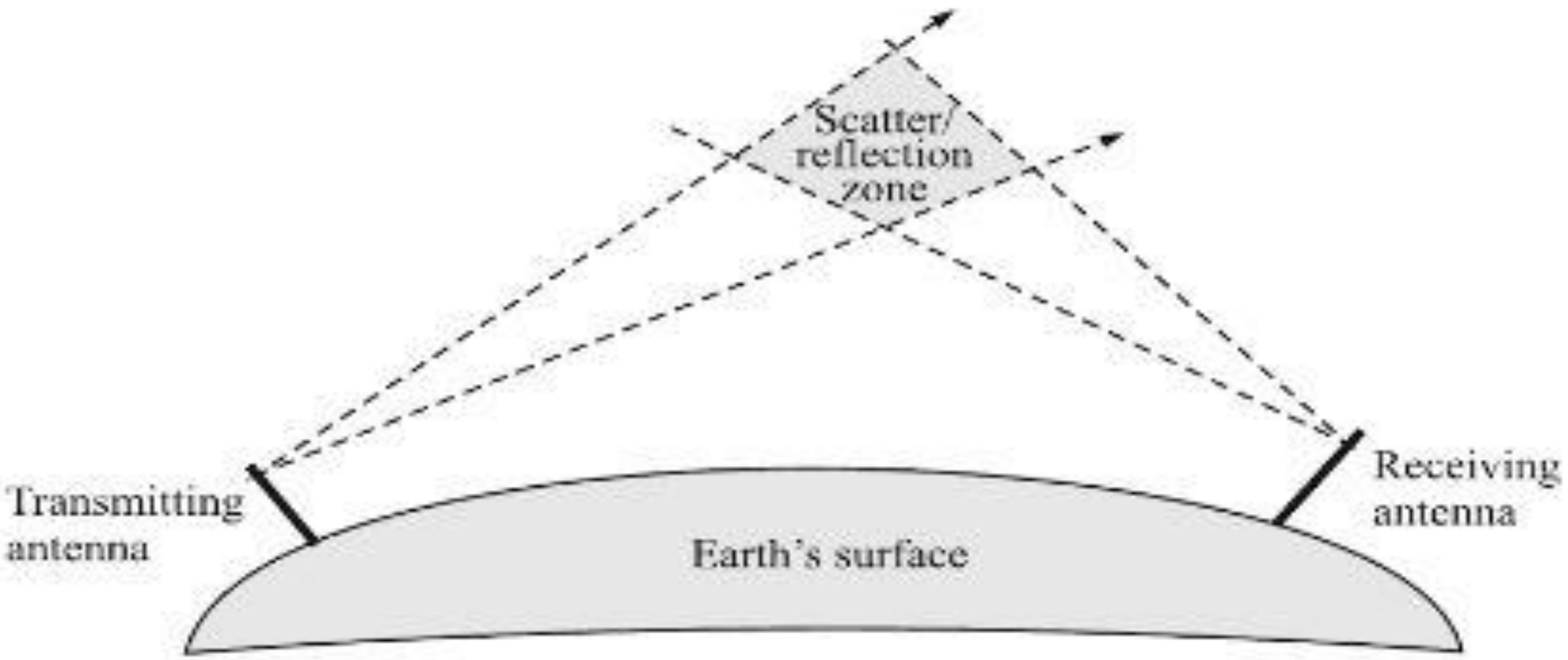


FIGURE 2.21 Tropospheric scattering.

(c) Continuous variation in refractive index under standard atmospheric condition produces small reflections that scatter energy into the shadow zone as done by eddies.

Ionospheric Wave Propagation

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.

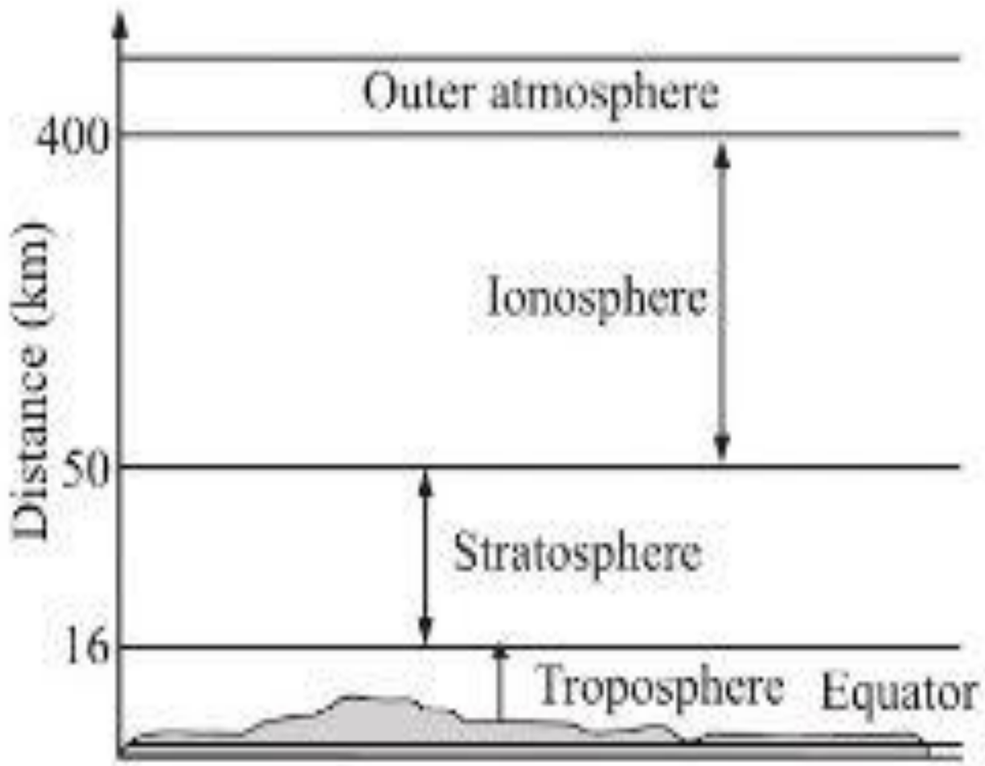


FIGURE 3.1 Earth's atmosphere.

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).

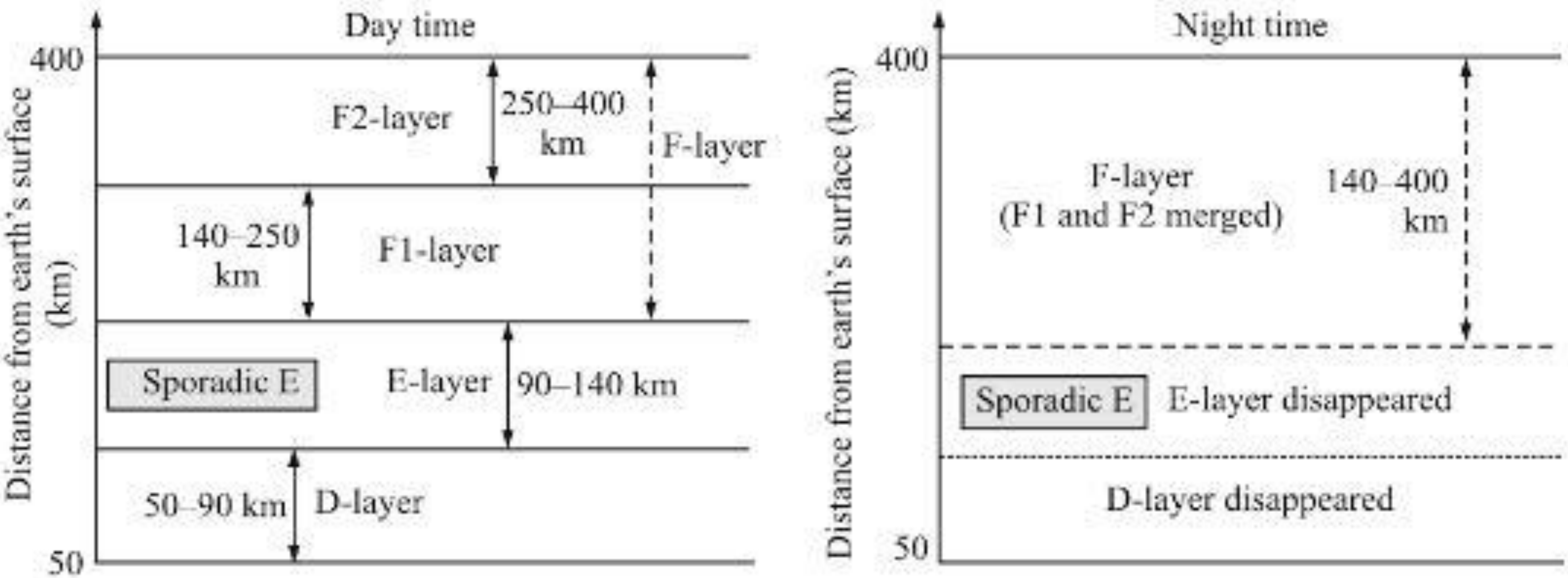


FIGURE 3.2 (a) Structure of ionosphere during day time (b) Structure of ionosphere during night time.

(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.

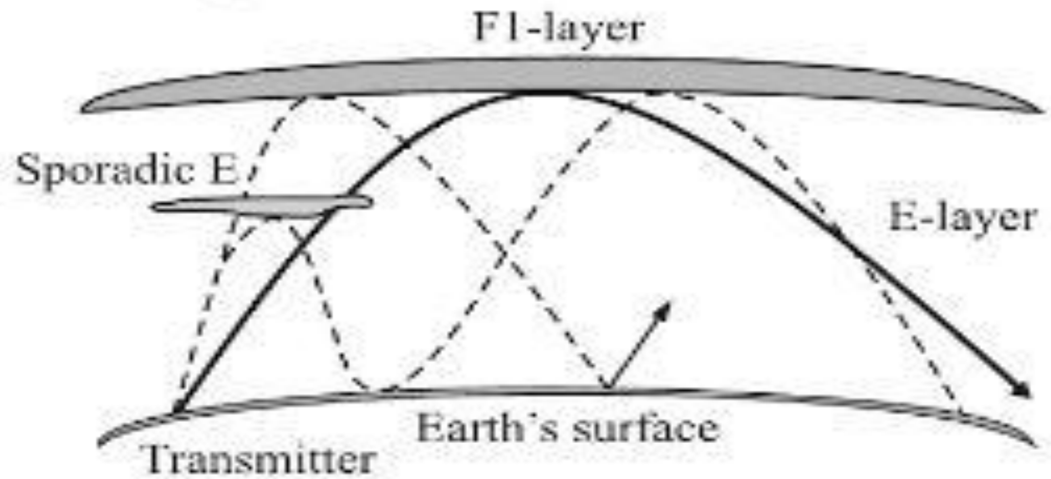


FIGURE 3.3 Fading due to sporadic E-layer.

(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	$\sim 10^6$	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.

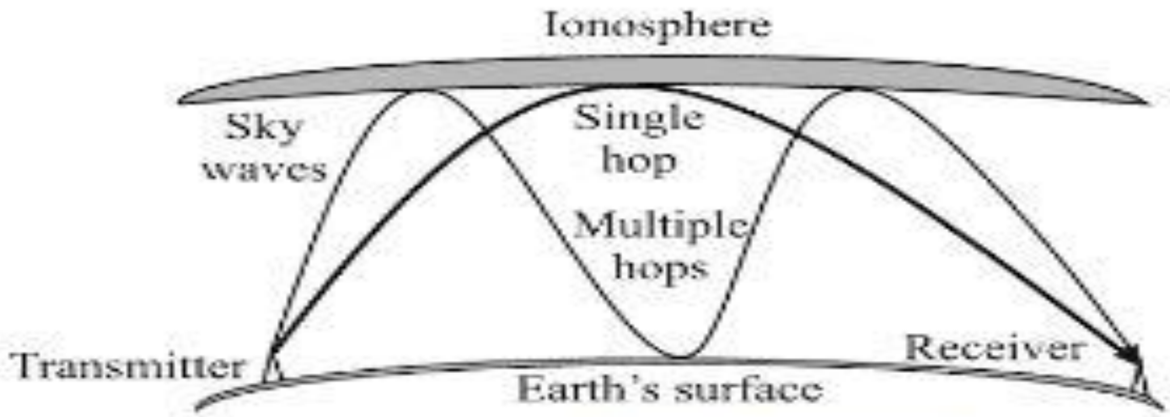


FIGURE 3.4 Sky wave propagation.

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.

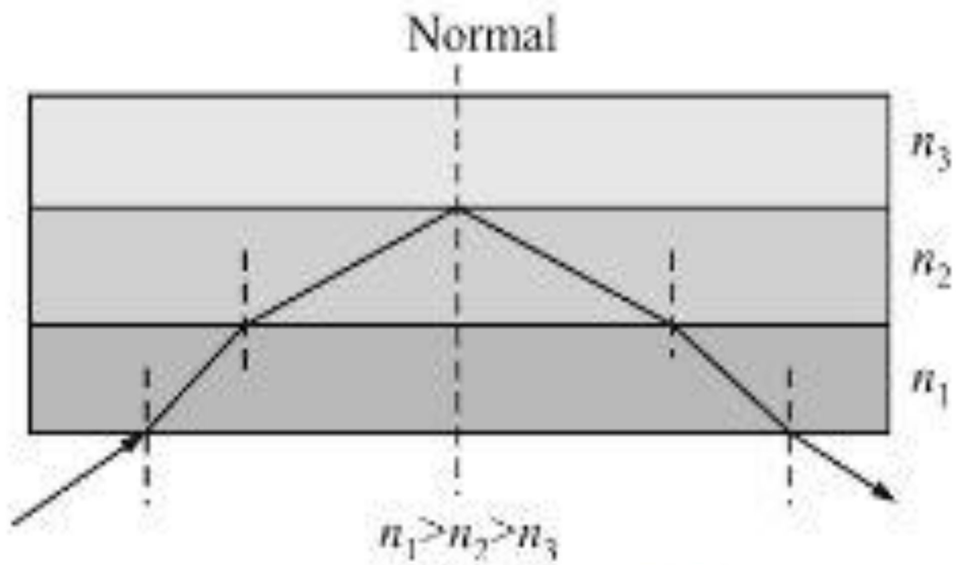


FIGURE 3.5 Refraction of radio wave by ionosphere.

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

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

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

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

The acceleration of the electron can be written as:

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

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

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

or

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

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

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

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:

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

The resultant current density in the ionosphere is given as:

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

or

$$J = \omega \varepsilon \, E_0 \cos \omega t \qquad ...(3.9)$$

where,

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

The relative permittivity of the ionosphere can be written as:

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

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:

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

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:

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

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:

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

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:

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

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:

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

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:

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

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

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

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

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

or

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

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

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:

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

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

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

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

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

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

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

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

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:

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

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.

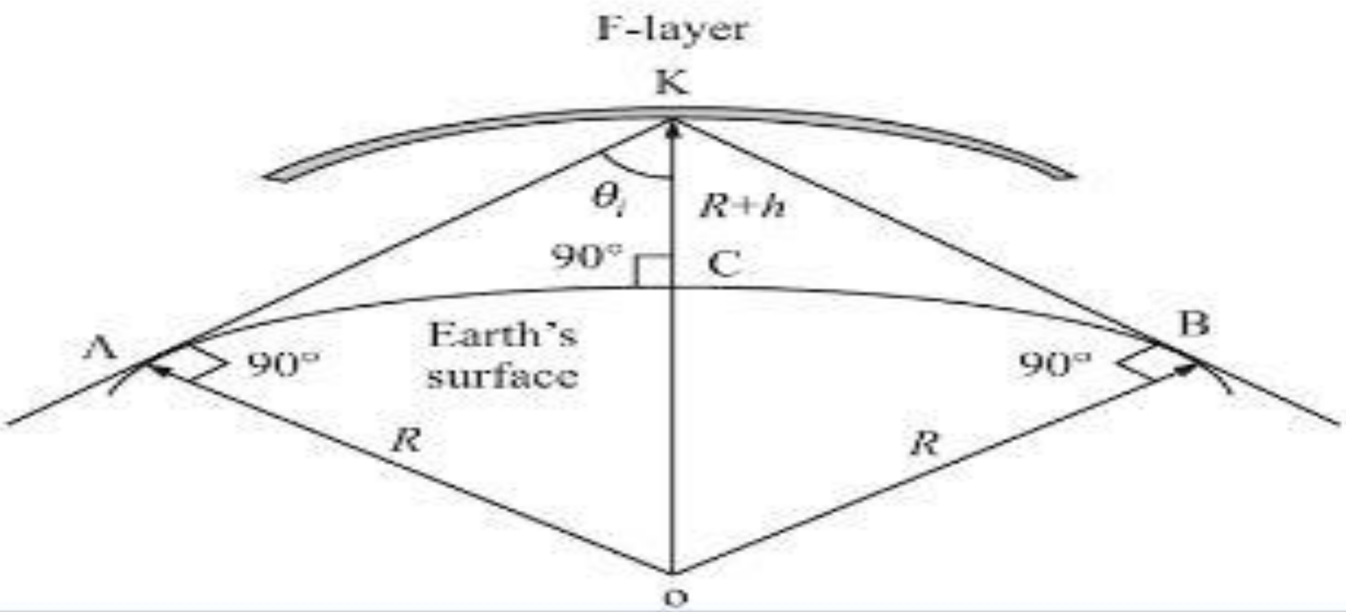
- MUF ranges from 8 MHz to 30 MHz. It may go up to 50 MHz during peak solar activity.
- As shown in Figure 3.6, if the radio wave is transmitted from the transmitter (at point A) to the receiver (at point B) at θ_i angle of incidence, then the maximum angle of incidence for curved earth's surface is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

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



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:

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

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

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

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

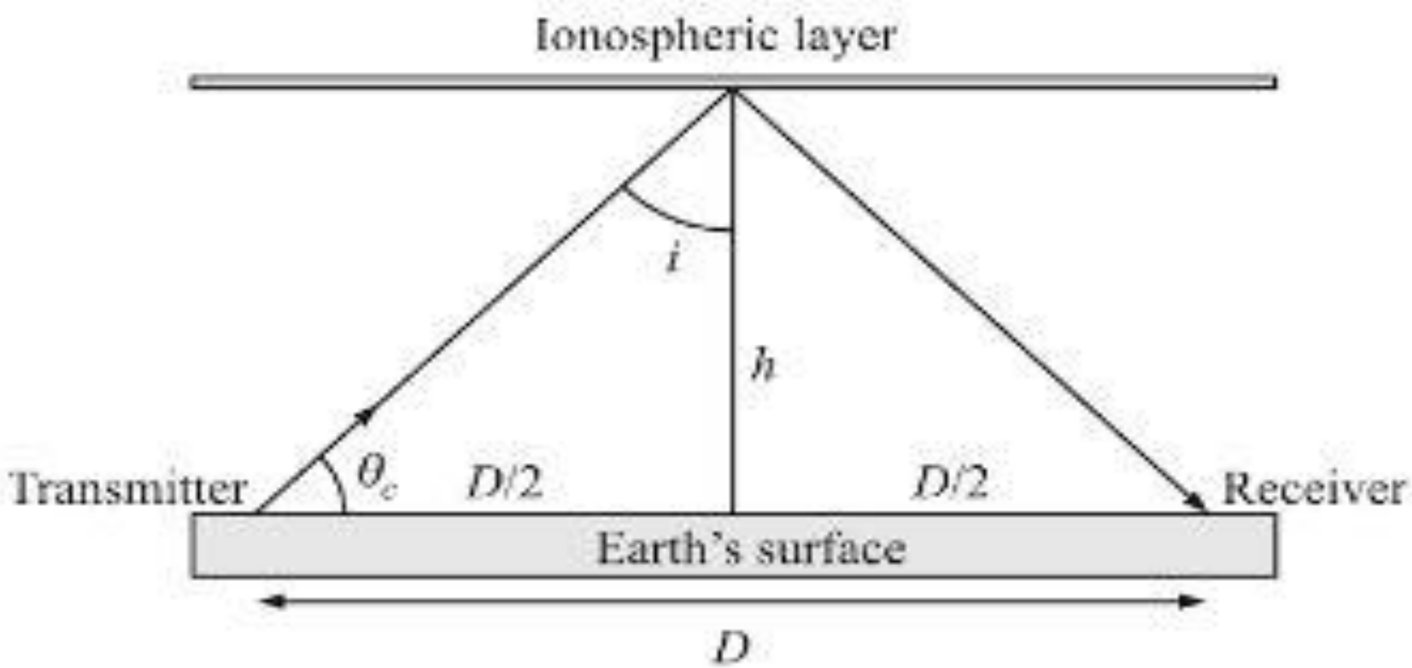


FIGURE 3.7(a) Depiction of flat earth's surface.

PROBLEM 9: For a high frequency radio communication link, the separation between two stations is 2500 km on the earth's surface. If the height of the ionosphere is 200 km and critical frequency is 5 MHz, calculate the maximum usable frequency for this link.

Solution: Given:

$D = 2500$ km; $h = 200$ km; $f_c = 5$ MHz

The maximum usable frequency (MUF) is given by Eq. (3.36) as:

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

or $$f_{\mathrm{MUF}} = 5\sqrt{1+\frac{(2500)^2}{4\times(200)^2}}\ \mathrm{MHz}$$

or $$f_{\mathrm{MUF}} = 31.64\ \mathrm{MHz}$$

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.

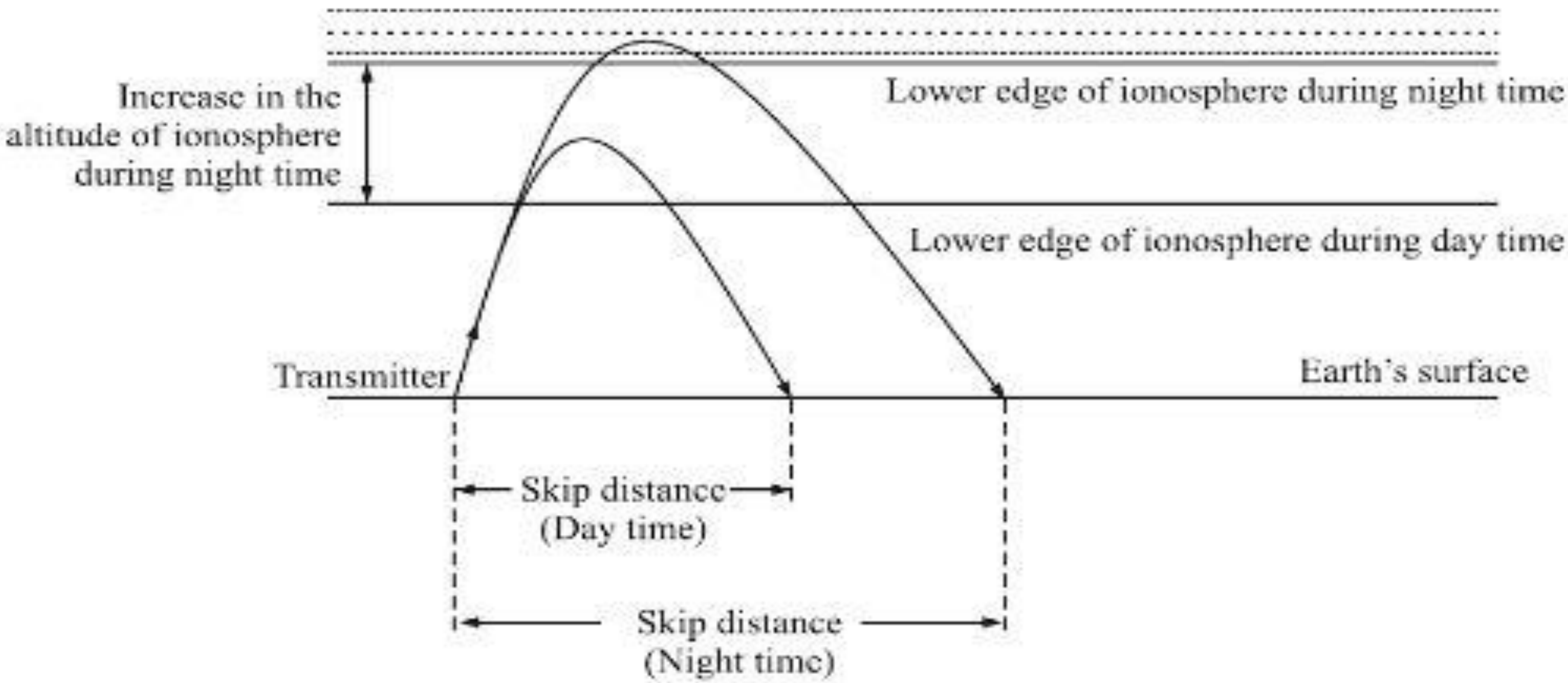


FIGURE 3.8 Increase in skip distance with increase in ionosphere altitude.

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.

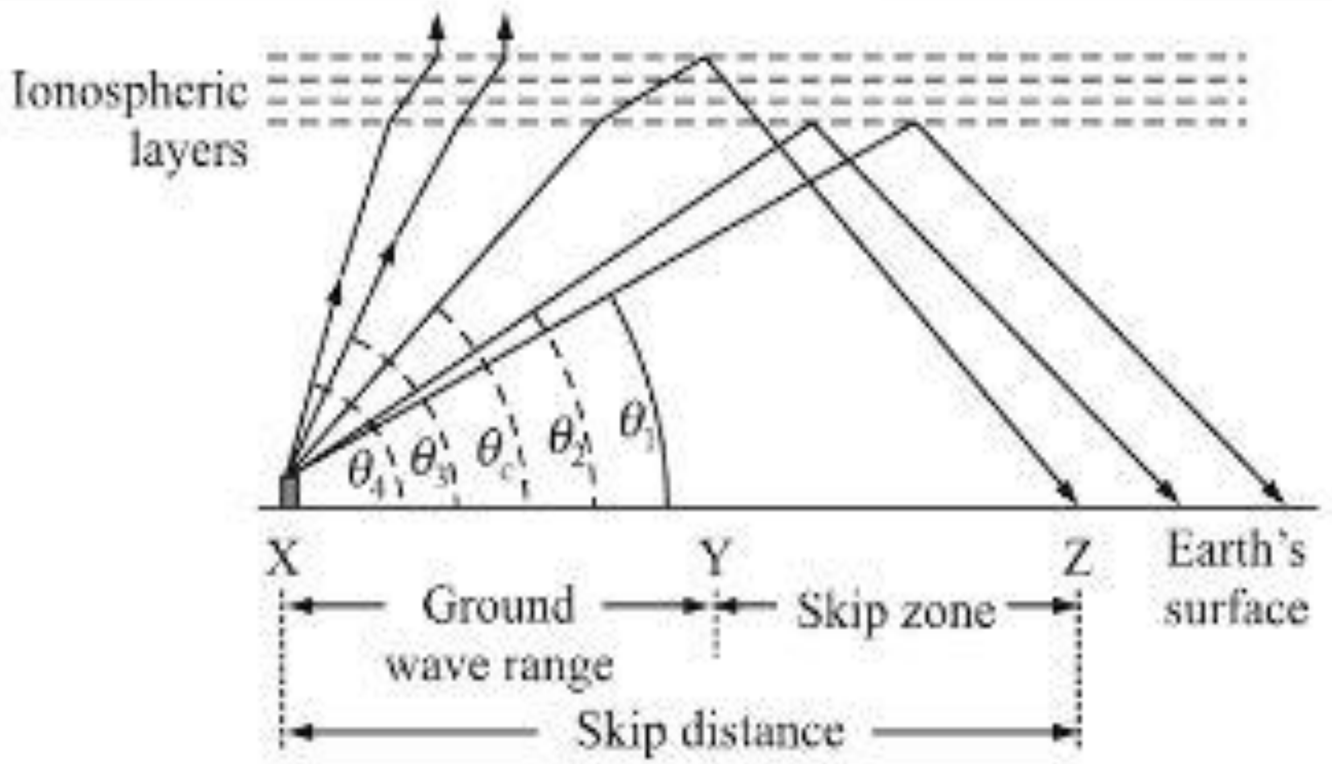


FIGURE 3.9 Depiction of critical incidence angle and skip distance.

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

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

PROBLEM 13: A transmitter antenna has a height of 200 m and the receiving antenna has the height of 16 m. The transmitted signal has the frequency of 1 GHz then calculate the radio horizon.

Solution: Given:

$$h_t = 200 \text{ m};\ h_r = 16 \text{ m};\ f = 1 \text{ GHz}$$

The transmitted signal frequency is 1 GHz, it means the space wave propagation takes place between transmitter and receiver hence the radio horizon is defined as:

$$d = 4.12(\sqrt{h_t} + \sqrt{h_r}) \text{ km}$$

$$d = 4.12(\sqrt{200} + \sqrt{16}) \text{ km}$$

$$d = 74.75 \text{ km}$$

This indicates that the radio horizon will lie up to almost 75 km for the given antenna heights.

PROBLEM 14: A transmitter antenna has a height of 160 m. Calculate the height of receiving antenna so that the transmitted signal can be received at the distance of 70 km.

Solution: Given:

$$h_t = 160 \text{ m}; d = 70 \text{ km}$$

By radio horizon equation,

$$d = 4.12(\sqrt{h_t} + \sqrt{h_r}) \text{ km}$$

$$70 = 4.12(\sqrt{160} + \sqrt{h_r})$$

$$h_r = 18.84 \text{ m}$$

Hence, the receiving antenna height should be 18.84 m in order to receive the transmitted signals at the distance of 70 km from the transmitter.

PROBLEM 15: A transmitter antenna has a height of 100 ft and the receiving antenna has the height of 64 ft. The transmitted signal has the frequency of 100 MHz. Calculate the maximum range of tropospheric transmission in miles.

Solution: Given:

$$h_t = 100 \text{ ft};\ h_r = 64 \text{ ft};\ f = 1 \text{ GHz}$$

The transmitted signal frequency is 100 MHz, it means the tropospheric wave propagation takes place between transmitter and receiver hence the maximum range of propagation in miles is defined as:

$$d = (\sqrt{2h_t} + \sqrt{2h_r}) \text{ miles}$$

$$d = (\sqrt{2 \times 100} + \sqrt{2 \times 64}) \text{ miles}$$

$$d = 25.45 \text{ miles}$$

5.11.5 Critical Frequency

> The critical frequency of an ionized layer of the ionosphere can be defined as the critical frequency in the highest frequency which can be reflected back to earth by a particular layer at vertical incidence.

(Critical frequency is different for different layers, it is denoted by f_c. As we know)

$$\boxed{\mu = \frac{\sin i}{\sin r} = \sqrt{1 - \frac{81N}{f^2}}} \qquad \ldots(5.93)$$

By definition $i = 0°$, $N = N_{max}$ and $f = f_c$.

Then the highest frequency that can be reflected back by the ionosphere is one for which refractive index μ becomes zero. So,

$$\mu = \frac{\sin 0°}{\sin r}$$

$$\sqrt{1 - \frac{81N_m}{f_c^2}} = 0$$

$$1 = \frac{81N_m}{f_c^2}$$

or

$$f_c = \sqrt{81\,N_m}$$

or

$$\boxed{f_c = 9\sqrt{N_{max}}\ ;\ \text{where } f_c \text{ is expressed in MHz and } N_{max} \text{ per cubic metre}} \qquad \ldots(5.94)$$

Below critical frequency, electromagnetic wave will reflect back to earth by the ionised layers, called ionosphere. The frequency will be determined by N, the ionic density.

5.12 VIRTUAL HEIGHT

The idea of virtual height* can be understood with help of figure 5.28. This figure show that as the wave is refracted, it bends down gradually rather than sharply. However, below ionosphere, the incident and refracted rays follow path that are exactly the same as they would have been if reflection had taken place from a surface located at a greater height; called the virtual height of this layer. If the virtual height of a layer is known, it is then quite simple to calculate the angle of incidence required for the wave return to ground at a selected spot.

> In other words, virtual height of an ionospheric layer may be defined as the height to which short pulse of energy sent vertically upward and travelling with the speed of light would reach taking the same two ways travel time as does the actual pulse reflected from the layer. Practically, virtual height is always greater than the actual height.

* Virtual height is always greater than the actual height.

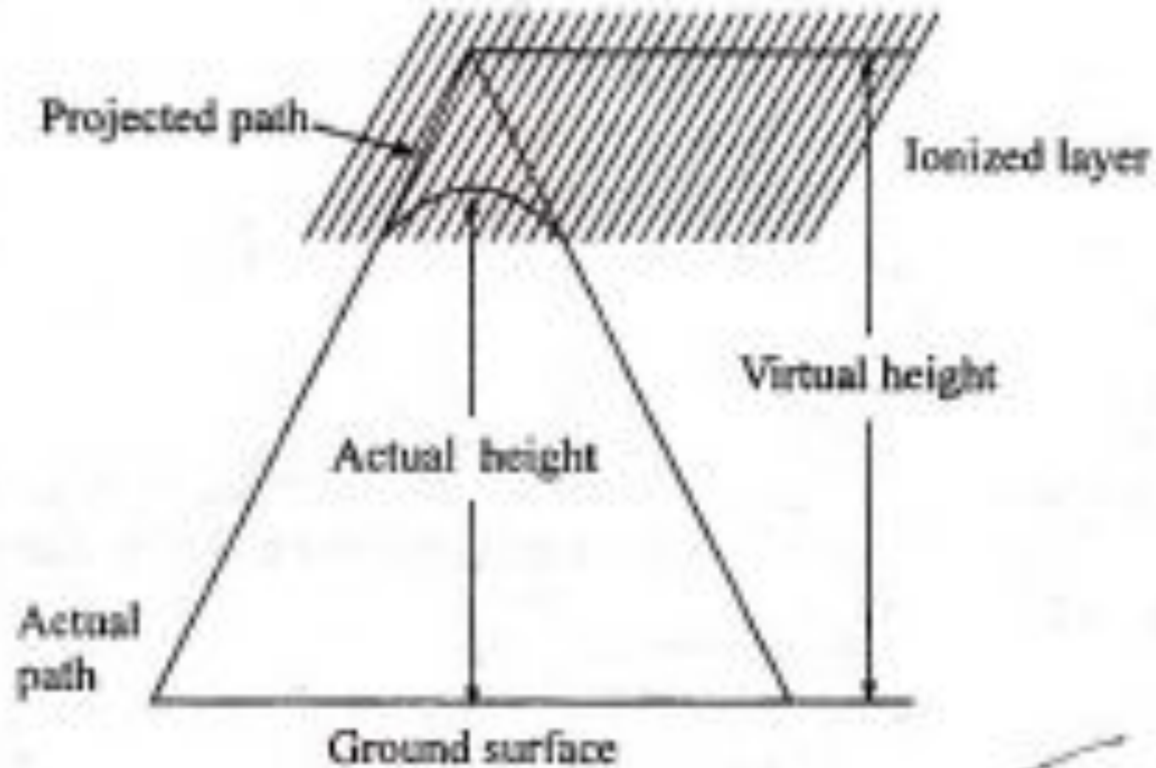


Fig. 5.28 *Actual height and virtual heights of an ionized layer.*

5.13 MAXIMUM USABLE FREQUENCY (MUF)

Critical frequency is the maximum frequency of the radio wave which is returned via a ionized layer at vertical incidence. Although when the frequency of radio wave exceeds the critical frequency, then the communication by the layer depends upon the angle of incidence at the ionosphere. Therefore, the maximum usable frequency (MUF) is also a limited frequency which can be reflected back to earth but this time for the specific angle of incidence rather than vertical. The maximum possible value of frequency for which reflection takes place for a given distance of propagation, is called as the maximum usable frequency (MUF) for that distance, and for the given ionosphere layer. For a sky wave to return to earth, angle of reflection, i.e., $\angle r = 90°$.

> MUF is a highest frequency of wave that can be reflected back by the layer for a specific angle of incidence other than vertical or normal incidence.

$$\mu = \frac{\sin i}{\sin r} = \sqrt{1 - \frac{81N_m}{f_{muf}^2}}$$

$$\mu = \frac{\sin i}{\sin 90^\circ} = \sqrt{1 - \frac{81N_m}{f_{muf}^2}}$$

$$\boxed{\mu = \sin i = \sqrt{1 - \frac{81N_m}{f_{muf}^2}}} \quad ...(5.95)$$

or $$\sin^2 i = 1 - \frac{81N_m}{f_{muf}^2}$$

But $$f_c^2 = 81N_{max}$$

or $$1 - \frac{f_c^2}{f_{muf}^2} = \sin^2 i$$

or $$f_c / f_{muf}^2 = 1 - \sin^2 i$$

$$\frac{f_c^2}{f_{muf}^2} = \cos^2 i$$

or

$$f_{muf}^2 = \frac{f_c^2}{\cos^2 i}$$

$$= f_c^2 \sec^2 i$$

or

$$\boxed{f_{muf} = f_c \sec i} \quad \text{...(5.96)}$$

This means that f_{muf} is greater than f_c by a factor sec i. This is known as SECANT LAW and gives the maximum frequency which can be used for sky wave communication for a given angle of incidence (i) between two points on the earth.

5.14 SERVICE RANGE AND SKIP DISTANCE

The service range at a particular frequency is the difference between maximum range from the transmitter corresponding to grazing angle of incidence at the ionosphere and the minimum distance from the transmitter corresponding to the critical ray. The distance between the point where the sky wave is first-received and the transmitting centre is called the skip distance. The skip distance* is the shortest distance from a transmitter, measured along the surface of the earth, at which a sky wave of fixed frequency (more than f_c) will be returned to earth as shown in figure 5.29.

When the angle of incidence is made quite large, as for ray 1 of figure 5.29, the sky wave returns to earth at a long distance from transmitter. As angle slowly reduces, naturally the wave returns closer and closer to the transmitter, as shown by rays 2 and 3. If the angle of incidence is now made significantly less than that of ray 3, the ray will be too close to the normally to be returned to earth. It may be too close to the normal to be returned to earth. It may bend noticeably, as for ray 4, or only slightly as for ray 5. The bending will be insufficient to return, unless the frequency being used for communication is less than the critical frequency. Finally, If the angle of incidence is only just smaller than that of ray 3, the wave may be returned, but a distance farther than the return point of ray 3; a ray such as this is ray 6 of figure 5.29.

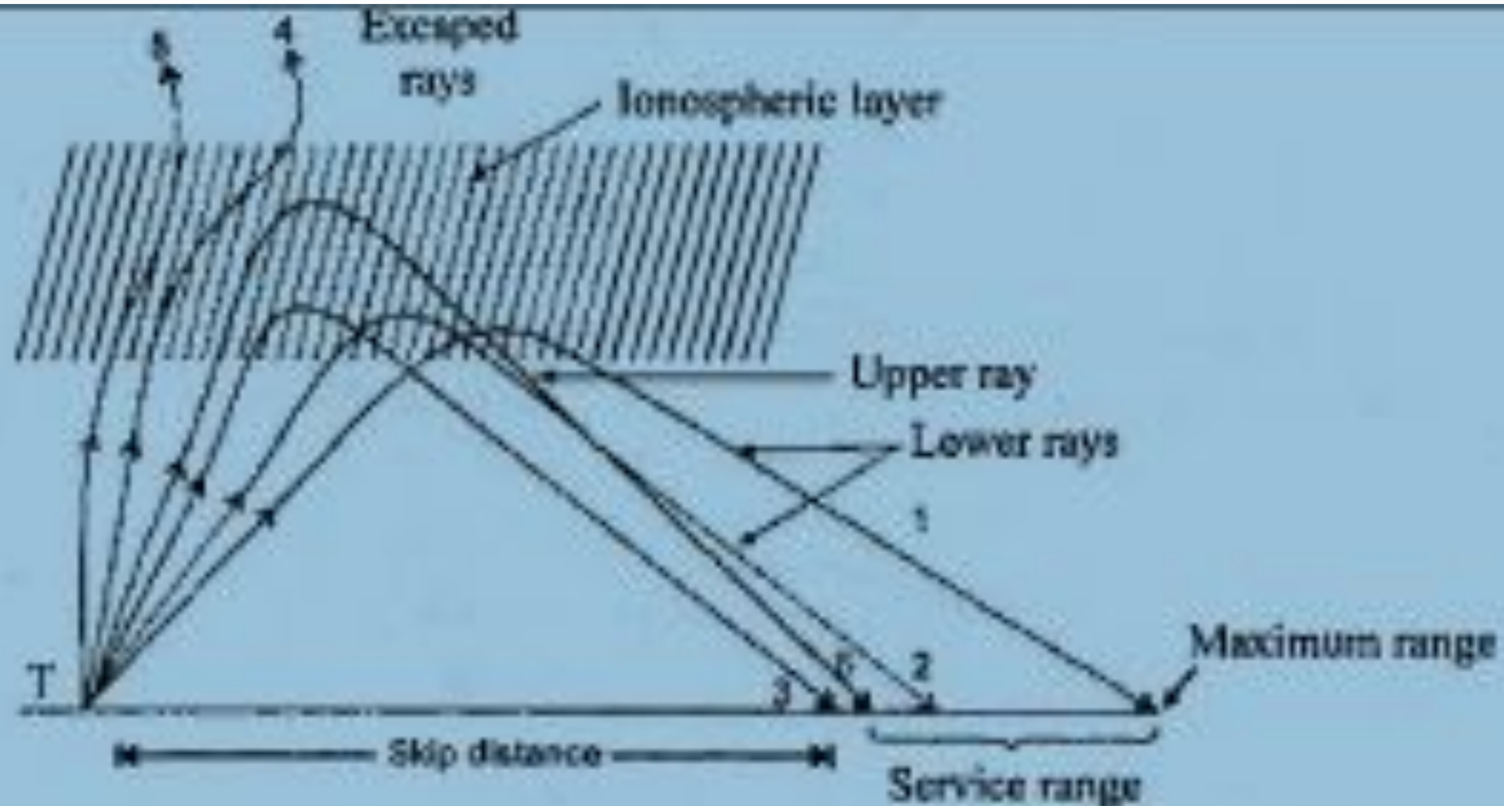


Fig. 5.29 *Effects of ionosphere on rays of varing incidence*

Ray 3 is incident at an angle which results in its being returned as close to the transmitter as a wave of this frequency can be. So the distance is the skip distance, it thus follows that any higher

* Skip distance is the minimum distance of the broadcasting coverage.

frequency beamed up at the angle of ray 3 will not return to ground. It is seen that the frequency which makes a given distance correspond to the skip distance is the MUF for that pair of point. The skip distance is a variable dependent upon frequency and ionosphere conditions. In propagation at low frequencies where there is both ground wave and sky wave skip distance get reduced by the reach of the ground wave. This distance is called the skip zone. Skip distance also indicate the maximum distance on electromagnetic ray may reach on single hop. This is achieved when the critical ray coincides with the angle of grazing incidence.

5.15 CALCULATION OF MUF* AND SKIP DISTANCE

Case I When earth is Flat: The ionized layer may be assumed to be thin layer with sharp ionization density gradient, which gives mirror like reflection of radio waves as shown in figure 5.30. For shorter distance the earth can be assumed to be flat.

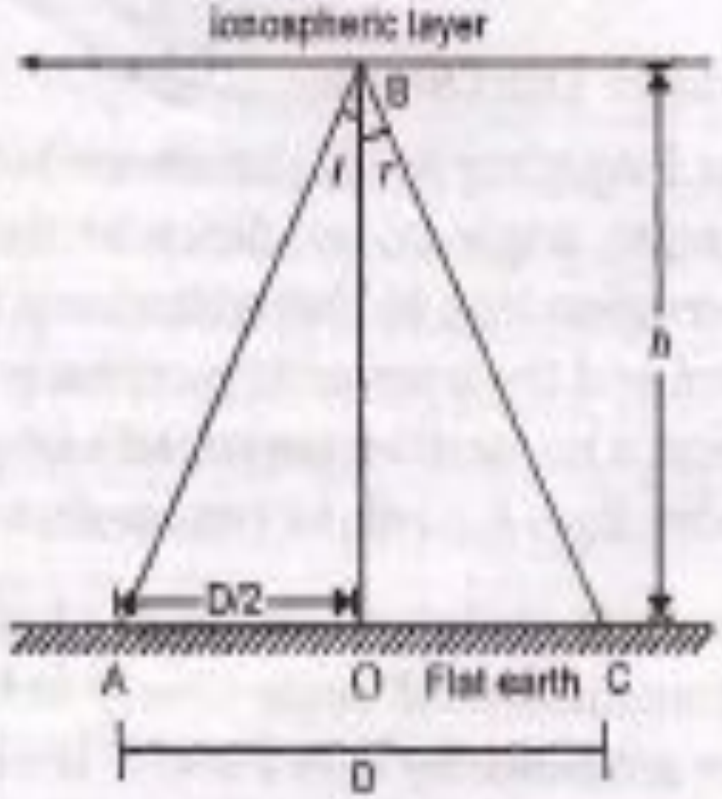


Fig. 5.30 *Reflection from a thin layer on flat earth*

From the figure 5.30

$$\cos i = \frac{BO}{AB}$$

$$= \frac{h}{\sqrt{h^2 + \frac{D^2}{4}}}$$

$$= \frac{2h}{\sqrt{4h^2 + D^2}}$$

where h = height of layer and D = propagation distance AC.

The maximum usable frequency for which the wave is to be reflected from the layer for returning to earth.

$$\boxed{\mu = \sin i = \sqrt{1 - \frac{81N_m}{f_{muf}^2}}}$$

$$\sin^2 i = 1 - \frac{f_c^2}{f_{muf}^2}$$

$$\frac{f_c^2}{f_{muf}^2} = \cos^2 i = \frac{4h^2}{4h^2 + D^2}$$

* MUF is also called maximum usuable frequency. It is a maximum frequency.

$$\frac{f_{\text{mut}}^2}{f_c^2} = \frac{4h^2 + D^2}{4h^2} \qquad \text{...(5.98)}$$

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

or

$$\boxed{f_{\text{mut}} = f_c \sqrt{1 + \left(\frac{D}{2h}\right)^2}} \qquad \text{...(5.99)}$$

The skip distance can be calculated as

$$\frac{f_{\text{mut}}^2}{f_c^2} = \left(1 + \frac{D^2}{4h^2}\right)$$

$$\left(\frac{D}{2h}\right)^2 = \left(\frac{f_{\text{muf}}^2}{f_c^2} - 1\right)$$

$$D^2 = (2h)^2 \left(\frac{f_{\text{muf}}^2}{f_c^2} - 1\right)$$

$$\boxed{D = 2h \sqrt{\frac{f_{\text{muf}}^2}{f_c^2} - 1}} \qquad \text{...(5.100)}$$

- **CALCULATION OF MUF AND SKIP DISTANCE FOR EARTH AS CURVE.(REFER A.K. GAUTAM: ANTENNA AND WAVE PROPAGATION BOOK)**

THANK YOU