UNIT V

PROPAGATION OF RADIO WAVES

Modes of propagation , Structure of atmosphere , Ground wave propagation , Tropospheric propagation , Duct propagation, Troposcatter propagation , Flat earth and Curved earth concept Sky wave propagation – Virtual height, critical frequency , Maximum usable frequency – Skip distance, Fading , Multi hop propagation

5.1 RADIO WAVE PROPAGATION

The process of communication involves the transmission of information from one location to another. When electromagnetic waves (EM) carrying information are generated by the transmitting antenna, they propagate towards the receiver after undergoing different phenomena.

Propagation characteristics of EM wave (Radio wave)

An EM wave radiated by a transmitting antenna is a transverse wave.

A ***transverse wave is*** a wave which occurs in directions perpendicular to the direction of propagation.e.g., When a stone is dropped in water, water moves up and down. This movement is transmitted in the form of expanding circles of waves called transverse waves.

From the transmitting antenna, the EM waves propagate towards the receiving antenna in the following ways:

(i) A part of the wave travels near the surface of the earth. This wave is called ***ground wave*** (or) ***surface wave.***

(ii) Some waves travel directly from the transmitting to the receiving antenna. These waves are called ***space waves*** (or***) tropospheric waves***.

(iii) Some waves travel upwards into space, towards the sky and get reflected back to the receiver. These waves are called ***sky waves*** (or) ***ionospheric wave***.

These three waves results in three modes of propagation

5.1.1 Modes of Propagation

An EM wave travels from the transmitter to the receiver through any of the following modes of propagation.

1. **Ground wave (or) surface wave propagation.**
2. **Space wave propagation (or) tropospheric propagation.**
3. **Sky wave or ionospheric wave propagation**.

(i) Ground wave propagation (upto 2 MHz): The propagation of electromagnetic waves near the surface of the earth is known as ***ground wave propagation***. Here, the transmitting and receiving antennas are close to the surface of the earth and are vertically polarized.

e.g., Broadcast at low frequencies during day time are due to ground waves. It is useful for communication at VLF, LF and MF.

(ii) Space wave propagation (Above 30 MHz): The propagation of electronic magnetic waves directly from the transmitter to the receiver in the tropospheric region is called ***space wave propagation***

e.g., FM reception is normally due to space waves.

(iii) Sky wave propagation (between 2 to 30 MHz): Some waves propagate towards the sky and the signal gets reflected from the ionosphere is called ionospheric (or) sky wave propagation.

e.g., Long distance communication is due to sky waves.

There are several factors that influence the propagation. They are:

1. Earth's characteristics in terms of conductivity, permittivity and permeability.
2. Curvature of the earth, Roughness of the earth.
3. Type of earth like hilly terrain, forest, sea water or river water.
4. Frequency of operation.
5. Polarization and height of the transmitting antenna.
6. Transmitting power.
7. Obstacles between the transmitter and receiver.
8. Electrical characteristics of the atmosphere in the tropospheric region.
9. Moisture content in the troposphere.

10. Characteristics of the ionosphere.

11. Earth's magnetic field.

12. Refractive index, permittivity of troposphere and ionosphere.

13. The distance between the transmitter and the receiver.

5.1.2 GROUND WAVE PROPAGATION :

The propagation of electromagnetic waves near the surface of the earth including propagation in the troposphere is known as ***ground wave propagation.***

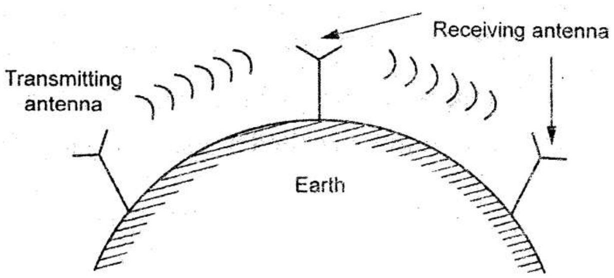


Fig 5.1 : ground wave between transmitting and receiving antenna

Features of ground wave propagation

1. Ground waves propagate by gliding over the surface of the earth.
2. It exists for vertically polarized antennas.
3. Ground wave field strength varies with the characteristics of the earth. v
4. Ground waves require relatively high transmitting power.
5. They are not affected by the changes in atmospheric conditions

Uses of Ground wave propagation

1. It is suitable for very low frequency (VLF), low frequency (LF) and medium frequency (MF) communications.

2. Frequency range used is 15 kHz to 2 MHz.

3. It can be used for radio navigation, maritime mobile communications and for broad casting.

5.1.3 . FREE SPACE PROPAGATION

- Free space means an infinite space without any medium or objects that can interact with the electromagnetic waves.
- When EM waves are radiated by an antenna, at large distances, the radiated fields are in the form of spherical waves.
- The power received is given by the Frii's formula

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2}$$

where, $P_t =$ transmitting power

$G_t \; and \; G_r$ = transmit and receive antenna gains

R = distance between transmit and receive antenna

- The transfer of electromagnetic energy takes place in a straight line path and hence such a communication link is called a line-of-sight (LOS) link.
- The factor $\left[\frac{\lambda}{4\pi R}\right]^2$ is called free space path loss (P_L). It is expressed in decibel (dB) as

$$P_L = 10 \log \left(\frac{4\pi R}{\lambda}\right)^2 \quad dB \qquad \ldots\ldots\ldots (5.9)$$

5.1.4 GROUND REFLECTION:

If the transmit and receive antenna are situated close to the ground, then any wave that falls on the ground is reflected. This is due to the discontinuity in the electrical properties at the air-ground interface.

The amount of reflection depends on

- ✓ angle of incidence
- ✓ polarization of the wave
- ✓ electrical properties of ground like conductivity and dielectric constant.
- ✓ frequency of the propagating wave.

Therefore, the field at any point above the ground is vector sum of field due to direct path and the ground reflected path.

$$i.e\ Total\ field(E) = \left\{ \begin{matrix} Field\ due\ to \\ direct\ wave\ (E_1) \end{matrix} + \begin{matrix} Field\ due\ to\ ground \\ reflected\ wave\ (E_2) \end{matrix} \right\}$$

In order to calculate the total field (E) due to direct and ground reflected wave, let us consider a transmit antenna located at point **'P'** and a receive antenna at point **'Q'** as shown in Fig.5.2.

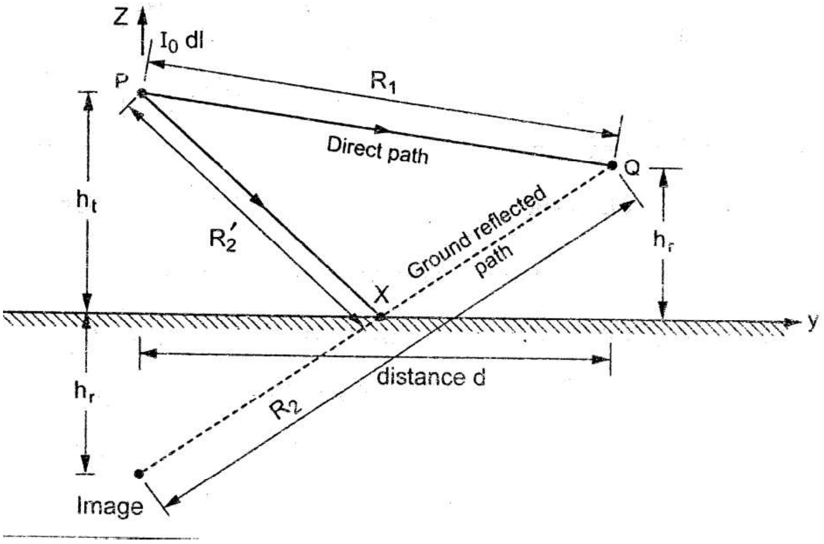


Fig 5.2: direct and ground reflected paths of wave propagation

Let d = horizontal distance between two antennas
h_t = height of the transmit antenna
h_r = height of the receive antenna
X = point at which reflection takes place and it depends on h_t, h_r and *d*

Let us assume that the transmit antenna is an infinitesimal dipole oriented along the X-axis. The incident ray PX , the reflected ray XQ , and the normal to the surface are all contained in the y-z plane. The y-z plane is also known as the plane of incidence.

The electric field at $'Q'$ due to the direct wave is given by

$$E_1 = jk\eta \frac{I_o dl e^{-jk R_1}}{4\pi R_1} \qquad \ldots\ldots\ldots..(5.10)$$

The incident field at X is given by

$$E_i = jk\eta \frac{I_o dl e^{-jkR_2{}'}}{4\pi R_2{}'} \qquad \ldots\ldots\ldots\ldots\ldots(5.11)$$

Where $R_2{}'$ = distance from the transmitter to the point $'X'$

Now , the reflected wave depends on the polarization of the incident wave at point X as shown in fig 5.3.

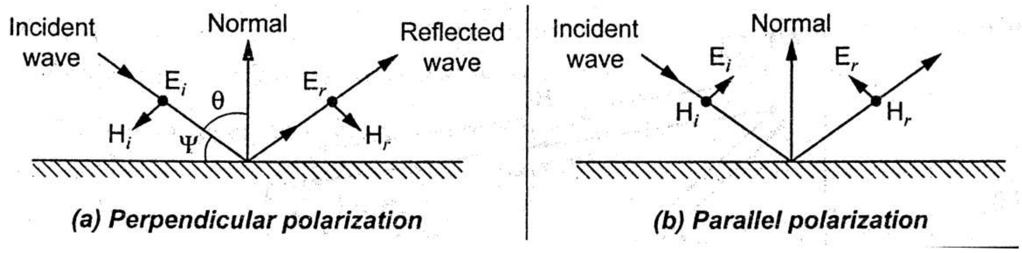


Fig .5.3 Plane wave incident on a boundary

Reflection Factor for Perpendicular (Horizontal) Polarization (R_h)

When the incident $'E'$field vector is perpendicular to the plane of incidence (parallel to the reflecting surface), the reflection factor is given by

$$R_h = \frac{reflected\ electric\ field\ strength\ (E_r)}{incident\ electric\ field\ strength\ (E_i)}$$

$$R_h = \frac{\sin\Psi - \sqrt{(\varepsilon_r - j\chi) - \cos{}^{2}_{\Psi}}}{\sin\Psi + \sqrt{(\varepsilon_r - j\chi) - \cos{}^{2}_{\Psi}}} \qquad \ldots\ldots\ldots.(5.12)$$

Where $\chi = \frac{\sigma}{\omega\varepsilon_o}$

and σ = conductivity of the ground
ω = angular frequency
Ψ = grazing angle of incidence
ε_o = dielectric constant of free space

Now , the electric field at point Q due to the reflected wave is

$$E_2 = jk\eta R_h \frac{I_o dl e^{-jkR_2}}{4\pi R_2} \qquad \ldots\ldots\ldots..(5.13)$$

The total electric field at Q is given by

$$E = E_1 + E_2$$

$$= jk\eta \frac{I_o dl}{4\pi}\left(\frac{e^{-jkR_1}}{R_1} + R_h \frac{e^{-jkR_2}}{R_2}\right) \qquad \ldots\ldots..(5.14)$$

If the point Q is situated far away from the transmitter , then the approximation $R_2 \approx R_1$ can be used in the denominator.

$$\therefore E = jk\eta \frac{I_o dl}{4\pi}\frac{e^{-jkR_1}}{R_1}\left(1 + R_h e^{-jk\,(R_2 - R_1)}\right) \qquad \ldots\ldots.(5.15)$$

From the above equation , it is clear that the total field E is the product of the free space and environmental factor F_h which is given by

$$\boxed{F_h = 1 + R_h e^{-jk\,(R_2 - R_1)}} \qquad \ldots\ldots.(5.16)$$

∴ Equation (5.15) becomes

$$\boxed{E = jk\eta \frac{I_o dl}{4\pi}\frac{e^{-jkR_1}}{R_1} F_h} \qquad \ldots\ldots.(5.17)$$

Reflection Factor for Parallel (Vertical) Polarization (R_v)

When the incident electric field is parallel to the plane of incidence (perpendicular to the reflecting surface), the reflection factor is given by

$$R_v = \frac{(\varepsilon_r - j\chi)\sin\Psi - \sqrt{(\varepsilon_r - j\chi) - \cos{}^{2}_{\Psi}}}{(\varepsilon_r - j\chi)\sin\Psi + \sqrt{(\varepsilon_r - j\chi) - \cos{}^{2}_{\Psi}}} \qquad \ldots\ldots\ldots.(5.18)$$

Similar to the horizontal polarization , the total field at point Q is given by

$$\boxed{E = jk\eta \frac{I_o dl}{4\pi}\frac{e^{-jkR_1}}{R_1} F_v} \qquad \ldots\ldots\ldots\ldots\ (5.19)$$

Where $F_v = 1 + R_v e^{-jk\,(R_2 - R_1)}$ $\qquad \ldots\ldots\ldots(5.20)$

From fig 5.2 R_1can be calculated as

$$R_1 = \sqrt{d^2 + (h_r - h_t)^2} \qquad \ldots\ldots\ldots(5.21)\backslash$$

$$= d\sqrt{1 + \left(\frac{h_r - h_t}{d}\right)^2} \qquad \ldots\ldots\ldots(5.22)$$

For $d >> h_r \;\; and \; d \gg h_t, equation \; (5.22) becomes$

$$R_1 = d\left[1 + \frac{1}{2}\left(\frac{h_r - h_t}{d}\right)^2\right] \qquad \ldots\ldots\ldots(5.23)$$

$$\left[\because \sqrt{1+x} = 1 + \frac{x}{2} \; for \; x << 1 \; according \; to \; binomial \; expansion\right]$$

Similarly , R_2can be approximated to

$$R_2 \approx d\left[1 + \frac{1}{2}\left(\frac{h_r + h_t}{d}\right)^2\right] \qquad \ldots\ldots\ldots(5.24)$$

The path difference $R_2 - R_1 \; is \; given \; as$

$$R_2 - R_1 = \frac{2h_r h_t}{d} \qquad \ldots\ldots\ldots(5.25)$$

For $\frac{h_r h_t}{d} << \lambda$,

$$\Delta\theta = k(R_2 - R_1) = \frac{4\pi h_r h_t}{d\lambda} \qquad \ldots\ldots\ldots\ldots(5.26)$$

If $\Delta\theta$ is small , we can write

$$e^{-jk(R_2 - R_1)} \approx 1 - j\frac{2kh_r h_t}{d}$$

For low angle of incidence

$$R_h \approx R_v \approx -1$$

and hence we can write

$$F = F_h = F_v \approx j\frac{2kh_r h_t}{d} \qquad \ldots\ldots\ldots(5.27)$$

Taking into account the ground reflection , the power received by the receive antenna can be written as

$$P_r = P_{st} G_t G_r \left(\frac{\lambda}{4\pi R_1}\right)^2 \ |F|^2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots (5.28)$$

If $h_r\, and\ h_t$ is small compared to $'d'$, then equation (5.23) becomes $R_1 \approx d$

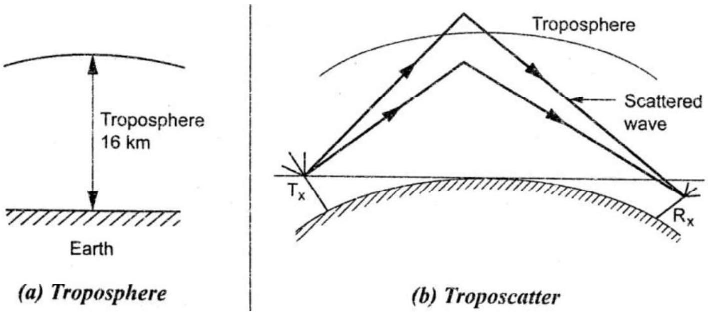
Therefore ,the received power is approximately given by

$$\boxed{P_r = \frac{P_t G_t G_r (h_r h_t)^2}{d^4}}$$

For large value of d, the received power decreases in proportion to d^4. This rate of change of power with distance is much faster than that observed in the free space propagation condition.

5.2 TROPOSPHERIC PROPAGATION (OR) SPACE WAVE PROPAGATION

The EM wave that propagates from the transmitter to the receiver in the earth's troposphere is called space wave or tropospheric wave. Troposphere is the region of the atmosphere within 16 km above the surface of the earth. The relative dielectric constant is slightly higher than unity in this region. This is due to the presence of water vapour in the atmosphere. But the value of dielectric constant decreases as a function of height above the surface of the earth.



(a) Troposphere *(b) Troposcatter*

Fig 5.4

In the tropospheric wave propagation (or) space wave propagation , the field strength at the receiver is contributed by

1. Direct ray from the transmitter.
2. Ground reflected ray.
3. Reflected and refracted rays from the troposphere.

4. Diffracted rays around the curvature of the earth , hills and so on.

We know that the velocity of the electromagnetic wave in a medium deoands on the dielectric constant of the medium.

$$v = \frac{C}{\sqrt{\varepsilon_r}} = \frac{C}{n} \qquad \ldots\ldots\ldots (5.41)$$

Where C = velocity in vacuum.

$n = \sqrt{\varepsilon_r}$ is the refractive index of the medium

At the surface of the earth $n = 1.000289$

The refractivity $N = (n - 1) \times 10^6$

Thus at the surface of the earth N = 289

For a standard atmosphere , the refractivity falls of linearly upto a height of 2km ,

Now , $N = 289 \ - 39\,h$

Where h = height in km

∴ The refractive index of the standard atmosphere is given by

$$n = 1 + \ (289 - 39h) \times 10^{-6} \qquad \ldots\ldots (5.42)$$

The path of a wave propagating in a medium is derived as follows:

Let us assume that the earth is flat and the troposphere is made up of stratified layers parallel to the surface of the earth .

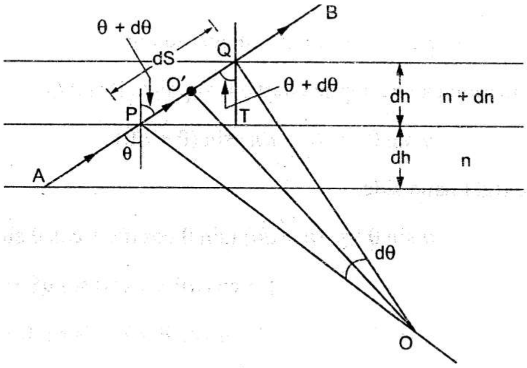


Fig 5.5. Wave propagation in a stratified medium

Consider a layer that has a height $= dh$

Its refractive index $= n + dn$

A ray incident from the lower layer at point $= P$

It is refracted through the layer dh and touches the point $= Q$

Angle of incidence $= \theta$

Angle of refraction $= \theta + d\theta$

In fig , $\angle APQ = \pi - d\theta$

Since OP bisects $\angle APQ$, $\angle OPQ = \frac{1}{2}\angle APQ = \frac{\pi}{2} - \frac{d\theta}{2}$

Draw OO' perpendicular to PQ .

$$\angle POO' = \frac{\pi}{2} - \angle OPQ = \frac{d\theta}{2}$$

$$\angle POQ = 2\angle POO' = d\theta$$

The length $dS = r\, d\theta$ …………..(5.43)

From $\Delta\, PQT$, $dS = \frac{dh}{\cos(\theta + d\theta)} \approx \frac{dh}{\cos\theta}$ $for\ small\ d\theta$ ……. (5.44)

Substituting the value of dS in equation (5.43)

$$r = \frac{dS}{d\theta} = \frac{dh}{\cos\theta\, d\theta} \qquad \dots\dots\dots (5.45)$$

Where r = radius of the curvature.

The law of refraction can be applied to the two points P and Q.

$$n \sin\theta = (n + dn)\sin(\theta + d\theta)$$

Expanding the right hand side,

$$n \sin\theta = (n + dn)(\sin\theta \cos d\theta + \cos\theta \sin d\theta)$$

$$[\because \cos d\theta \approx 1 \ \ and\ \sin d\theta = d\theta]$$

$$n \sin\theta = n\sin\theta + n\cos\theta\, d\theta + dn \sin\theta + dn\cos\theta\, d\theta$$

Ignoring the last term , as it is product of two infinitesimals

$$n\sin\theta = n\sin\theta + ncos\theta\, d\theta + dn\sin\theta$$

Which can be written as

$$cos\theta\, d\theta = \frac{-\sin\theta dn}{n} \qquad \dots\dots(5.46)$$

Substituting (5.46) in equation (5.45) we get

$$r = \frac{dh}{-\sin\theta\left(\frac{dn}{n}\right)} = \frac{n}{\sin\theta\left(-\frac{dn}{dh}\right)} \qquad \dots\dots\dots(5.47)$$

∴ The radius of the curvature of the ray incident from the layer with refractive index $'n'$ and refracted through the next layer with refractive index $(n + dn)$is given by

$$\boxed{r = \frac{n}{\sin\theta\left(-\frac{dn}{dh}\right)}} \qquad \dots\dots\dots.(5.48)$$

The radius of the curvature can also be written in terms the grazing angle Φ, and it is related to θ by

$$\theta = \frac{\pi}{2} - \Phi$$

Now, radius of curvature in terms of Φ is written as

$$r = \frac{n}{cos\Phi\left(-\frac{dn}{dh}\right)} \qquad \dots\dots(5.49)$$

We can express the radius of curvature in terms of the refractivity gradient as

$$r = \frac{10^6}{\left(-\frac{dN}{dh}\right)}$$

For standard atmosphere , $\frac{dN}{dh} = \ -39\, per\ km$

In this case, $r = \frac{1}{39 \times 10^{-6}}$

= 25641 km

∴ If $\frac{dN}{dh}$ tends to zero, the radio wave follows a straight line path instead of undergoing refraction.

5.2.1 Duct Propagation

Duct propagation is a phenomenon of propagation making use of the atmospheric duct region.

In duct region, variation of modified refractive index with height is minimum.

In duct propagation, the ray which is parallel to the earth's surface travels round the earth in a series of hops with successive reflections from the earth.

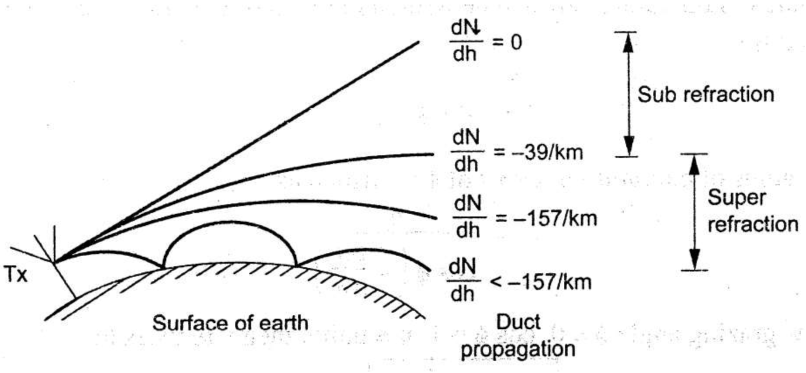


Fig :5.6. Wave propagation through a stratified medium above the spherical earth

Fig.5.6 shows the propagation of a radio wave launched at low grazing angles for various values of refractivity gradients (dN/dh),

(i) If $\frac{dN}{dh} = 0$, the waves travel along straight lines.

(ii) ***Sub refraction***: If $0 < \frac{dN}{dh} < -39\ /km$, then the wave is refraction of EM wave less than standard atmosphere. This is known as sub-refraction.

(iii) ***Super refraction***: If the refractivity slope is less than standard atmosphere i.e., $\frac{dN}{dh} < -39\ /km$, then the wave is refracted more than that in a standard atmosphere and it is known as super refraction.

(iv) ***Parallel propagation***: If $\frac{dN}{dh} = -157\ /km$, then the Radius of curvature of ray, $r = \frac{1}{157\times10^{-6}}$

r = 6370 km = Radius of the earth.

Hence a horizontally incident wave travels parallel to the surface of the earth.

(v) ***Duct propagation***:

$$\frac{dN}{dh} < -157\ /km,$$

Radius of curvature of the ray < Radius of the earth ,

Therefore the ray, touch the surface of the earth and get reflected from the surface and it is known as tropospheric duct propagation.

Calculation of height of the propagating radio wave as a function of distance

On a spherical earth, the maximum possible direct wave communication distance depends on the heights of the transmit and the receive antennas as well as the atmospheric conditions.

If the refractivity, $\frac{dN}{dh} = 0$, then the radio waves travel along straight lines.

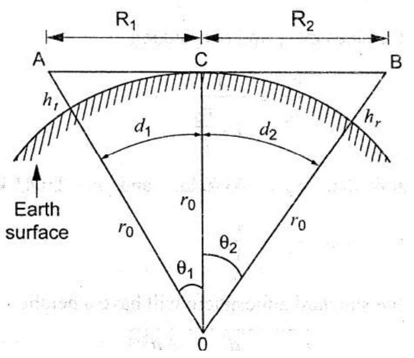


Fig . 5.7: Propagation path of radio waves over the surface of the earth with $\frac{dN}{dh} = 0$

From Fig.5.7, in Δ AOC, the distance between the transmit antenna and the point of contact on the surface of the earth is given by

$$R_1^2 \ = \ (r_0 + h_t)^2 \ - r_o^2 \ = 2r_0 \, h_t + h_t^2$$

Since $r_0 \gg h_t$, $R_1^2 \ = 2r_0 \, h_t$

Similarly , from Δ BOC , $R_2^2 \ = 2r_0 \, h_r$

$\therefore$ The line-of-sight distance between the transmit and the receive antenna is given

by $R = R_1 \ + R_2 = \ \sqrt{2r_0}\left(\sqrt{h_t} \ + \sqrt{h_r}\right)$

Under standard atmosphere condition ($\frac{dN}{dh} < \ -39 \ /km$)

Under standard atmosphere condition a horizontally launched ray from the surface of the earth follows a curved path with a radius of curvature ***r***.

Curvature of equivalent ground = Curvature of earth − curvature of the ray

$$\frac{1}{r_e} = \frac{1}{r_0} - \frac{1}{r}$$

Multiplying both the sides by r_0 and rearranging

$$\frac{r_e}{r^0} = \frac{1}{1 - r_0}$$

We know that $r_0 = 6370$ km and ***r*** = 25641 km

A ray travel in the standard atmosphere will have a height

$$h \approx \frac{d^2}{2r_e} = \frac{3d^2}{8r_0}$$

The standard atmosphere is valid unto a height of 2 km from the surface of the earth.

The variation of the modified refractivity with height

(i) If $\frac{dM}{dH} \angle$ 118/km, then wave undergoes super refraction.

(ii) If $\frac{dM}{dH} = 0$ with $\frac{dN}{dn} = -157.\text{km}$,then

(iii) If $\frac{dM}{dH} \angle 0$,then duct propagation is observed.

The gradient of the modified refractivity can change with height. This can result in different modes of propagation in the troposphere, as shown in Fig.5.8

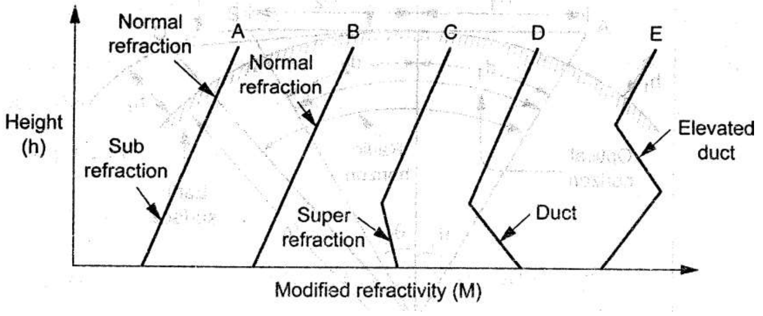


Fig 5.8 : Several possible refractivity profiles

In profile A,EM waves undergo sub refraction near the surface, normal refraction at greater heights.

In profile B, EM waves undergo normal refraction.

In profile C,EM waves undergo super refraction near the surface of the earth.

In profile D, the gradient of M is negative, ducts propagation is observed. This is known as surface duty.

Profile E shows an elevated duct.

In the atmosphere, the ducts are observed upto a height of 1500m.

If the waves is launched into the elevated duct at low grazing angles, an antenna at the height of the duct will be able to receive strong signals.

5.3. TROPOSPHERIC SCATTER

This is a mechanism by which propagation is possible by the scattered and diffracted rays. The scattering takes place by the tropospheric region . Due to this scatter, receivers even at shadow zone gets large field strengths.

The curvature of the earth limits the maximum line-of-sight distance between the transmit and the receive antennas in a communication link.

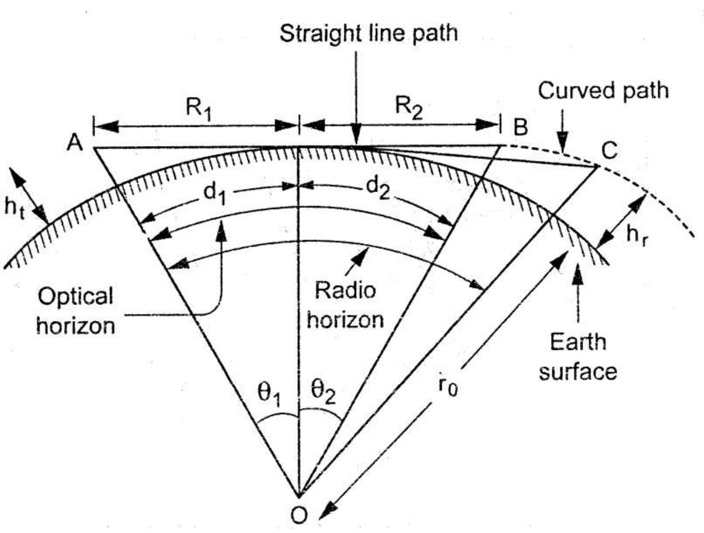


Fig. 5.9. Optical and radio horizons

As shown in Fig.5.9, if

h_t = height of the transmitting antenna
h_r = height of the receiving antenna ,
then, straight line AB = LOS path between two antennas

LOS: Line of sight is defined as the distance that is covered by a direct wave from the transmitting antenna to the receiving antenna.

Optical horizon is the maximum distance between the two antennas along the surface of the earth, for which the line AB just touches the surface of the earth.

From Fig.5.9,

Optical horizon,$d = r_o(\theta_1 + \theta_2)$

Where $r_o =$ Radius of the earth

and $\theta_1 = \tan^{-1}\left(\frac{R_1}{r_o}\right)$

$$\theta_2 = \tan^{-1}\left(\frac{R_2}{r_o}\right)$$

The straight line path lengths are given by

$$R_1 = \sqrt{(r_0 + h_t)^2 - r_o^2}$$

$$R_2 = \sqrt{(r_0 + h_r)^2 - r_o^2}$$

The radio waves take a curved propagation path through the atmosphere, and hence can reach a longer distance.

The curved line AC corresponds to the radio horizon. ***Radio horizon*** is the maximum distance over which a direct radio wave link can be established.

To compute the radio horizon, $r_0$is replaced by $\left(\frac{4}{3}\right) r_0$,because

Bending of the radio wave propagation can take earth's radius = $\left(\frac{4}{3}\right) r_0$

Because of tropospheric scatter, communication is possible much beyond the radio horizon. But tropospheric scattering is disturbed by

1. Variation of dielectric constant.
2. Uneven variations of refractive index.
3. Variation of effective earth radius factor.
4. Temperature or humidity or dust particles.

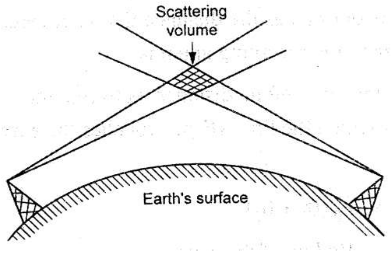


Fig .5.10 : Illustration of a troposcatter link

From the Fig.5.10, it is shown that the scattering volume is the common volume shared by the two beams and is just a few kilometers from the surface of the earth.

Due to the random nature of scattering, the received signal strength also shows random fluctuations. Therefore the signals from the transmitter reaches the receiver in a multipath environment. Thus, the signals received by the troposcatter link also show fading.

Uses of troposcatter

1. Troposcatter is used to establish communication links in the UHF and microwave frequency bands.
2. Distance coverage is upto 1000 km.
3. Bandwidth utilized is few MHz.

Applications

1. Troposcatter link can be used in multi-channel telephony, and
2. Television applications.

5.4. IONOSPHERIC PROPAGATION (SKY WAVE PROPAGATION)

- Ionospheric propagation is also called sky wave propagation. Ionosphere is the upper portion of the atmosphere. It extends from 60 km to 400 km and situated above the troposphere as shown in Fig.5.11.
- The radiation from the space, in particular that from the sun, ionizes the ga; molecules present in the atmosphere.
- The range of atmosphere between 60 km to 400 km is ionized by absorbing large quantities of radiation energy from the sun.
- The major ionization is from a, P and y radiations from the sun and cosmic rays and meteors.
- Ionization is a process by which a neutral atom or molecule gains or loses electrons and is left with a net charge.

5.4.1. STRUCTURE OF THE IONOSPHERE

The physical properties of the ionosphere vary from time to time as the temperature, ionization density and composition change regularly .So, it does not have regular and constant distribution. Ionosphere is divided into different regions (or) layers. They are

1. D-layer 2. E-layer 3. E_s-layer

4. F, - layer 5. F_2 - layer

- These layers are formed due to the variations in the physical properties such as temperature, pressure, density, composition, *etc.,* and also by the absorption of different radiations by the ionosphere.

1.D-layer

- It is the lowest layer of the ionosphere.
- It exists at about 70 km height, thickness is 10 km.
- It exists only in day time.
- Suitable for VLF and LF communication.

2. E - layer

- It is next to D - layer.
- Height is about 100 km.
- Thickness is 25 km.
- It exists only in day time.
- It is suitable for HF communication.
- It also assists the surface wave propagation of MF waves.

3. Es – layer

- It is a sporadic E layer
- It is a thin layer
- It exists in both day and night time.
- This layer has very high ionization density.
- It will not help for long distance communication. But sometimes it provides better reception during night.

4. F_1 layer

- It exists at an average height of about 180 km.
- During day time , its thickness is approximately 20 km and during night time it combines with F_2 layer.
- Eventhough some HF waves are absorbed by the F_1 layer, most of the HF waves are penetrated through the F_1 layer and are reflected by the F_2 layer.
- The absorption is double in his layer as compared to any other layer. [This is because waves are absorbed while on the way to the F_2 layer and the way down after reflection from the F_2 layer].

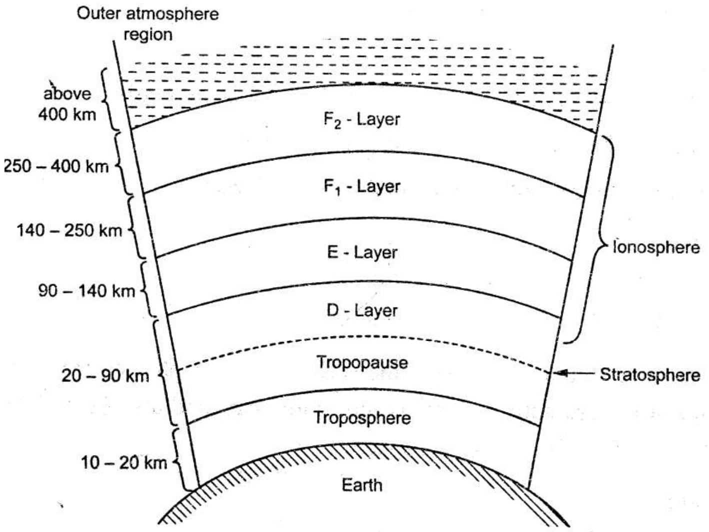


Fig .5.11 Structure of the ionosphere including troposphere

5. F_2 - layer

- This is the most important layer to reflect the HF waves.
- During day time, it is located around 250 to 450 km above the earth's surface. But during night time, it appears at the height of 300 km with the F, layer.
- Its thickness is about 200 km. It is the thickest of all the four layers.
- The main difference between combined 'F' layer and other layers is that it exists at night also and therefore ***HF reception is better during night time.***
- The region at a height of 400 km above the earth's surface is called G-region. This region consists of the charged particles trapped by the terrestrial magnetic field having shape similar to that of the magnetic lines of force.

Mechanism of Ionospheric Propagation

Ionospheric propagation takes place through reflection and refraction of EM waves by the ionospheric layers

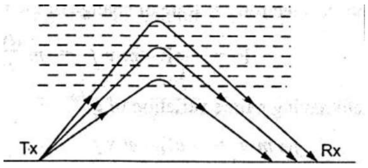


Fig. 5.12. Ionospheric wave propagation and ray paths

Due to variation in the refractive index and dielectric constant in the layer, the incident wave bent away from the normal.

This bending follows optical laws.

$$n = \frac{\sin\theta_i}{\sin\theta_r}$$

$\theta_{i\Rightarrow}$ angle of incidence at lower edge of the ionosphere.

$\theta_{r\Rightarrow}$ angle of refraction.

5.4.2 ELECTRICAL PROPERTIES OF THE IONOSPHERE

Consider the motion of an electron in an electric field strength (E) volt/ meter.

The force the electron = $-\,eE \quad Newton$

In the event of a collision between the electron and gas molecule, energy is lost in the form of heat.

$$\text{The frictional force } = \frac{mv}{T} \ (or) \quad mv \times f$$

Where T = mean time between collision

v = velocity of electron

f = frequency of collision

m = mass of the electron

Net force on the electron = Rate of change of the momentum

$$F = -eE - m\,v\,f = m\frac{dv}{dt}$$

For a sinusoidal field having a time variation of $e^{j\omega t}$,

$$j\omega\, m\, v = -eE - m\, vf$$

$$v = \frac{-eE}{(j\omega\, m + f\, m)} \quad \ldots\ldots\ldots..(5.56)$$

Since the moving charge is the current, the induced current density in an ionized gas containing N electrons per unit volume is

$$J = -eN\,v \;{}^{A}/_{m^2} \qquad \ldots\ldots\ldots\ldots\ (5.57)$$

Substituting (5.56) in (5.57), $J = \frac{Ne^2E}{m(f+j\omega)}\ {}^{A}/_{m^2} \qquad \ldots\ldots\ldots\ldots..(5.58)$

An expression for the complex dielectric constant of the ionized air can be derived as follows:

Based on Maxwell's curl equation

$$\nabla \times H = j\omega\epsilon_0 E + J \qquad \left[\text{since } \nabla\times H = J + \frac{\partial D}{\partial t}\ and\ D = \epsilon E\right]$$

Substituting for 'J' from equation (5.58), we get

$$= j\omega\epsilon_0\left[1 - \left(\frac{Ne^2}{m\epsilon_0}\right)\frac{1}{\omega(\omega - jf)}\right]E \qquad \ldots\ldots\ldots\ldots.(5.59)$$

Where , $\omega_p = \sqrt{\frac{Ne^2}{m\epsilon_0}}$ is known as plasma frequency of the ionized medium

Plasma frequency is defined as the natural frequency of oscillation of charged particles in plasma region . Plasma is a completely ionized gas at very high temperature consisting of the nuclear and negative electrons.

From equation (5.59) , the complex relative dielectric constant medium is given by

$$\varepsilon_r^{\sim} = 1 - \frac{{\omega_p}^2}{\omega(\omega - j\,f)}$$

Multiplying and dividing by the complex conjugate of the denominator and expanding

$$\varepsilon_r^{\sim} = \left(1 - \frac{{\omega_p}^2}{\omega^2 + f^2}\right) - j\left({\omega_p}^2\frac{{}^{f}/_{\omega}}{\omega^2 + f^2}\right) \qquad \ldots\ldots..(5.60)$$

For a lossy medium, $\varepsilon_r^{\sim} = \epsilon_r - j\frac{\sigma}{\omega\epsilon_0} \qquad \ldots\ldots.(5.61)$

Where ϵ_r = relative permittivity.

σ = conductivity of the medium.

Comparing equation (5.60) with (5.61), we can write

$$\epsilon_r = 1 - \frac{{\omega_p}^2}{\omega^2 + f^2} \qquad \ldots\ldots\ldots(5.62)$$

$$\sigma = \left(\frac{\epsilon_0\, {\omega_p}^2}{\omega}\right)\left(\frac{\frac{f}{\omega}}{1 + \frac{f^2}{\omega^2}}\right)$$

In the ionosphere, $f = 10^6 Hz$ at 90km from the surface of the earth

and, $f = 10^3 Hz$ at 300 km

For $f \ll \omega, \sigma$ is small. Therefore effective dielectric constant $\varepsilon_r^{\sim} = \epsilon_r$

Hence equation (5.62) becomes $\epsilon_r \approx 1 - \frac{Ne^2}{m\epsilon_0(\omega^2)}$ $\left[\because \omega_p = \sqrt{\frac{Ne^2}{m\epsilon_0}}\right]$

Substituting for $\epsilon_0 = 8.854 \times 10^{-12} \frac{F}{m}$, $e = 1.602 \times 10^{-19}\, C$ and

$$\boxed{\epsilon_r = 1 - \frac{{\omega_p}^2}{\omega^2} = 1 - \frac{81N}{f^2} \qquad \ldots\ldots\ldots\ldots(5.63}$$

Ignoring the conductivity of the ionosphere, the propagation constant

$$k = \omega\sqrt{\mu_o \epsilon_0}\epsilon_r = k_0\sqrt{\epsilon_r} \quad rad/m$$

Where k_0 = propagation constant in vacuum

Conclusion

1 .The relative dielectric constant of the ionosphere depends on the ratio of the plasma frequency ω_p and the wave frequency ω

2. For $\omega < \omega_p$, ϵ_r is negative. Propagation constant is purely imaginary. Under this condition, the plane wave becomes purely evanescent.

3. when $\omega = \omega_p$, $\epsilon_r = 0$

   For $\omega > \omega_p$, $\epsilon_r < unity$

The region with high conductivity has high absorption at D - layer. So, F layer is suitable for long distance communication.

5.4.3. VIRTUAL HEIGHT

It is defined as the height that is reached by a short pulse of energy which has the same time delay as the original wave.

Virtual height > Actual height

Virtual height of the layer is useful to find the angle of incidence required for the wave to return to earth at a specified point.

Consider an EM wave from a transmitter reaching the receiver after being reflected by the ionosphere as shown in Fig.5.13.

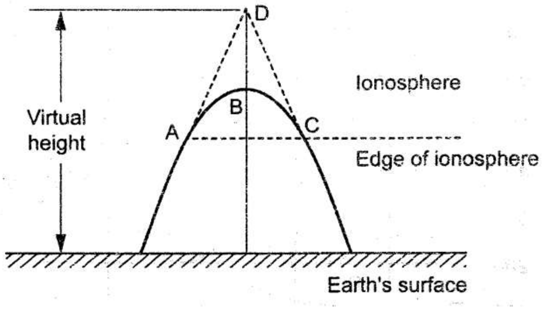


Fig. 5.13. Propagation path in the ionosphere and the depiction of virtual height

Let the wave enter the ionosphere at point A, and take a curved path ABC before it emerges out of the ionosphere.

If the incident and the reflected rays are extended, they meet at point D as shown inFig.5.19.

The vertical height from the earth's surface to the point D is known as the virtual height.

Measurement of Virtual Height

- ***Ionosonde*** is the instrument used to measure the virtual height of the ionosphere.
- This instrument transmits an RF pulse vertically into the ionosphere from the ground. This pulse reflected from the ionosphere is received by the ionosonde.
- The time delay between the transmit and the receive pulse is measured and plotted as a function of frequency of the electromagnetic wave. This time delay is a measure of the virtual height of the ionosphere.
- ***Ionogram*** is a plot of the virtual height as a function of frequency.

A typical ionogram for day time is shown in Fig.5.20.

As the frequency of EM wave increases, virtual height also increases. It means, high frequencies are returned from higher layers like F, and F_2.

As the frequency approaches the critical frequency, the virtual height steeply increases.

After reaching the critical frequency, the virtual height drops back to steady value.

Critical frequency for F_1 layer = 5 MHz

5.4.4. CRITICAL FREQUENCY (f_C)

It is defined as the highest frequency that will be reflected back to earth by a particular ionospheric layer at vertical incidence (θ_i, = 0).

It is also defined as the limiting frequency, because

If $f < f_C$,the wave is reflected for any angle of incidence.
and if $f > f_C$, the wave penetrates through the ionospheric layer.
In general, the refractive index $n = \sin\theta_i$ …………(5.64)

...

where θ_i = angle of incidence of the EM wave

We know $n = \sqrt{\varepsilon_r} = \sqrt{1 - \frac{81N}{f^2}}$ ……….(5.65)

Comparing equation(5.64) and (5.65)

$$\sin\theta_i = \sqrt{1 - \frac{81N}{f^2}} \quad \text{………..5.67}$$

When $\theta_i = 0, \quad N = N_{mzx} \;\; and\, f = f_C$

Therefore, equation(5.66)becomes $1 - \frac{81N_{max}}{f^2{}_C} = 0$

$$f_C = \sqrt{81N_{max}}$$

Therefore When an electromagnetic wave launched vertically into the ionosphere having a maximum electron density N, then the critical frequency is given by

$$\boxed{f_C = \sqrt{81N_{max}} = 9\sqrt{N_{ma}}}$$

Now, the condition for the wave to be reflected back is given by

$$\sin\theta_i > \sqrt{1 - \frac{81N_{max}}{f^2}}$$

But $$f_C = \sqrt{81N_{max}}$$

Therefore $$\sin\theta_i > \sqrt{1 - \left(\frac{f_C}{f}\right)^2}$$

The above equation gives the relation between the angle of incidence of the EM wave and the critical frequency.

5.4.5. MAXIMUM USABLE FREQUENCY (f_{MUF})

It is defined as the highest frequency of wave that is reflected by a particular ionospheric layer at an angle of incidence other than normal (vertical incidence). MUF depends on the time of a day, distance, direction, season and solar activity.

Consider that a communication is to be established between two points which are 400 km distance apart. For such shorter distance, the earth can be assumed to be flat r as shown in Fig.5.14.

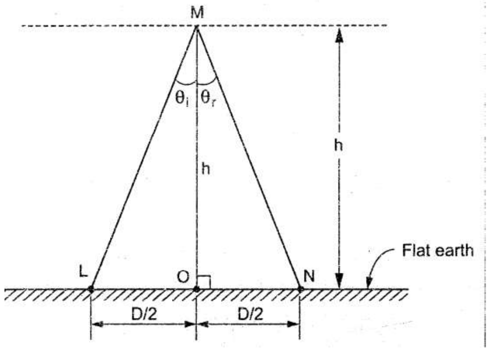


Fig 5.14. Reflection from a thin layer on the flat earth

Let D = distance between the transmitter and receiver

h=height of the ionospheric layer

considering Δ LOM in fig 5.14

$$\cos\theta_i = \frac{h}{LM} = \frac{h}{\sqrt{\left(\frac{D}{2}\right)^2 + h^2}} = \frac{2h}{\sqrt{D^2+4h^2}} \qquad \ldots\ldots..(5.69)$$

At angle of refraction $\theta_r = 90^0, f = f_{MUF}\ and\ N = N_{max}$

$$n = \sin\theta_i = \sqrt{1 - \frac{81N_{max}}{f^2{}_{MUF}}}$$

$$\sin^2\theta_i = 1 - \frac{81N_{max}}{f^2{}_{MUF}}$$

$$\cos^2\theta_i = \frac{81N_{max}}{f^2{}_{MUF}}$$

We know that $f_C = \sqrt{81N_{max}}$

Therefore $\cos^2\theta_i = \frac{f_C{}^2}{f^2{}_{MUF}}$

$$\boxed{\cos\theta_i = \frac{f_C}{f_{MUF}}} \qquad \ldots\ldots\ldots(5.70)$$

Comparing equations (5.69) and (5.70)

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

$$f_{MUF} = f_C\left[\frac{\sqrt{D^2+4h^2}}{2h}\right]$$

$$\boxed{f_{MUF} = f_C\sqrt{\left(\frac{D}{2h}\right)^2 + 1}} \qquad \text{………(5.71)}$$

Therefore

$$\boxed{f_{MUF} > f_C}$$

From equation (5.70),

$$\boxed{f_{MUF} = f_C \sec\theta_i} \qquad \text{…….. (5.72)}$$

Equation (5.72) is called **secant law** and it indicates the highest frequency to be used for the sky wave propagation for a given angle of incidence θ_i.

5.4.6. SKIP DISTANCE (D_{skip})

It is defined as the shortest distance from the transmitter that is covered by a fixed frequency. Let Q_m be the angle of incidence of a wave of frequency f_{MUF} which gets reflected from the ionosphere.

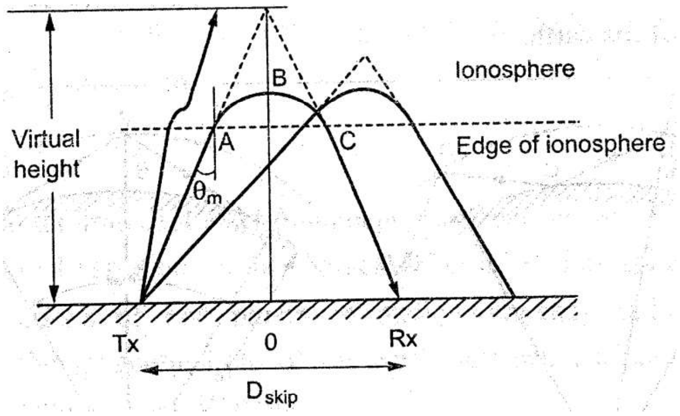


Fig 5.15 .Ray paths for different angles of incidence illustrating skip distance

In order to calculate the skip distance, let us assume the ionosphere to be a flat reflecting surface at a height ***'h'*** from the flat earth as shown in Fig.5.15.

Let θ_m = angle of incidence of a wave with frequency/$_{MUF}$
For $\theta_i > \theta_m$, the wave is reflected back by the ionosphere.
For $\theta_i < \theta_m$, the ionosphere cannot reflect the waves back.
For $\theta_i = \theta_m$,the wave return back to the earth at a distance of D_{skip} from the transmitter. This distance is known as skip distance.

For a given frequency,$f = f_{MUF}$, the skip distance can be calculated as

$$f_{MUF} = f_C\sqrt{\left(\frac{D_{skip}}{2h}\right)^2 + 1}$$

$$\left(\frac{f_{MUF}}{f_C}\right)^2 = 1 + \left(\frac{D_{skip}}{2h}\right)^2$$

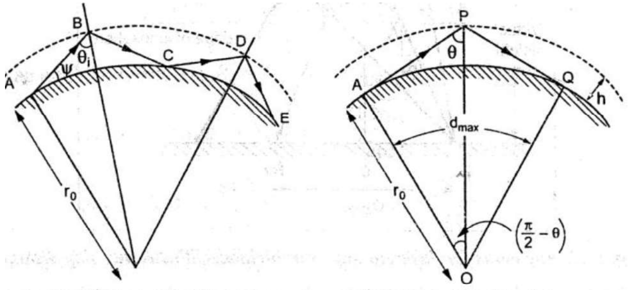
$$D_{skip} = 2h\sqrt{\left(\frac{f_{MUF}}{f_C}\right)^2 - 1} \qquad \text{……….(5.73)}$$

Therefore the transmission path is limited by the skip distance and curvature of the earth.

5.4.7. SKY WAVES – MULTIHOP PROPAGATION

Let us consider the transmit and receive antennas are located on the surface of the spherical earth.

The ionosphere is modeled as a spherical reflecting surface at a virtual height *h* from the surface of the earth.



(a) Multihop propagation (b) Maximum single hop distance

Fig. 5.16.

From Fig.5.16(a), a wave launched at a gracing angle Ψ from point A gets reflected by the ionosphere and reaches the surface of the earth at C.

If the earth is a good reflector, the wave can undergo multi-hops. Thus a communication link is established between the points A and E.

From Fig.5.16(b), a single hop is possible for $\Psi = 0$ or horizontal launch.

The incident angle at point P is given by

$$`\theta = \sin^{-1}\left(\frac{r_o}{r_o+h}\right)$$

The maximum single hop distance is

$$d_{max} = 2r_o\left(\frac{\pi}{2} - \theta\right)$$

For example, the reflection from the E layer with h=100 km, the angle of incidence is

$$\theta = \sin^{-1}\left(\frac{6370}{6470}\right) = 79.91^o = 1.395\, rad$$

The maximum single hop distance is

$$d_{max} = 2 \times 6370 \times \left(\frac{\pi}{2} - 1.395\right) = 2240\, km$$

Similarly, for F layer,

Virtual height = 300km, maximum angle of incidence is 72.75^o.

And $d_{\max} = 3836$ km

5.4.8 FADING AND DIVERSITY TECHNIQUES:

Fading is the change in signal strength at the receiver. Most of the receivers are designed with an automatic volume control (AVC) circuit which reduces the effect of fading if the change in signal strength is small . fading up to 20 dB is common.

The main causes of fading are

1. Variation in ionospheric conditions and
2. Multi path reception.

As the ionosphere is not stable and electron density changes, signal path changes and hence there will be a change in phase. This causes the received field strength to change.

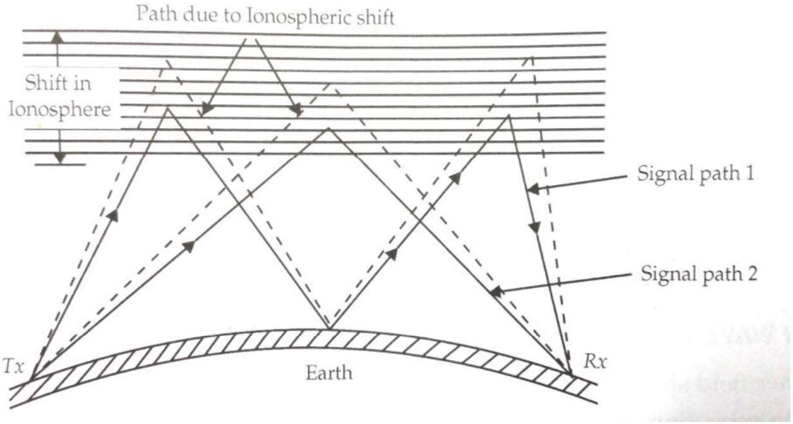


Fig 5.17:Fading

Fading is classified in terms of the duration of the variation in signal strength. They are:

1. **Rapid fluctuations :** These are due to multi path interference and they occur for a few seconds.
2. **Short –term fluctuations :** These are due to variation in the characteristics of the propagating medium and they occur for a few hours.
3. **Long –term fluctuations:** These are due to seasonal variations in the propagation medium and they occur for a few days.
   Fade out (total fading) occurs during sudden ionospheric disturbances, ionospheric storms, sun spot cycle and so on

Types of fading:

1. Selective fading
2. Interference fading
3. Absorption fading
4. Polarization fading
5. Skip fading

1. **Selective fading**
   - ✓ It produces serious distortion of modulated signal
   - ✓ It is more prominent at high frequencies at which sky-wave propagation is used.
   - ✓ It is large with AM signals at high percentage of modulation.
   - ✓ AM signals are more distorted by selective fading than SSB signals.
   - ✓ Selective fading can be reduced by the use of SSB system.

2. **Interference fading**

✓ It is produced by interference between rays.

✓ It is also produced by the interference between waves reaching the receiver by different paths.

✓ It is also produced by the interference between a ground wave and sky wave.

✓ It occurs due to fluctuations of layer height at a fixed frequency.

✓ As the path length of the wave varies, the relative phase of waves reaching the receiver also varies.

✓ Interference fading can be minimized by different diversity techniques.

3. **Absorption fading :**

This takes place due to absorption of waves by the ionosphere.

4. **Polarization fading:**

✓ This takes place do to change of polarization of EM wave.

✓ This is caused by cross-polarized waves.

✓ When polarization changes, the signal amplitude Changes in the receiver.

✓ This type of fading is reduced by polarization diversity.

5. **Skip fading:**

✓ This occurs near the skip distance.

✓ The variation of height of density of the layer causes skip fading.

✓ This is minimized by AVC and AGC in the receiver.

It is difficult to control short and long term fluctuations. But the fading due to rapid fluctuations can be reduced by different diversity techniques.

The diversity techniques are:

1. Frequency diversity
2. Space diversity
3. Polarity diversity
4. Time diversity

1. **Frequency diversity:** In this, the transmitter will send two or more frequencies simultaneously with the same modulating information. As the different frequencies will fade differently, one will always be strong. This scheme is shown in Figure

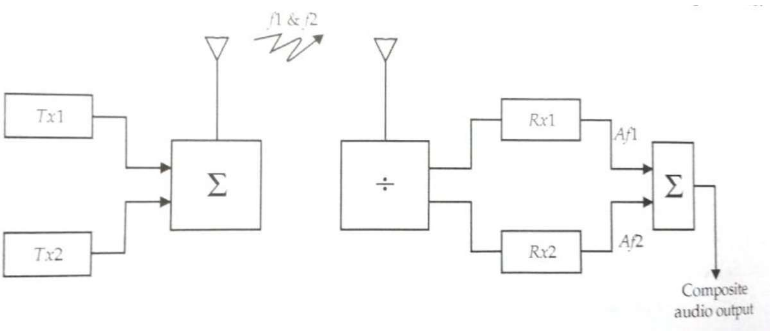


Fig 5.18 : Frequency diversity to reduce fading

2. **Space diversity technique**: A single transmitter frequency is used. At the receiving site, two or more receiving antennas spaced at one-half wavelength apart are used. The signal will fade at one antenna while it increases at the other antenna. A three antenna system may be used. Three separate but identical receivers tuned by the same master local oscillator are connected to three antennas. Audio mixing on the basis of the strongest signal keeps the audio output constant while RF signal fades. This scheme is shown in Figure

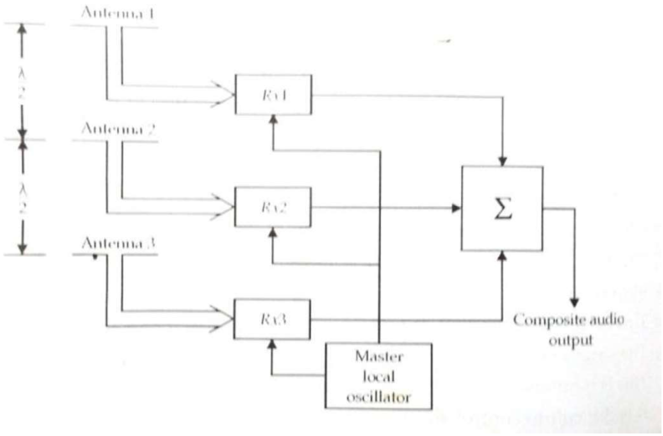


Fig 5.19: Space diversity

3. **Polarity diversity system**: In this, vertical and horizontal polarisation antennas are used to receive the signal. As in the case of space diversity system, the two receivers are combined to produce constant output. This scheme is shown in Figure

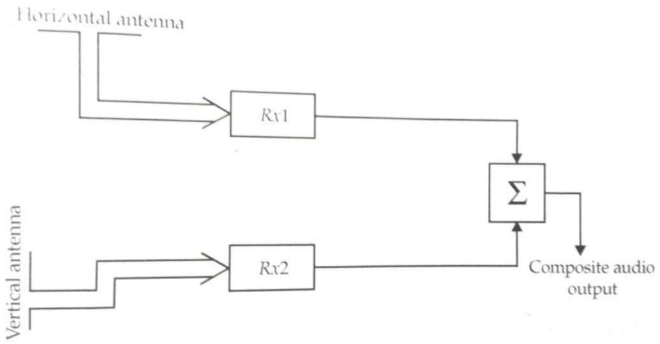


Fig 5.20: Polarity diversity

4. **Time diversity**: In this, the same signals are transmitted at different times. As fading is time-dependent, some signals may be strong and fading is less.

TWO MARK QUESTION

1. What are the various modes of radio wave propagation.

(i) Ground waVe propagation (or) Surface wave propagation.

(ii) Space wave propagation (or) tropospheric wave propagation.

(iii) Sky wave propagation (or) ionospheric propagation.

2. What are the main factors which influence the direction of propagation.

1. Earth characteristics in terms of conductivity, permittivity and permeability.

2. Frequency of operation.

3. Height and polarisation of the transmitting antenna.

4. Distance between the transmitter and receiver.

5. Type of earth like hilly terrain, forest, sea water (or) river water. I 6. Earth's magnetic field.

3. What is meant by ground wave propagation ?

The wave which propagate along the surface of the earth is called as ground wave propagation or surface wave propagation.