CHAPTER

18

Module 6

Ground and Space Wave Propagation

18.1 INTRODUCTION

In general any radio communication system consists of three parts.

1. Transmitter 2. Receiver
3. Media between these two.

When the current is passed through a radiating system at the transmitter side, the waves are generated and escape into the media between the transmitter and receiver. The radiating element is called as an **antenna**. The waves generated are known as electromagnetic waves.

These waves propagates into the media and the propagation is governed by the characteristic of the medium. The propagating waves reach the receiver where the receiving antenna receives it.

In this chapter the propagation in the media is to be discussed. The simplest type of media is the free space, which is discussed next.

18.2 FREE SPACE

Free space is a space that has following characteristics :

1) It does not interfere with the normal radiation and propagation of radio waves.
2) It has no magnetic or gravitational fields.
3) It has no solid bodies.
4) It has no ionised particles.

But the free space does not exist anywhere. However the propagation of waves can be very easily explained in the free space. Also many times the propagating conditions are approximately same as free space.

18.3 FUNDAMENTAL EQUATIONS FOR FREE SPACE PROPAGATION (FRISS FREE EQUATIONS)

Consider an isotropic source radiates a power P_T in free space. The power density at a distance 'd' from it where the receiver is placed is given by,

$$\text{Power density} = W_o = \frac{P_T}{4\pi d^2} \text{ (W/m}^2\text{)} \quad \text{...(18.3.1)}$$

Where 'W' letter is used for power density in Watts / m^2 and letter P for power in watts.

This expression is valid for isotropic source which radiates equally in all directions. But practical antennas are directional, radiating more in a particular direction and less in other directions.

The gain in radiation in maximum direction over isotropic antenna is called as directive gain, defined as

$$G_T = \frac{\text{Power density in the maximum direction of practical antenna } (W_D)}{\text{Power density due to isotropic antenna } (W_o)}$$

W_D stands for power density of a directional antenna and G_T for gain of the transmitting antenna . Thus

$$W_D = G_T W_o$$

Using Equation (18.3.1)

$$W_D = G_T \frac{P_T}{4\pi d^2} \quad \text{...(18.3.2)}$$

A receiving antenna having an effective area (or aperture) A_e can be positioned to collect maximum power from the wave. Then the power delivered by the antenna to the receiver is

$$P_R = W_D A_e = \frac{G_T P_T A_e}{4\pi d^2} \quad \text{...(18.3.3)}$$

For any antenna the maximum directive gain and effective area are related by

$$G = \frac{4\pi}{\lambda^2} A_e \quad \text{...(18.3.4)}$$

For receiving antenna with gain G_R

$$A_e = \frac{\lambda^2}{4\pi} G_R \quad \text{...(18.3.5)}$$

Using Equation (18.3.5) in (18.3.3),

$$P_R = \frac{G_T G_R P_T}{4\pi d^2}\left(\frac{\lambda^2}{4\pi}\right) \text{ Watts} \quad \text{...(18.3.6)}$$

or

$$\frac{P_R}{P_T} = G_T G_R \left(\frac{\lambda}{4\pi d}\right)^2 \quad \text{...(18.3.7)}$$

or

$$\frac{P_R}{P_T} = \frac{G_T G_R}{\left(\frac{4\pi d}{\lambda}\right)^2} \quad \text{...(18.3.8)}$$

This is the **fundamental equation for free space transmission.**

18.3.1 Transmission Path Loss

The term $(4\pi d/\lambda)^2$ is called as **spatial attenuation**, denoted by

$$L_S = \left(\frac{4\pi d}{\lambda}\right)^2 \quad \text{...(18.3.9)}$$

In decibels

$$10 \log\left(\frac{P_R}{P_T}\right) = 10 \log G_T + 10 \log G_R + 10 \log\left(\frac{\lambda}{4\pi d}\right)^2 \quad \text{...(18.3.10)}$$

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or $10 \log P_R = 10 \log P_T + 10 \log G_T + 10 \log G_R + 10 \log \left(\frac{\lambda}{4\pi d}\right)^2$ ...(18.3.11)

or $P_R(dB) = P_T(dB) + G_T(dB) + G_R(dB) - L_S(dB)$ ...(18.3.12)

where $-L_S(dB) = 10 \log \left(\frac{\lambda}{4\pi d}\right)^2 = 20 \log \left(\frac{\lambda}{4\pi d}\right)$ ...(18.3.13)

Using $\lambda = \frac{c}{f} = \frac{3 \times 10^8}{f} = \frac{300}{f(MHz)}$

Also if d is distance in kilometers then

$$-L_S(dB) = 20 \log \left(\frac{300}{4\pi f(MHz) \, d \times 10^3}\right)$$

$$= 20 \log \left(\frac{300}{4\pi \times 10^3}\right) - 20 \log f(MHz) - 20 \log d$$

$\therefore L_S(dB) = +32.44 + 20 \log f(MHz) + 20 \log d(km)$ ...(18.3.14)

It is called as **transmission path loss.**

18.3.2 Field Strength at the Receiving Antenna

Many times we require to obtain field at a distance d, it is done as follows :

Using Poynting theorem

$W_D = \bar{E} \times \bar{H}$ and knowing $\frac{E}{H} = \eta = 120\pi$ for free space

In scalar form, $W_D = E\left(\frac{E}{\eta}\right) = \frac{E^2}{\eta} (\text{Watt}/m^2)$

or $E = \sqrt{W_D \cdot \eta}$

$= \sqrt{\frac{G_T P_T}{4\pi d^2} \times 120\pi}$ using Equation (18.3.2)

or $E = \frac{\sqrt{30 G_T P_T}}{d} (V/m)$ ...(18.3.15)

This is the equation for **field strength at the receiving antenna,** for free space conditions.

For the receiving antenna with an effective length (l_e), the open circuit voltage in the antenna terminals is given by

$V_{oc} = E \, l_e$ ...(18.3.16)

Ex. 18.3.1 : In satellite communication system, the height of the satellite is 36,000 km above earth, and operated at 4000 MHz. The gain of the transmitting antenna is 20 dB and that of receiving antenna is 40 dB. Find

(i) the free space transmission loss,

(ii) the power received when the power transmitted is 200 W.

Assume free space conditions.

☑ **Soln. :**

Given : d = 36,000 km, f = 4000 MHz,

$G_T = 20$ dB, $G_R = 40$ dB

$P_T = 200 = 10 \log (200) = 23$ dB.

(a) Free space transmission loss

Using Equation

$L_s(dB) = 32.44 + 20 \log f(MHz) + 20 \log d(km)$

$= 32.44 + 20 \log (4000) + 20 \log (36,000)$

$= 195.61$ dB

(b) Power received

Using Equation

$P_R(dB) = P_T(dB) + G_T(dB) + G_R(dB) - L_s(dB)$

$= -112.60 (dB) = 10 \log (P_R)$

$\rightarrow P_R = 10^{-11.26} = 5.5 \times 10^{-12}$ W = 5.5 pW.

Ex. 18.3.2 : Find the open circuit voltage in a $\lambda/2$ dipole antenna when 20 W at 150 MHz is transmitted from another $\lambda/2$ dipole at a distance of 50 km from first dipole. The antennas are positioned for optimum transmission and reception and consider gain of $\lambda/2$ dipole is 1.64 and effective length is (λ/π).

☑ **Soln. :**

Given : $f = 150$ MHz $\rightarrow \lambda = \frac{c}{f} = \frac{3 \times 10^8}{150 \times 10^6} = 2$ m

Using Equation

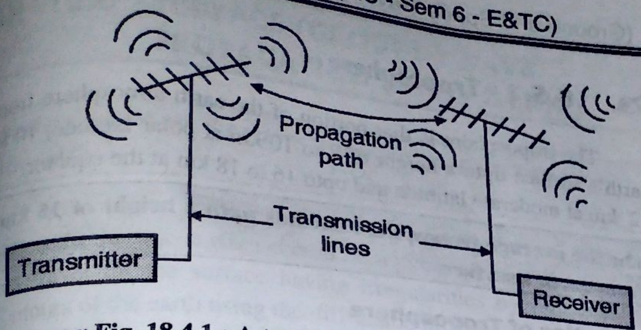
$E = \frac{\sqrt{30 G_T P_T}}{d} = \frac{\sqrt{30 \times 1.64 \times 20}}{50 \times 10^3} = 627.38 \, \mu V/m$

Using Equation

$V_{oc} = E \, l_e = (62.74 \times 10^{-3}) \times (\lambda/\pi) = 399.4 \, \mu V$

18.4 MODES OF PROPAGATION

A typical radio communication link used to communicate between the transmitting and receiving station is shown in Fig. 18.4.1. The link consists of transmitter, transmission lines, transmitting antenna, propagation path, receiving antenna, and receiver.



aw(2.6) **Fig. 18.4.1 : A typical radio communication link**

The transmitter generates a radio signal. The transmission line carries the signal from the transmitter to the transmitting antenna. The transmitting antenna sends the signal into space toward the receiving antenna.

The path in space the radio signal follows as it goes to the receiving antenna is the propagation path.

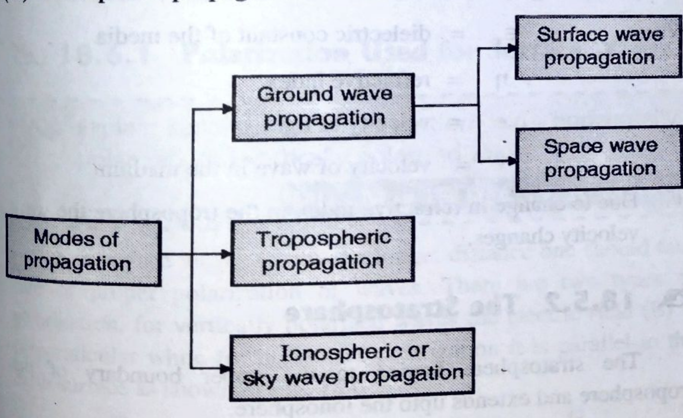
The receiving antenna intercepts or receives the signal and sends it though the transmission line to the receiver.

The wave radiated by a transmitting antenna may reach the receiving antenna over any of many possible propagation paths. The way of propagation also called as mode of propagation. There are three major propagation modes as shown in Fig. 18.4.2.

(i) Ground wave propagation

(ii) Tropospheric propagation

(iii) Ionospheric propagation



aw(2.7) **Fig. 18.4.2 : Modes of propagation**

18.4.1 Ground Wave Propagation

UQ. Write short note on : Ground wave propagation. **(MU - Q. 6(b), Dec. 19, 5 Marks)**

Ground waves are the waves propagating near to the earth surface.

Components of Ground Waves

Depending upon whether waves propagate along or over the earth surface, ground wave is further classified into,

(a) Surface wave (b) Space wave.

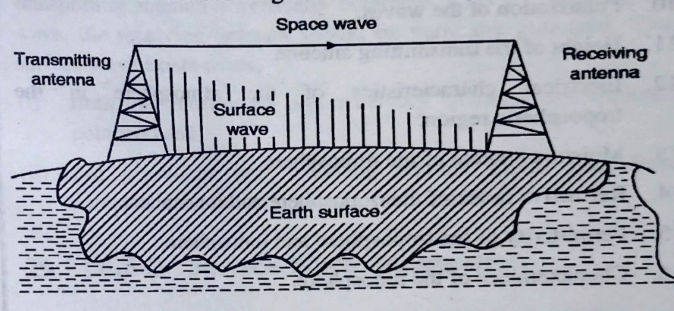
The classification of these two types of waves is very simple.

- **(a) Surface wave**

The surface wave is the wave which travels along the earth surface making all the time direct contact with the surface. Refer Fig. 18.4.3.

- **(b) Space wave**

The space wave is the wave which travels over the earth surface, taking direct path through air from the transmitting antenna to the receiving antenna. Refer Fig. 18.4.3.



aw(2.8) **Fig. 18.4.3 : Ground wave propagation**

18.4.2 Tropospheric Propagation

The troposphere is the region of the atmosphere within 16 km from the earth surface. Waves which reach the receiving antenna by reflection or scattering in the troposphere are termed as tropospheric waves. The propagation of these waves is named as tropospheric propagation.

18.4.3 Ionospheric or Sky Wave Propagation

The upper part of the atmosphere from 50 km to 400 km where ionization is largely present is called as ionosphere.

When the radio waves between transmitter and receiver take a path through ionosphere, the mode of propagation is called as ionospheric propagation.

In the ionospheric propagation, waves arrive at the receiving antenna after reflection or scattering in the ionosphere. The ionospheric propagation is also called as sky wave propagation.

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The factors that affect propagation over each of these modes will be considered in detail in next sections.

18.4.4 Factors Affecting Radio Wave Propagation

When an EM wave travel from the transmitter to the receiver, there are many factors that affect the propagation. These factors are

1. Obstacles between the transmitter and receiver.
2. Roughness of the earth.
3. Type of the earth like seawater, river water or forest.
4. Curvature of the earth.
5. Earth's characteristics (σ, ϵ and μ).
6. Earth's magnetic field.
7. The distance between the transmitter and receiver.
8. Power transmitted.
9. Frequency of operation.
10. Polarization of the waves.
11. Height of the transmitting antenna.
12. Electrical characteristics of the atmosphere in the tropospheric region.
13. Moisture content of the troposphere.
14. Refractive index of the troposphere and ionosphere.
15. Permittivity of the troposphere and ionosphere.
16. Characteristics of the ionosphere.

18.5 STRUCTURE OF ATMOSPHERE

In case of radio wave communication using transmitting and receiving antennas, waves which are transmitted travels through the surrounding media to reach receiving antenna. The medium between the transmitting and receiving antennas plays an important role in communication. Therefore, it is necessary to study the medium above earth through which radio wave propagate.

The atmosphere, which consists largely of oxygen (O_2) and nitrogen (N) gases is broken into three major regions.

Atmospheric regions

1. Troposphere
2. Stratosphere
3. Ionosphere.

18.5.1 Troposphere

The troposphere is that portion of the earth atmosphere from earth's surface upto a height of 8 to 10 km at polar latitude, 10 to 12 km at moderate latitude and upto 16 to 18 km at the equator.

On the average troposphere extends upto a height of 15 km from earth's surface.

Properties of Troposphere

(i) In the troposphere, the percentage of the gas components remains almost constant with increase of height.

(ii) The water vapour components sharply decreases with height.

(iii) The temperature decreases with increase of height at the rate of 6.5° per kilometer and reaches at about – 50°C at the upper boundary.

(iv) The region next higher to troposphere is the stratosphere, where the temperature almost remains constant to – 50°C.

(v) The dielectric constant of the atmosphere is slightly greater than unity at the earth's surface and decreases to unity at greater heights where air density approaches zero.

(vi) Thus, the troposphere is an inhomogeneous dielectric medium whose refractive index varies with height. The dielectric constant, refractive index and velocity of a wave are related using

$$\eta = \frac{c}{v} = \sqrt{\epsilon_r} \quad ...(18.5.1)$$

Where ϵ_r = dielectric constant of the media

η = refractive index

c = velocity of light

v = velocity of wave in the medium

(vii) Due to change in refractive index in the troposphere the wave velocity changes.

18.5.2 The Stratosphere

The stratosphere begins to the upper boundary of the troposphere and extends upto the ionosphere.

The stratosphere is called an **isothermal region** because the temperature in this region is somewhat constant to - 50°C irrespective of change in height.

18.5.3 The Ionosphere

The upper part of the atmosphere where the ionization (separation of positive and negative charges) is appreciable is known as ionosphere.

It is present from 50 to 400 km from earth surface.

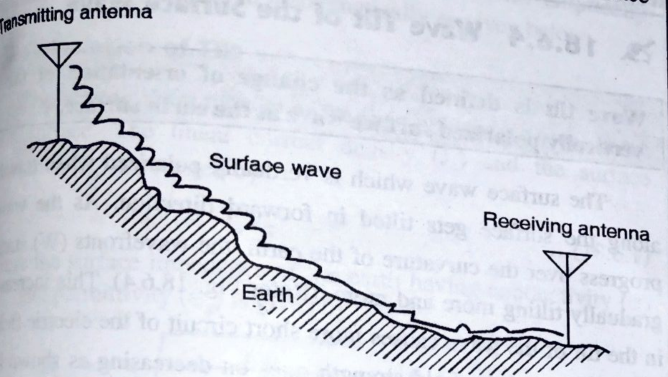
18.6 SURFACE (GROUND) WAVE PROPAGATION (UPTO 2 MHZ)

Surface waves are the waves travelling along the surface of the earth.

For surface waves to travel along the surface it is not necessary that the surface should be a plane surface. These waves can travel on the surface having irregularities by following the contours of the earth using the diffraction process.

In the diffraction process when a surface wave meets an object and the dimensions of the object do not exceed its wavelength, the wave tends to curve or bend around the object.

The smaller the object, the more pronounced the diffractive action will be. The surface waves travelling along the earth surface is shown in Fig. 18.6.1.

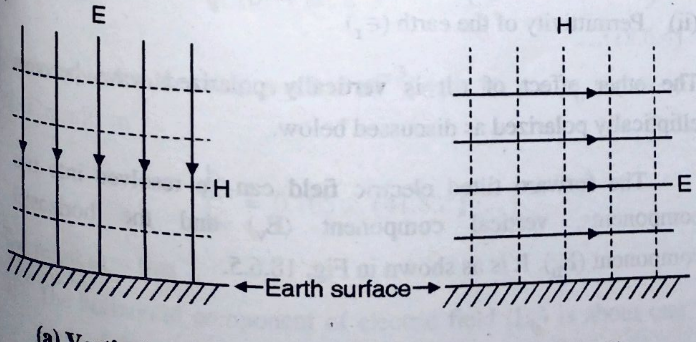


aw(2.11) **Fig. 18.6.1 : Surface wave propagation**

18.6.1 Polarization Used for Surface Waves

UQ. Explain plane earth reflection on horizontally polarized and vertically polarized wave.
(MU - May 15, Dec. 15, 10 Marks)

For surface waves to travel a longer distance one should take care of proper polarization of waves. There are two types of polarization, for vertically polarized waves the electric field (E) is perpendicular while for horizontal polarization it is parallel to the earth surface as shown in Fig. 18.6.2.



(a) Vertical polarization **(b) Horizontal polarization**

aw(2.12) **Fig. 18.6.2 : Polarization of the wave**

As the surface wave passes over the ground, the wave induces a voltage in the earth. The induced voltage takes energy away from the surface wave, resulting in weakening or attenuating the wave as it moves away. To reduce the attenuation the amount of induced voltage must be reduced.

For vertically polarized wave since the electric field is vertical, the extent to which electric field is in contact with the earth is minimized resulting in less attenuation.

When the surface wave is horizontally polarized, the electric field of the wave is parallel to the earth surface and is constantly in contact with it. The wave is then completely attenuated within a short distance from the transmitting antenna. For this reason,

Vertical polarization is very superior to horizontal polarization for surface wave propagation.

18.6.2 Requirement for Surface Wave Propagation

The vertically polarized wave is generated when the transmitting antenna is vertically polarized. Also for receiving this wave, the receiving antenna should be vertically polarized. Thus surface wave exists when,

(i) Both the transmitting and receiving antennas are vertically polarized and

(ii) For generating and receiving surface waves both these antennas must be very close to earth surface.

18.6.3 Surface Wave Attenuation

The surface wave travelling along the earth surface gets attenuated due to following reasons.

1) Ground losses

Any wave travelling in free space without making contact with conducting surface gets attenuated due to atmospheric absorption. Surface wave in addition to above loss also suffers ground losses. These losses are caused by ohmic resistive losses in the conductive earth, and to the dielectric properties of the earth. In other words, the signal heats up the ground.

Even though surface wave is vertically polarized, the earth offers electrical resistance to the electric field and returns currents to the following waves as shown in Fig. 18.6.3. The conductivity of the surface determines how much energy is returned. Thus the attenuation that a surface wave undergoes because of ground losses depends on the electrical properties of the terrain over which the wave travels. **The better the conductivity, the less the attenuation.** Table 18.6.1 gives the typical properties of various surfaces of the earth.

Fig. 18.6.3 also shows distortion of vertically polarized electric field due to lossy ground. Here original field (which is

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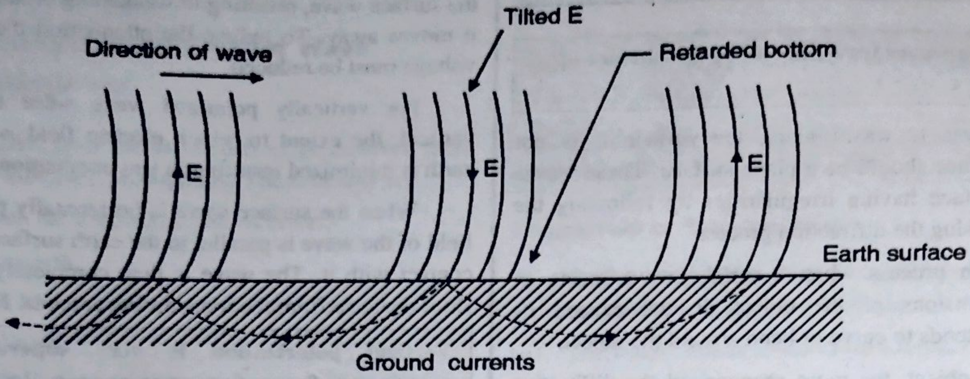
normal to the earth surface) gets tilted and wavefront's bottom tends to retard. The tilt angle is a function of frequency which increases with frequency. The effect of tilt is explained in the next section.



aw(2.13) **Fig. 18.6.3 : Effect of lossy ground**

Table 18.6.1 : Electrical properties of earth surfaces

Type of surface	Relative quality
Large body fresh water	Best
Ocean or sea water	Good
Rocky hills	Poor
Desert	Poor
Cities	Poor
Jungle	Very poor

2) Frequency effects

Another major factor in the attenuation of surface waves is frequency. The frequency and wavelength are related by

$$\lambda = \frac{v}{f}$$

This relation says that higher the frequency of a radio wave, shorter its wavelength will be.

In the previous discussion we studied that when the surface wave meets an object in the path, the wave gets diffracted provided that the object size do not exceed its wavelength.

At high frequencies (short wavelength) the waves are not normally diffracted but are absorbed by the earth at point relatively close to the transmitting site, resulting in loss by attenuation.

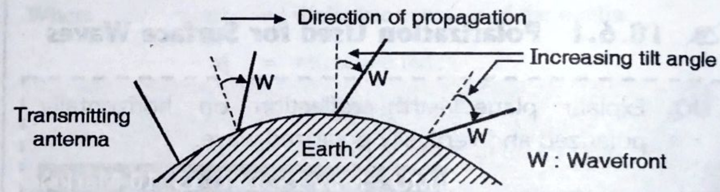
The surface wave is impractical for long distance transmissions at frequencies above 2 megahertz.

On the other hand, when the frequency of a surface wave is low enough, the diffraction is sufficient for propagation well beyond the horizon. Using very low frequency range and high transmitting power the surface wave can be propagated great distances. But this process is not effective at the mid frequency (MF) band (higher side) where attenuation is more.

18.6.4 Wave Tilt of the Surface Wave

Wave tilt is defined as the change of orientation of the vertically polarized surface wave at the earth surface.

The surface wave which is vertically polarized when travels along the surface gets tilted in forward direction. As the wave progress over the curvature of the earth, the wavefronts (W) starts gradually tilting more and more. (Refer Fig. 18.6.4). This increase in the tilt of the wave causes more short circuit of the electric field component and the field strength goes on decreasing as shown in Fig. 18.6.4.



aw(2.14) **Fig. 18.6.4 : Showing increase in tilt**

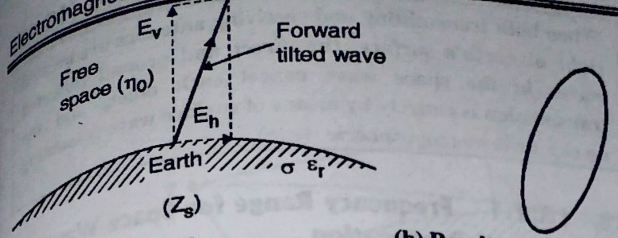
The magnitude of the tilt depends upon two factors,

(i) Conductivity of the earth (σ), and

(ii) Permittivity of the earth (ϵ_r).

The other effect of tilt is vertically polarized wave becomes elliptically polarized as discussed below.

The forward tilted electric field can be resolved into two components, vertical component (E_v) and the horizontal component (E_h). It is as shown in Fig. 18.6.5.



(a) Tilt of the wave (b) Resultant ellipse

aw(2.15) **Fig. 18.6.5**

The horizontal component of the field is responsible for power dissipation in the earth over which the wave is passing. In general, the vertical and horizontal components (E_v and E_h) are not in phase. Two perpendicular field vectors having some phase difference and unequal magnitudes, when combine results in a elliptically polarized wave. Thus the vertically polarized surface wave when travels along the earth surface becomes elliptically polarized. This can be proved mathematically as given below.

Calculation of Tilt

The horizontal component of the field induces a current in the earth surface. The linear current density (J_s) and the surface impedance (Z_s) are related by

$$E_h = J_s Z_s \quad ...(18.6.1)$$

Where the surface impedance of the earth having conductivity (σ) and permittivity ($\in_r$) is given by

$$Z_s \simeq \sqrt{\frac{\omega\mu}{(\sigma^2 + \omega^2 \in^2)^{1/2}}} \angle \left(\frac{1}{2}\tan^{-1}(\sigma/\omega\in)\right) \quad ...(18.6.2)$$

The vertical component of the electric field which is present in free space above the earth surface is given by

$$E_v = H\eta_0 \quad ...(18.6.3)$$

Where η_0 is the intrinsic impedance of the free space ($\simeq$ 377 Ω). Taking the ratio of E_h and E_v.

$$\frac{E_h}{E_v} = \frac{J_s(Z_s)}{H\eta_0} = \frac{Z_s}{\eta_0}$$

$$= \frac{1}{377}\sqrt{\frac{\omega\mu}{(\sigma^2 + \omega^2 \in^2)^{1/2}}} \angle \left(\frac{1}{2}\tan^{-1}(\sigma/\omega\in)\right) \quad ...(18.6.4)$$

For the typical values with $\sigma = 5 \times 10^{-3}$, $\in_r = 10$, $\mu = \mu_0$ and f = 1 MHz, results in

$$\frac{E_h}{E_v} = 0.105 \angle (41.83°)$$

This result says that

(i) The horizontal component of electric field (E_h) is about one tenth of the vertical component (E_v) and

(ii) E_h leads E_v by an angle of 41.83°.

When these fields are plotted at various instant of time, the locus of the end points of the resultant of E_h and E_v would be an ellipse. This is shown in Fig. 18.6.5(b).

18.6.5 Effect of Earth's Conductivity

> **UQ.** Explain plane earth reflection on horizontally polarized and vertically polarized wave.
> **(MU - May 15, Dec. 15, 5 Marks)**

- The wave propagation can be obtained by means of space wave propagation when the transmitting and the receiving antennas are elevated.
- The propagation is called as the line of sight propagation because the two antennas are within the site of each other. The resultant signal obtained is the combination of the space and surface wave.
- The direct and reflected waves will have the same amplitudes if the earth is considered to be a perfect conductor having infinite conductivity.
- If the surface of the earth is smooth and has finite conductivity, then the amplitude and phase of the reflected wave can be obtained using the concept of reflection at a perfect dielectric.
- If the surface of the earth is rough, then the reflected wave will be scattered. Their amplitude will reduce as compared to the amplitude of a smooth surface.
- The scattering of the reflected waves is obtained due to the **Rayleigh's criterion** which states that if the reflecting surface is rough, the reflection is similar to that of smooth surface provided the angle of incidence is large.
- It is given by,

$$R = \frac{4\pi\sigma \sin\phi}{\lambda} \quad ...(i)$$

Where R = Measure of roughness

σ = Standard deviation of surface irregularities from mean height

ϕ = Angle of incidence

λ = Wavelength.

- Depending on the value of R obtained the surface is smooth or rough. If the value of R is less than 0.1 then the surface is smooth whereas if the value of R is greater than 10 then the surface is a rough surface and leads to scattering of the reflected wave.

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- The Rayleigh's criterion states that if the angle of incidence is large then the rough surface is analogous to a smooth surface with angle of incidence ϕ approaching to the grazing angle.
- When the angle of incidence is approximately equal to grazing angle the reflection coefficient approaches to – 1.0 irrespective of the wave polarization.
- The earth is not a perfect conductor or a perfect dielectric. It posseses some conductivity. This factor must be taken into account while measuring the reflection of the waves from the earth's surface.

18.7 SPACE WAVE PROPAGATION (ABOVE 30 MHZ)

UQ. Describe the space wave propagation and derive relation for maximum distance between transmitting and receiving antenna. Earth is assumed to be flat. **(MU - May 16, 10 Marks)**

The space wave is the wave which travels over the earth surface. It is radiated many wavelengths above the surface.

The space wave follows two distinct paths from the transmitting antenna to the receiving antenna, as shown in Fig. 18.7.1.

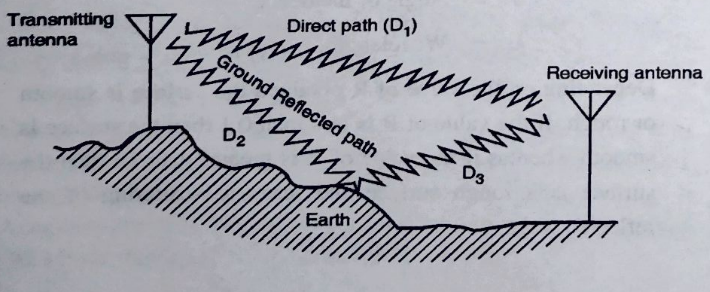
1) Direct space wave path

The primary path of the space wave is directly from the transmitting antenna to the receiving antenna. It is of length D_1.

2) Ground reflected space wave path

The ground reflected wave reaches the receiving antenna after being reflected from the earth's surface. The total path length of the ground reflected wave is $D_2 + D_3$.

These two waves when reach the receiving antenna the total field received by the receiving antenna is obtained by adding the two waves algebraically. Since the two signal paths have different lengths (i.e. D_1 is less than $D_2 + D_3$), the two signals will have some phase difference. Due to which addition of these two waves will either increase or decrease the received field strength.



aw(2.16) **Fig. 18.7.1 : Space wave propagation**

When both transmitting and receiving antennas are located right at earth's surface, the direct and ground reflected waves in the space wave cancel each other, and the transmission is entirely by means of surface wave (assuming no sky wave or tropospheric wave).

18.7.1 Frequency Range for Space Wave Propagation

The space wave propagation is mainly used at VHF (between 30 MHz to 300 MHz), UHF and microwaves, and used in televisions, radar, frequency modulators etc.

At such frequencies sky wave and surface wave propagation both fail.

Beyond 30 MHz sky wave fails as at such a high frequency the wavelength is too short to be reflected from the ionosphere. This will be seen in the next sections.

The surface wave propagation fails because at such a high frequency the waves along the earth surface are highly attenuated and can travel only a distance of few hundred feet after which it will totally die out.

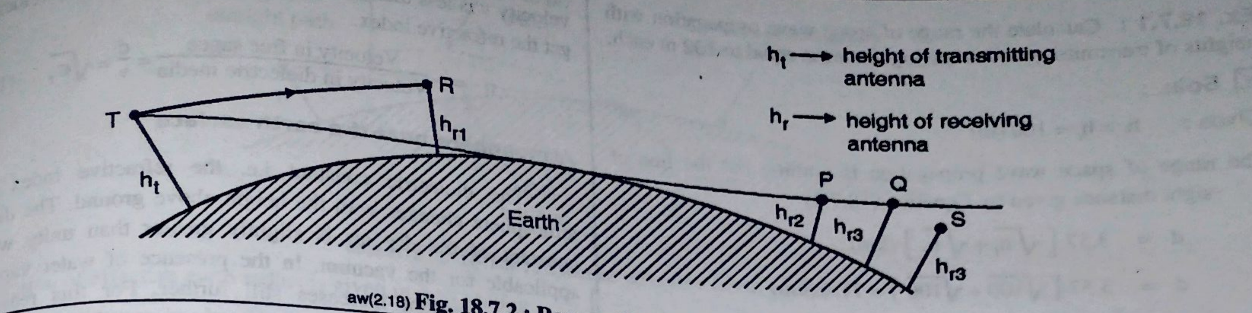
18.7.2 Line of Sight (LOS) Propagation

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

The space wave propagation is also called as line of sight propagation because the range of propagation is limited by the line of sight distance. It is also limited by the curvature of the earth.

The range of communication i.e. line of sight can be increased by increasing the heights of transmitting or receiving antenna or both as illustrated in Fig. 18.10.2. Note that the direct wave will reach the receiving antenna as long as the transmitting antenna can see the receiving antenna that is both are in the line of sight.

As shown in figure, with the height of the transmitting antenna h_t and receiving antenna h_{r1}, the direct wave communication range is TR. As the receiving antenna is moved away from R, the distance is reached (point P) when the line of sight distance from T and P will just graze over the surface of the earth. Then distance TP represents the maximum range of line of sight distance with the transmitting and receiving antennas of height h_t and h_{r2}. If this receiving antenna of height h_{r2} is moved further, it will not come in line of sight with the transmitter. Now the communication can be achieved either by increasing height h_t or h_{r2} or both. Let the height of the receiving antenna is increased to h_{r3}. Here the communication range is increased from TP to TQ. This receiving antenna of height h_{r3} if moved further away to point S, now it goes out of line of sight and then the signal reception is not possible.



aw(2.18) **Fig. 18.7.2 : Range of LOS communication**

18.7.3 Line of Sight Distance or Range of Space Wave Propagation

Line of sight is nothing but the distance covered by a direct space wave from the transmitting antenna to the receiving antenna.

To calculate this distance refer Fig. 18.7.3, where

h_t = height of the transmitting antenna

h_r = height of the receiving antenna

d = distance between transmitter and receiver

r = radius of the earth (= 6370 km = 3960 miles)

From triangle OAB,

$$d_1^2 + r^2 = (r + h_t)^2$$

or $$d_1^2 = (r + h_t)^2 - r^2 = 2r\,h_t + h_t^2$$

Since $2r\,h_t >> h_t^2$, the above expression reduces to

$$d_1^2 = 2\,r\,h_t$$

or $$d_1 = \sqrt{2r\,h_t}\ (m) \quad ...(18.7.1(a))$$

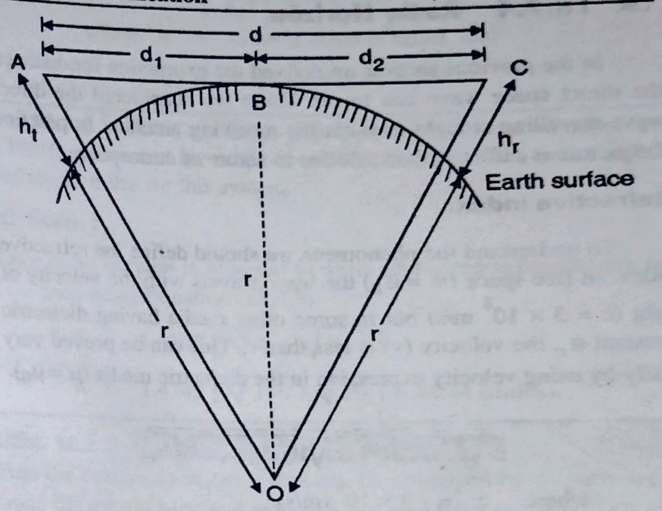
Similarly from triangle OBC, we get

$$d_2 = \sqrt{2r\,h_r}\ (m) \quad ...(18.7.1(b))$$

The line of sight distance is

$$d = d_1 + d_2 \quad ...(18.7.2)$$

Using Equations (18.7.1(a)) and (b) in Equation (18.7.2)



aw(2.19)**Fig. 18.7.3 : To calculate the line of sight distance**

$$d = \sqrt{2r\,h_t} + \sqrt{2r\,h_r} = \sqrt{2r}\,[\sqrt{h_t} + \sqrt{h_r}]\ (m) \quad ...(18.7.3)$$

Putting the value of radius of the earth

$$r = 6370\ km = 6370 \times 10^3\ (m)$$

$$d = \sqrt{2 \times 6370 \times 10^3}\,[\sqrt{h_t} + \sqrt{h_r}]$$

or $$d = 3.57\,[\sqrt{h_t} + \sqrt{h_r}]\ (km) \quad ...(18.7.4)$$

Note that in the above expression h_t and h_r are measured in meters.

From this equation we find that the line of sight range depends on :

(i) Height of the transmitting antenna (h_t)

(ii) Height of the receiving antenna (h_r)

(iii) Radius of the earth (r).

Thus the line of sight distance can be increased by increasing the heights h_t and h_r.

However space wave communication greater than 100 km is hardly used in commercial communication.

Ex. 18.7.1 : Calculate the range of space wave propagation with heights of transmitting and receiving antennas equal to 100 m each.

☑ Soln. :

Given : $h_t = h_r = 100$ (m)

The range of space wave propagation is nothing but the line of sight distance given by Equation (18.7.4)

$$d = 3.57\left[\sqrt{h_t}+\sqrt{h_r}\right] \text{ (km)}$$

$$d = 3.57\left[\sqrt{100}+\sqrt{100}\right] = 71.4 \text{ (km)}$$

18.7.4 Radio Horizon

In the previous section we derived the expression for distance the direct space wave can travel. There we considered the direct wave travelling straight towards the receiving antenna. In practice the picture is different than this due to nature of atmosphere.

Refractive index

To understand the phenomena we should define the refractive index. In free space ($\in = \in_0$) the wave travels with the velocity of light ($c = 3 \times 10^8$ m/s) but in some other media having dielectric constant $\in_r$, the velocity (v) is less than c. This can be proved very easily by using velocity expression in the dielectric media ($\mu = \mu_0$).

$$v = \frac{1}{\sqrt{\mu\in}} = \frac{1}{\sqrt{\mu_0 \in_0 \in_r}} = \frac{c}{\sqrt{\in_r}}$$

where $c = 3 \times 10^8$ (m/s)

Since $\in_r$ for the dielectric is always greater than one, we find velocity v is less than c. Taking the ratio of these two velocities we get the refractive index.

$$\eta = \frac{\text{Velocity in free sapce}}{\text{Velocity in dielectric media}} = \frac{c}{v} = \sqrt{\in_r} \quad ...(18.7.5)$$

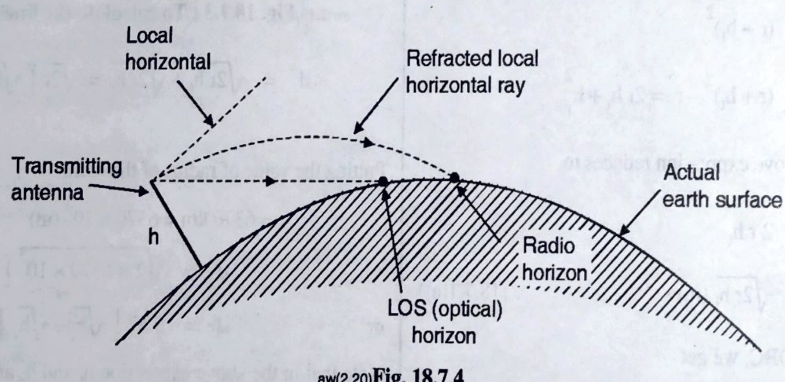
Atmosphere near the earth surface

The dielectric constant i.e. the refractive index of the atmosphere changes with the height above ground. The dielectric constant of the dry air is slightly greater than unity which is applicable for the vacuum. In the presence of water vapour the dielectric constant increases still further. For this reason, the dielectric constant of the atmosphere is greater than unity near the earth's surface, but decreases to unity at greater heights where the air density approaches to zero.

This decrease in refractive index with height causes refraction of radio waves passing through it, resulting in bending of waves from low refractive index to high refractive index i.e. towards the earth. This increases the communication range of direct space wave. This range is called as radio horizon. The straight line of sight distance is called as optical horizon. This is illustrated in Fig. 18.7.4.

Due to refraction, radio horizon is always greater than optical horizon. Radio horizon is about 15 percent further than optical horizon.

It is interesting to note that the ray that reaches the radio horizon is not the same ray that is directed at the LOS horizon, it leaves the source at a slightly greater elevation angle.

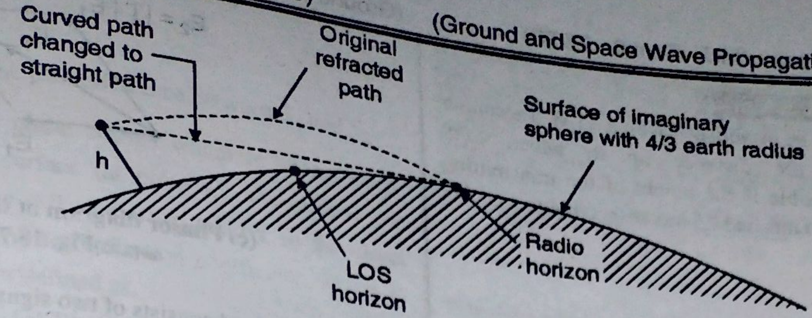


aw(2.20)**Fig. 18.7.4**

In order to obtain the radio horizon let us replace the earth surface with radius r (= 6370 km) by a new spherical surface with radius equal to Kr. The value of K is such that, the horizon appears at a point where a straight ray from the source intersects the new spherical surface. That is the curved path of refracted ray looks like a straight path upto radio horizon. For this to happen it is proved that the value of K must be 4/3, assuming the standard atmosphere at sea level. So for radio horizon calculations we consider the radius of earth to be 4/3 of actual radius. This new radius of sphere is called as effective earth radius (r_e). Refer Fig. 18.7.5.

$$\textbf{Effective earth radius, } r_e = \frac{4}{3} \times \textbf{Actual earth radius}$$

i.e.
$$r_e = \frac{4}{3} r \quad ...(18.7.6)$$



aw(2.21) **Fig. 18.7.5 : Effect of effective earth radius**

The derivation of effective earth radius is given in next section.

The LOS distance is already obtained in Equation (18.7.3). By replacing r in the expression by r_e we get a distance which is a radio horizon.

$$d = \sqrt{2 r_e}\left[\sqrt{h_t}+\sqrt{h_r}\right] \quad ...(18.7.7)$$

Replacing r_e using Equation (18.7.6),

$$d = \sqrt{2\times\frac{4}{3} r}\left[\sqrt{h_t}+\sqrt{h_r}\right]$$

Using the value of r = 6370 km

$$d = \sqrt{\frac{8\times 6370\times 10^3}{3}}\left[\sqrt{h_t}+\sqrt{h_r}\right]$$

$$= 4.12\left[\sqrt{h_t}+\sqrt{h_r}\right]\times 10^3 \text{ (m)}$$

$$= 4.12\left[\sqrt{h_t}+\sqrt{h_r}\right] \text{ (km)}$$

Radio horizon, $$d = 4.12\left[\sqrt{h_t}+\sqrt{h_r}\right] \text{ (km)} \quad ...(18.7.8)$$

where d = radio horizon in km

h_t, h_r = heights of transmitting and receiving antennas in meters

Radio horizon in miles

Sometimes h_t and h_r are given in feet and we require radio horizon in miles. In this situation we require to modify Equation (18.7.7) using r_e in miles and expressing h_t and h_r also in miles.

We have

$$r = 6370 \text{ km} = 3960 \text{ miles}$$

then

$$r_e = \frac{4}{3} r = \frac{4}{3}(3960)$$

Also

$$1 \text{ feet} = 1/5280 \text{ (miles)}$$

Using the values in Equation (18.7.7)

$$d = \sqrt{2\times\frac{4}{3}(3960)}\left[\sqrt{\frac{h_t}{5280}}+\sqrt{\frac{h_r}{5280}}\right]$$

$$= \sqrt{\frac{2\times 4\times 3960}{3\times 5280}}\left[\sqrt{h_t}+\sqrt{h_r}\right]$$

or

$$d = 1.4142\left[\sqrt{h_t}+\sqrt{h_r}\right] \text{ (miles)} \quad ...(18.7.9)$$

where d = radio horizon in miles and

h_t, h_r = antenna heights in feet.

Ex. 18.7.2 : Given a point-to-point link with one end mounted on a 100(ft) tower and the other on a 50(ft) tower, which is the radio horizon in miles for this system.

☑ **Soln. :**

Since radio horizon is required in miles and antenna heights are in feet, using Equation (18.7.9).

$$d = 1.4142\left[\sqrt{h_t}+\sqrt{h_r}\right]$$

$$d = 1.4142\left[\sqrt{100}+\sqrt{50}\right] = 24.14 \text{ (miles)}.$$

UEx. 18.7.3 **MU - Dec. 11, Dec. 17, 5 Marks**

Find the maximum distance that can be conveyed by a space wave when the transmitting and receiving antenna heights are 60 (m) and 6 (m) respectively. Assume standard atmosphere.

☑ **Soln. :**

Since the heights of the antenna are given in meters, using Equation (18.7.8).

$$d = 4.12\left[\sqrt{h_t}+\sqrt{h_r}\right] = 4.12\left[\sqrt{60}+\sqrt{6}\right]$$

$$d = 42.00 \text{ (km)}.$$

UEx. 18.7.4 **MU - Dec. 16, 5 Marks**

The receiving antenna is located at 80 km from the transmitting antenna. The height of the transmitting antenna is 100(m). Find the required height of the receiving antenna.

☑ **Soln. :**

The distance between the transmitting and receiving antenna is equal to 80 km. considering it as the radio horizon (in kilometers), using Equation (18.7.8).

$$d = 4.12\left[\sqrt{h_t}+\sqrt{h_r}\right]$$

i.e. $$80 = 4.12\left[\sqrt{100}+\sqrt{h_r}\right]$$

or $$\sqrt{h_r} = \frac{80}{4.12}-\sqrt{100} = 9.417$$

or $$h_r = 88.68 \text{ (m)}.$$

Module 6

UEx. 18.7.5 **MU - May 18, 5 Marks**

A VHF communication is to be established with a 35 W transmitter at 90 MHz. Determine the distance up to which LOS communication may be possible if the height of the transmitting and receiving antennae are 40 mts and 25 mts respectively.

☑ **Soln. :**

We have

$$d = 4.12\left[\sqrt{h_t}+\sqrt{h_r}\right] \text{ (km)}$$

$$d = 4.12\left[\sqrt{40}+\sqrt{25}\right] = 46.657 \text{ (km)}$$

18.7.5 Field Strength of Space or Tropospheric Wave

In the section we are interested in finding the field strength of a received space wave signal. By assuming earth surface is flat surface, this can be done very easily. The simplified picture is as shown in Fig. 18.7.6(a). In the Fig. 18.7.6,

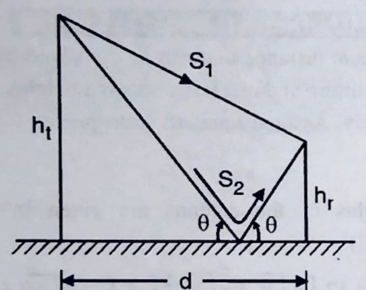
h_t = height of the transmitting antenna ;

h_r = height of the receiving antenna

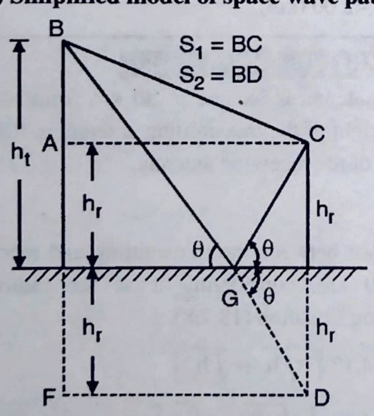
d = distance between two antennas ;

S_1 = directed path

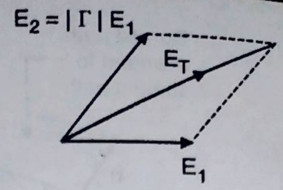
S_2 = reflected path



(a) Simplified model of space wave paths



(b) Geometry to find path difference
Fig. 18.7.6 Contd...



(c) Phasor diagram at the receiver
aw(2.23)**Fig. 18.7.6**

The signal received consists of two signals,

(i) direct path signal (S_1) (ii) reflected path signal (S_2)

In Fig. 18.7.6(b)

$$S_2 = BG + GC = BG + GD = BD \quad ...(18.7.10)$$

From triangle ABC,

$$BC^2 = AB^2 + AC^2$$

$$S_1^2 = (h_t - h_r)^2 + d^2 \quad ...(18.7.11)$$

From triangle FBD and using Equation (18.7.10),

$$BD^2 = (FB)^2 + (DF)^2$$

$$S_2^2 = (h_t + h_r)^2 + d^2 \quad ...(18.7.12)$$

Therefore

$$S_2^2 - S_1^2 = (h_t + h_r)^2 - (h_t - h_r)^2$$

$$S_2^2 - S_1^2 = 4\,h_t\,h_r \quad ...(18.7.13)$$

Applying the formula for the difference of two squares,

$$S_2^2 - S_1^2 = (S_2 + S_1)(S_2 - S_1) \quad ...(18.7.14)$$

The term $S_2 - S_1$ is nothing but path difference between two signals received. let

$$\Delta S = S_2 - S_1$$

Using it in Equation (18.7.14)

$$S_2^2 - S_1^2 = (S_2 + S_1)\,\Delta S \quad ...(18.7.15)$$

For most practical purposes with large d

$$S_1 \simeq S_2 \simeq d$$

$$\text{and} S_2 + S_1 \simeq 2d \quad ...(18.7.16)$$

Using Equations (18.7.13) and (18.7.16) in Equation (18.7.15)

$$4\,h_t\,h_r = (2d)\,\Delta S$$

$$\text{or} \quad \Delta S = \frac{2\,h_t\,h_r}{d} \quad ...(18.7.17)$$

Multiplying the path difference by phase constant ($\beta = 2\pi/\lambda$) we get the phase difference between the direct and reflected rays as

$$\alpha = \Delta S\left(\frac{2\pi}{\lambda}\right) = \frac{2\,h_t\,h_r}{d}\left(\frac{2\pi}{\lambda}\right)$$

or

$$\alpha = \frac{4\pi h_t h_r}{\lambda d} \quad ...(18.7.18)$$

Note that α is due to the path difference between S_1 and S_2.

This is not the only phase change which is taking place. Reflection at the earth's surface (at point G) also affects the amplitude and phase of the reflected wave relative to the direct wave. This is represented by the reflection coefficient, which in general is a complex number defined as,

$$\Gamma = \frac{\text{Reflected electric field}}{\text{Incident electric field}} = |\Gamma| \angle \beta \quad ...(18.7.19)$$

The incident electric field is nothing but that of direct waves at point G. the magnitude and angle of reflection coefficient is decided by properties of earth surface. Thus we write,

(i) Magnitude of reflected field = $|\Gamma| \times$ Magnitude of direct field

(ii) Phase of the reflected field = $\angle \beta$ + Phase of direct field

Now the phase angle α should be added with β to obtain total phase change of the received signal. Let the magnitude of direct field along S_1 be $|E_1|$. Then for second path S_2 it is $|\Gamma|\,|E_1|$. The phase angle of electric field along this path is

$$\theta = \alpha + \beta$$

The phase diagram showing electric fields along S_1 and S_2 is given in Fig. 18.7.6(c). The total electric field is

$$E_T = |E_1| e^{j0} + |\Gamma|\,|E_1| e^{j\theta} = |E_1| (1 + |\Gamma| e^{j\theta})$$

$$E_T = |E_1| \left[1 + |\Gamma| (\cos\theta + j \sin\theta) \right]$$

$$= |E_1| \left[(1 + |\Gamma| \cos\theta) + j\,|\Gamma| \sin\theta \right]$$

$$|E_T| = |E_1| \sqrt{(1 + |\Gamma| \cos\theta)^2 + (|\Gamma|^2 \sin^2\theta)}$$

$$= |E_1| \sqrt{1 + |\Gamma|^2 \cos^2\theta + 2|\Gamma| \cos\theta + |\Gamma|^2 \sin^2\theta}$$

$$= |E_1| \sqrt{1 + |\Gamma|^2 + 2|\Gamma| \cos\theta}$$

For the earth surface to be perfect conductor

$|\Gamma| = 1$ and $\beta = 180°$

$$|E_T| = |E_1| \sqrt{1 + 1^2 + 2(1)\cos\theta}$$

$$= |E_1| \sqrt{2 + 2\left[2\cos^2\left(\frac{\theta}{2}\right) - 1\right]} \quad \because \cos\theta = 2\cos^2\left(\frac{\theta}{2}\right) - 1$$

$$|E_T| = |E_1| \sqrt{4\cos^2\left(\frac{\theta}{2}\right)}$$

Putting $\beta = 180°$ $\theta = \alpha + 180°$

$$\cos\left(\frac{\theta}{2}\right) = \cos\left(\frac{\alpha + 180}{2}\right) = \cos\left(90 + \frac{\alpha}{2}\right) = -\sin\left(\frac{\alpha}{2}\right)$$

$$\therefore \quad |E_T| = |E_1| \sqrt{4\sin^2\left(\frac{\alpha}{2}\right)} = 2|E_1| \sin\left(\frac{\alpha}{2}\right)$$

Putting the value of α from Equation (18.7.18)

$$|E_T| = 2|E_1| \sin\left(\frac{4\pi h_t h_r}{2d\lambda}\right) = 2|E_1| \sin\left(\frac{2\pi h_t h_r}{d\lambda}\right) \quad ...(18.7.20)$$

When $d >> h_t, h_r \rightarrow \sin() \simeq ()$

$$|E_T| \simeq 2|E_1| \left(\frac{4\pi h_t h_r}{2d\lambda}\right)$$

or

$$|E_T| = |E_1| \left(\frac{4\pi h_t h_r}{d\lambda}\right) \quad ...(18.7.21)$$

In terms of transmitted power, the received signal strength is

$$|E_R| = \frac{88\sqrt{P}\, h_t h_r}{\lambda d^2} \quad ...(18.7.22)$$

From the expression we observe that the received field strength is

(i) Proportional to the height of the transmitting antenna.

(ii) Proportional to the height of the receiving antenna.

(iii) Inversely proportional to the square of the distance between them.

UEx. 18.7.6 MU - May 10, 10 Marks

A VHF communication is to be established with 35 W transmitter at 90 MHz. Find the distance upto which line of sight communication may be possible if the height of the transmitting and receiving antenna are 40 m and 25 m respectively. Also determine the field strength at the receiving end.

☑ **Soln. :**

Given : $P = 35$ watts, $h_t = 45$ m, $h_r = 25$ m, $f = 90$ MHz

$$\lambda = \frac{3 \times 10^8}{90 \times 10^6} = 3.33 \text{ (m)}$$

Using Equation (18.10.8)

$$d = 4.12 \left[\sqrt{h_t} + \sqrt{h_r}\right] \text{ km}$$

$$d = 4.12 \left[\sqrt{45} + \sqrt{25}\right] = 46.659 \text{ km}$$

Using Equation (18.10.34)

$$|E_R| = \frac{88\sqrt{P}\, h_t h_r}{\lambda d^2}$$

$$|E_R| = \frac{88\sqrt{35} \times 45 \times 25}{3.33 \times (46.66 \times 10^3)^2} = 80.79\ \mu\text{V/m}$$

Module 6

18.8 FACTORS AFFECTING FIELD STRENGTH OF THE SPACE WAVE SIGNAL

While deriving expression for field strength in the previous article we considered the ideal situation. In practice there are many factors which affects the field strength.

These are :

(i) Curvature of the earth.

(ii) Nature of the earth surface.

(iii) Obstacles in the path of the signal.

(iv) Height of the transmitting antenna.

(v) Transition between ground and space waves.

(vi) Polarization of the wave.

18.8.1 Effect of Earth Curvature

When the distance between transmitting and receiving antenna is small, the earth surface between these two can be consider to be plane in nature. But for larger distance the curvature of the earth plays an important role.

Effects are :

(i) The curvature of the earth prevents the wave from reaching the receiving point by a straight line path. These waves reaches the receiver by diffraction around the earth and refraction in the lower atmosphere above the earth. This problem can be solved by increasing heights of antennas so that both will be in the line of sight.

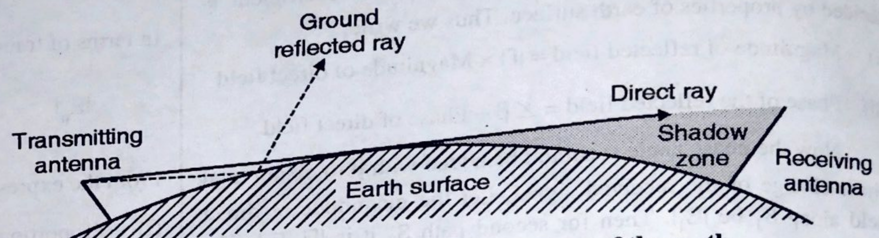


Fig. 18.8.1 : Effect of curvature of the earth

(ii) For the elevated antennas the space wave is affected in two different ways.

(a) The ground reflected wave is now reflected from a curved surface. Thus its energy is diverged more than in the case when it is reflected from a flat surface. This reduces the strength of the signal.

(b) For spherical earth the heights h_t' and h_r' of the transmitting and receiving antennas above the plane tangent to the surface of the earth at the point of reflection of the ground reflected wave are less than ht and hr above the surface of the earth as shown in Fig. 18.8.2.

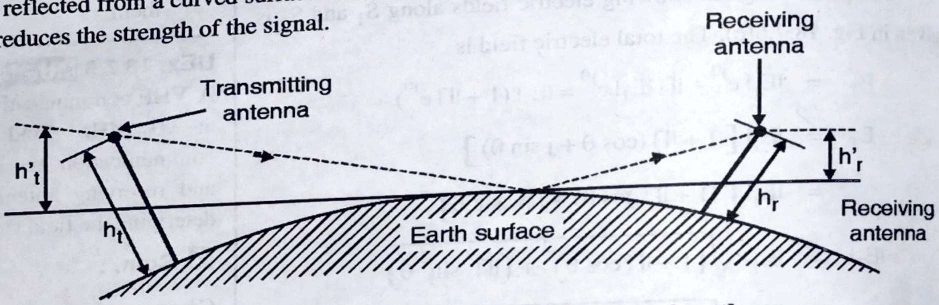


Fig. 18.8.2 : Effect of curvature of earth

The field strength of the received signal in this case is obtained by replacing ht and hr by h_t' and h_r'.

(iii) As shown in Fig. 18.11.1, a shadow zone is created on the receiver side where no signal reaches.

18.8.2 Effect of Nature of Earth Surface

In the analysis of field strength we considered earth's surface as a ideal reflector. For this case the incident and reflected waves are equal in magnitude and 180° out of phase.

But earth is basically imperfect and electrically rough. It results in

(i) The amplitude of the reflected wave is less than incident wave and

(ii) The phase change is different than 180°.

The net result is field strength of the received signal is reduced due to earth's imperfection and roughness.

18.8.3 Effect of Obstacles in the Path of the Signal

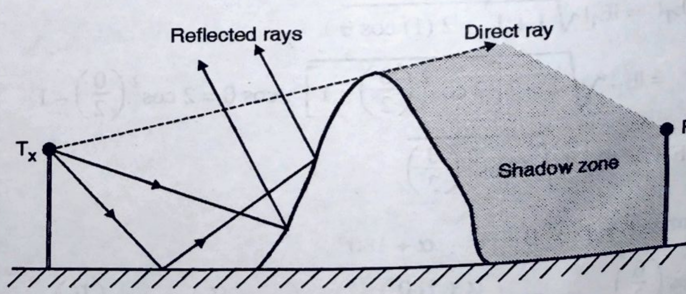


Fig. 18.8.3 : Effect of Obstacle on Space Waves

The ideal situation for receiving the signal is with no obstacle between the transmitter and receiver which interferes the transmitted wave.

Again this is a ideal situation. In practice obstacles like tall building, hills and other objects cannot be avoided. They produce shadow zone on the receiver side, reducing the distance of communication.

18.8.4 Effect of Height of the Transmitting Antenna

The field strength of the received signal varies with height as shown in Fig. 18.8.4. The variation consists of maximas and minimas, which depends also on frequency ground characteristics and polarization of the wave.

The plot gives variation of field with height for perfect earth, actual earth and free space conditions.

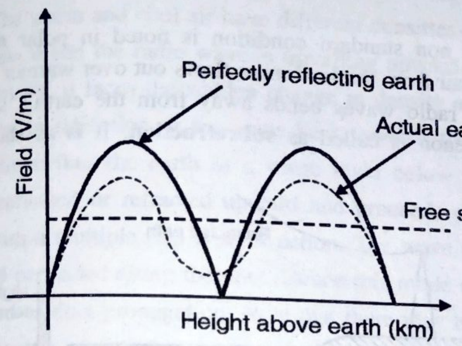


Fig. 18.8.4 : Effect of height on field strength

18.8.5 Effect of Transition between Ground and Space Waves

When the transmitting antenna is close to earth, ground waves are generated.

But when the height of the antenna is increased ground waves still exist but the field of direct and reflected waves (i.e. space waves) dominates the ground waves. This effect also depends on frequency, polarization and the nature of the earth.

For vertically polarized wave at heights greater than λ or 2λ space wave completely dominates ground wave.

For horizontally polarized wave the transition from space wave to ground wave takes place at heights less than $\lambda / 10$.

18.8.6 Effect of Polarization

(i) One of the component of the space wave which is the ground reflected wave, its magnitude is affected by the polarization used. The vertically polarized wave will have less magnitude as compared to horizontal polarized wave.

(ii) The height of antenna below which ground wave dominates space wave is much less with horizontal polarization than with vertical polarization.

(iii) The man made noise for example noise due to ignition systems, electrical and electronic equipments is generally vertically polarized. This noise affects the vertically polarized transmitted signal. Instead if horizontal polarization is used for transmission, effect of the noise is separated.

18.9 TROPOSPHERIC PROPAGATION (ABOVE 300 MHZ)

The tropospheric is a region of the atmosphere adjacent to the earth, extending upto about 16 kilometers.

Since the region adjacent to earth's surface is included in the troposphere, the waves (surface and space) which are adjacent to the earth's surface, are sometimes grouped into tropospheric waves. Because of which some older texts group tropospheric with ground wave (surface and space wave), but modern practice requires separate treatment. The older grouping overlooks certain common propagation phenomena that simply don't happen with space or surface waves.

18.9.1 Mechanisms of Tropospheric Propagation

The wave propagation beyond the line-of-sight is possible using this mode of propagation. The several mechanisms responsible are classified as

(i) Diffraction (ii) Normal refraction

(iii) Abnormal reflection and refraction, and

(iv) Tropospheric scatter.

The diffraction process and the normal refraction are already discussed with reference to surface wave and space wave respectively. The other mechanisms like abnormal reflection and refraction, also tropospheric scatter which was not observed with surface and space wave is discussed below.

18.10 STANDARD AND NON STANDARD ATMOSPHERE

Different mechanisms in the tropospheric propagation are due to non-standard atmospheric conditions. In order to understand non-standard atmosphere, let us first see what is standard atmosphere.

18.10.1 Standard Atmosphere

The standard dry atmosphere is having temperature decreasing with height at the rate of 6.5° per kilometer and reaches at about – 50°C at the upper boundary. The region next higher to troposphere is the stratosphere, where the temperature almost remains constant to – 50°C.

Thus under standard atmospheric conditions, the warmest air is found near the surface of the earth. The air gradually becomes cooler as height increases. In this situation simple refraction is observed as in case of space waves.

18.10.2 Non-standard Atmosphere

Inside the troposphere the atmosphere has a dielectric constant slightly greater than unity at the earth's surface where the density is most dense and this decreases to unity at great heights where the air density approaches zero.

The dielectric constant of dry air is slightly greater than unity but the presence of water vapour increases the dielectric constant still further. Thus the water content of the atmosphere has much more effect than temperature in deciding the dielectric constant of the atmosphere.

The moist standard atmosphere is specified as one which has a water vapour pressure of 10 millibars at sea level, which decreases with height at the rate of 1 millibar per thousand feet, upto 10,000 feet. If the temperature or water content differs from the standard conditions, then the **non-standard propagation** will result, where simple refraction does not occur.

The non-standard atmosphere especially play very important role in tropospheric propagation.

These effects are :

i) Super refraction ii) Sub-refraction

iii) Duct propagation iv) Tropospheric scatter

18.11 SUPER AND SUB-REFRACTION

18.11.1 Super Refraction

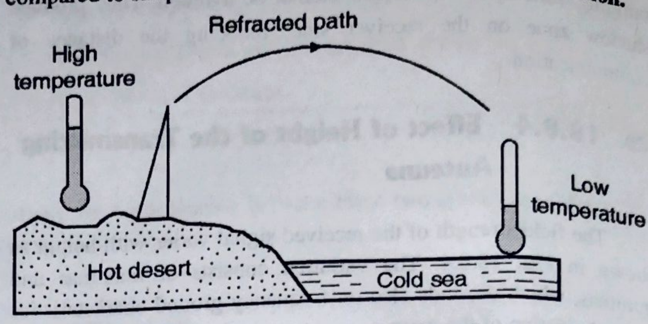
UQ. Explain super refraction. **(MU - Dec. 15, Dec. 16, 5 Marks)**

UQ. Explain super refraction and sub-refraction. **(MU - Dec. 17, 5 Marks)**

UQ. Explain the term super refraction with a neat labeled diagram. **(MU - May 18, 5 Marks)**

For example, in areas of the world where warmed air goes out over a cooler sea, the lower region of the atmosphere is cool while the upper region is warm. Examples of such areas have deserts that are adjacent to large body of water : the Gulf of Aden, the southern Mediterranean etc.

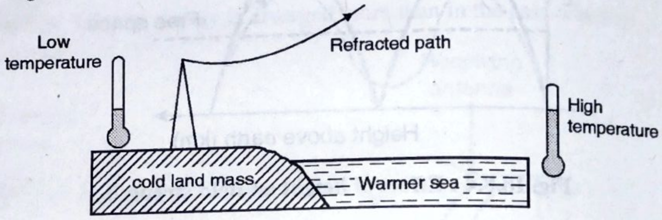
Refer Fig. 18.11.1. This is not a standard atmosphere. Here the propagation is via refraction but the curvature is more as compared to simple refraction, so it is called as **superrefraction.**



aw(2.24)**Fig. 18.11.1 : Superrefraction phenomena**

18.11.2 Subrefraction

Another non standard condition is noted in polar regions, where colder air from the land mass flows out over warmer sea. In this situation radio waves bends away from the earth's surface. This phenomenon is called as **subrefraction.** It is as shown in Fig. 18.11.2.



aw(2.25)**Fig. 18.11.2 : Subrefraction phenomena**

18.12 DUCT PROPAGATION

UQ. Explain ducting effect. Under what conditions this effect takes place. **(MU - May 16, Dec. 16, May 17, Dec. 17, May 18, 5 Marks)**

UQ. Explain the formation of inversion layer in troposphere. **(MU - Dec. 16, May 17, 5 Marks)**

In the duct propagation radio signal follows a particular channel or duct in the atmosphere. This duct can be near to the earth surface or elevated.

18.12.1 Inversion Layer

Inversion layer is a region where atmospheric conditions are exactly opposite to that of standard atmosphere.

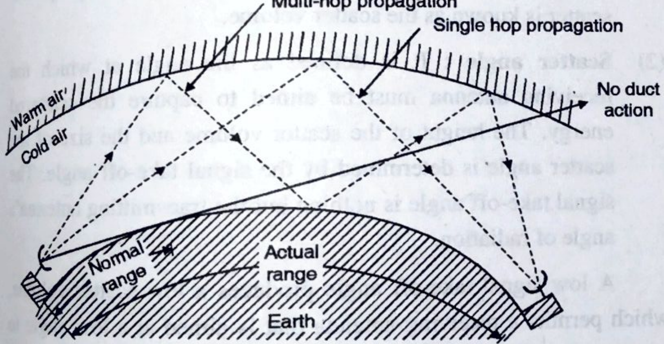
18.12.2 Formation of Duct and it's Effect

When the temperature increases with height over a certain range of heights, it is known as temperature inversion.

When inversion layer is sandwitched between the earth surface and standard atmosphere, then the cool air is trapped between the earth surface and the warm air. The region of cool air behaves like a **channel or duct** for radio waves.

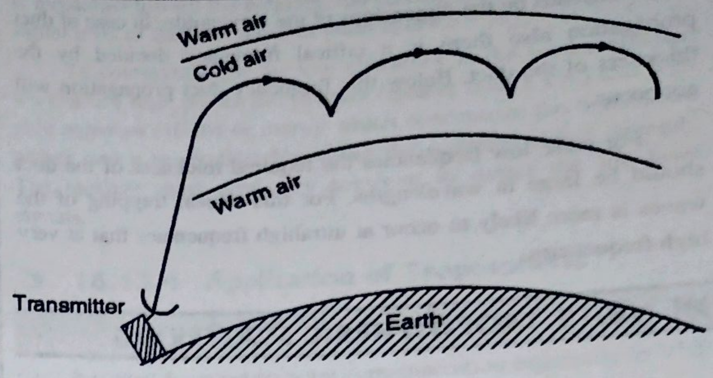
There is elevated inversion layer is present, in such a case the cool air is trapped between the warm air above and below it.

The warm and cool air have different densities and refractive qualities. When the radio wave is travelling upward from cool air to warm air, it faces the sudden change in density above the duct resulting in reflection of the wave back towards the earth. When the radio strikes the earth or a warm layer below the duct, it is again reflected or refracted upward and proceeds on through the duct with a multiple hop type of action. The wave now is said to trapped or guided along the duct. Hence this mode of propagation is called as duct propagation. Note that there may be surface duct or elevated duct, the propagation through it is shown in Fig. 18.12.1.



(a) Surface duct propagation

Fig. 18.12.1 Contd...



(b) Elevated duct propagation

aw(2.27b)**Fig. 18.12.1 : Duct propagation**

18.12.3 Condition for Duct Propagation

UQ. Explain formation of duct and condition for duct propagation. **(MU - Dec 17, 5 Marks)**

For the duct propagation to occur the condition is,

(i) The transmitting antenna is inside the duct or

(ii) The radio wave enters the duct at a very low angle of incidence.

If the angle of the wave with horizontal is small then only the wave is trapped in the duct. Otherwise for large angles, instead of wave getting reflected from warm air region, wave enters into it. This angle condition must be satisfied even if the transmitting antenna is inside the duct.

If the receiving antenna is elevated to within the duct, the received signal may be very large. However, if the receiving antenna is outside the duct, either below or above it, the received signal is very small.

When duct conditions are satisfied, VHF and UHF transmissions are possible far beyond normal line-of-sight distances. The range is typically several hundred kilometers.

18.12.4 Duct Propagation at Microwave Frequencies

In the previous article we studied formation of duct and propagation using it. This propagation is not possible at all frequencies.

Duct propagation is similar to propagation in the waveguide. In the waveguide propagation there is a certain critical frequency

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which depends on the dimensions of the waveguide. In case of duct propagation also there is a critical frequency decided by the thickness of the duct. Below this frequency duct propagation will not occur.

For these low frequencies the required thickness of the duct should be large in wavelengths. For this reason trapping of the waves is more likely to occur at ultrahigh frequencies that at very high frequencies.

18.13 TROPOSPHERIC SCATTERING

It is possible to communicate over long distances by means of tropospheric scatter. This phenomenon is due to irregularities in the atmosphere.

18.13.1 Atmospheric Blobs or Turbulences

At altitudes of a few kilometers, the air mass have varying temperature, pressure, and moisture content. Small fluctuations in tropospheric characteristics at high altitude create blobs, also called as turbulence. Within a blob, the temperature, pressure, and humidity are different from the surrounding air if the difference is large enough, it may modify the refractive index at VHF and UHF. A random distribution of these **blobs** exists at various heights at all times. These inhomogeneities in the refractive index of the atmosphere are responsible for the scattering phenomena.

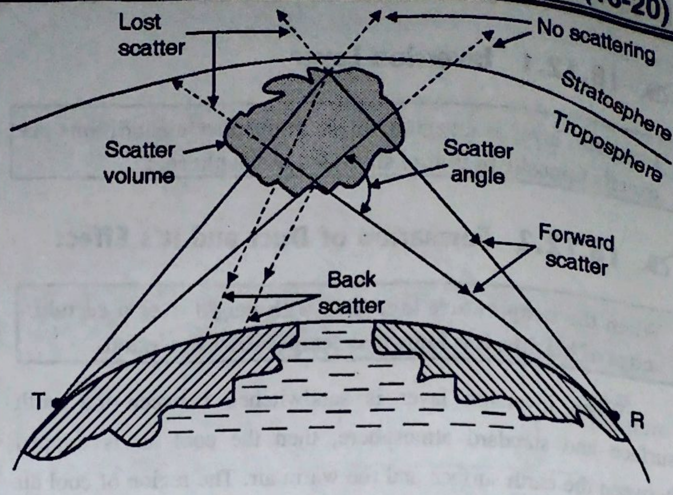
18.13.2 Scattering Phenomena

Consider a radio wave is transmitted into the troposphere. This radio wave when meets the turbulence in the troposphere, the velocity of the wave is changed. This causes a small amount of energy to be scattered. The phenomenon is repeated as the radio wave meets other turbulences in its path. The scattered rays in the direction of receiving antenna will be responsible for communication beyond the horizon.

The turbulence that causes the scattering can be visualized as a relay station located above the horizon. It receives the transmitted energy and reradiates it in the forward direction to some point beyond the line of sight distance.

The magnitude of the received signal depends on the number of turbulences causing scatter in the desired direction and the gain of the receiving antenna.

Fig. 18.13.1 shows the mechanism for scatter propagation. There are at least three modes of scatter.



aw(2.28)**Fig. 18.13.1 : Tropospheric scatter**

(i) **Backscatter :** The backscatter mode is a bit like radar, in that the signal is returned back to the transmitter site, or to regions close to the transmitter.

(ii) **Forward scatter :** This mode of scattering is responsible for receiving the wave at the receiver. The energy of the forward scattered signal is very small as compared to the energy of the signal incident on the turbulence.

(iii) **Side scatter :** Side scatter is similar to back and forward scatter, but the scattered rays are not directed towards either antenna. This scatter is considered to be a lost scatter.

As far as scattering is concerned there are two important terms related to it. Refer Fig. 18.13.1.

(1) **Scatter volume :** The scatter area used for tropospheric scatter is known as the scatter volume.

(2) **Scatter angle :** It is defined as the angle at which the receiving antenna must be aimed to capture the scattered energy. The height of the scatter volume and the size of the scatter angle is determined by the signal take-off angle. The signal take-off angle is nothing but the transmitting antenna's angle of radiation.

A low signal take-off angle produces a low scatter volume, which permits a receiving antenna that is aimed at a low angle to scatter volume for capturing the scattered energy.

As the signal take-off angle is increased, the height of the scatter volume is increased. When this occurs, the amount of received energy decreases. There are two reasons :

(i) As the height of the scatter volume increases, the amount of turbulence decreases, causing less scattered energy.

(ii) When the height of the scatter volume increases, the transmitted ray has to travel more distance to reach the receiver, causing more attenuation.

The tropospheric region that contributes most strongly to tropospheric scatter propagation lies near the midpoint between the transmitting and receiving antennas and just above the radio horizon of the antennas.

18.13.3 Fading due to Tropospheric Scatter

UQ. Explain tropospheric fading. **(MU - Dec. 15, 5 Marks)**

The tropospheric scatter propagation is subject to two forms of fading.

(i) **Slow fading :** The signal received by the receiving antenna using tropospheric scatter depends on the turbulence in the atmosphere. Thus changes in the atmospheric conditions have an effect on the strength of the received signal. The atmospheric variation is present both daily and seasonal. The fading due to this is very much slower.

(ii) **Fast fading :** This second type of fading is due multipath propagation. Note that the scattering is not at a point but from a scattering volume, so that several paths for propagation exist within the scatter volume. Since the turbulent condition is constantly changing, the path lengths and individual signal levels are also changing signal levels are also changing, resulting in a rapidly changing signal. In the worst case it may change several times per minute. That is why, this fading is referred as fast fading. It is often called as Rayleigh fading.

Another characteristic of a tropospheric scattered signal is its relatively low power level. Since very little of the scattered energy is reradiated toward the receiver, the efficiency is very low and the signal level of the final receiver point is low.

To compensate for the low efficiency in the scatter volume, we can use high power transmitters (greater than 1 kW) and high gain antennas (10 dB or more), which concentrate the transmitted power into a beam, thus increasing the scattered signal strength. The receiver must also very sensitive to detect the low-level signals.

18.13.4 Application of Tropospheric Scattering

(i) It is used for point-to-point communication especially in VHF and UHF band.

(ii) A properly designed tropospheric scatter circuit will provide highly reliable service for distances upto few hundred kilometers.

(iii) Tropospheric scatter systems may be particularly useful for communications to locations in rugged terrain that are difficult to reach with other methods of propagation. One reason for this is that the tropospheric scatter circuit is not affected by ionospheric and auroral disturbances.

(iv) One reason for scattering we have studied is blobs in the atmosphere. Another theory says that the rays are received from troposphere due to uncorrelated reflections from many layers of limited extent and arbitrary aspect.

Either way, this is a permanent state of affairs, not a sporadic phenomenon.

Chapter Ends...

□□□

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CHAPTER 19

Sky Wave Propagation

19.1 INTRODUCTION

When the radio signals are transmitted high in the atmosphere we expect them to enter into the atmosphere and will be lost. But surprisingly these waves are returned back to earth.

As such there is no surprise in it, it is due to refraction phenomenon which causes bending of waves, making them return back to earth.

Who is responsible for refraction and how they are refracted is studied in this chapter. First let us understand the process of ionization and recombination.

19.1.1 Ionization

If you consider a gas atom, it is electrically neutral since it contains both a positive proton in its nucleus and negatively charged electrons in its orbits.

When the gas is kept under very low pressure, by applying external energy it is possible to knock off one or two electrons from its parent atom.

When the negative electron is knocked free from the atom, the atom becomes positively charged called as positive ion, and remains in space along with the free electron.

Thus the electrically neutral atom is separated into positively charged ion and electrons.

The process of upsetting electrical neutrality of the atom is known as ionization.

19.1.2 Recombination

The reverse process of ionization is called recombination.

After ionization, the ions, electrons and atoms in a gas are constantly in motion, so frequent collisions occur between them. When the free electrons collide with positive ion, the positive ion returns to their original neutral atom state. This process is called as recombination.

19.2 STRUCTURE OF IONOSPHERE

UQ. What is ionosphere ? **(MU - Dec. 15, Dec. 16, Dec. 17, 2 Marks)**

The upper part of the atmosphere where the ionization is appreciable is known as ionosphere.

The upper part of the atmosphere is having low pressure favorable for the ionization process provided that external energy is available for knocking off the electrons. This energy comes from sun rays.

The upper part of the earth's atmosphere absorb large quantities of radiant energy from the sun. This not only heats the atmosphere but also produces ionizations.

The most important ionizing agents are **ultra-violet (UV) radiations, α, β rays, cosmic rays and meteors.** Thus the upper part of the atmosphere due to low pressure and ionizing agents gets highly ionized very easily.

Once the atom is ionized does not remain ionized indefinitely. The charged particles are constantly in motion resulting in collision causing recombination. How long the ionization remain depends on many factors.

i) Distance between charged particles. Less the distance more the collision and hence ionization remain for small time.

ii) Even if collision is more, if there is a constant source of ionization, then ionization remain for long time.

Since the radiated energy by the sun is coming from upward direction, the upper part of the atmosphere absorbs more of this energy causing more ionization.

The lower part of the atmosphere gets less radiated energy resulting in less ionization and also in this region recombination rate is high. This results in less ionization in the lower part of the atmosphere. This happens in lower region below about 50 km.

On the other hand, above the height of 400 km the air particles present are so few that the density of ionization is again very low.

In short, **a considerable ionization exits in the intermediate height between 50 km to 400 km**, called as ionosphere.

19.3 FORMATION OF IONIZATION LAYERS

The ionization region consists of different layers, namely D, E, and F layers.

Though ionosphere is one region of atmosphere where ionization is present, it consists of different layer having different height, thickness and ionization density. The reason of layer formation is as follows.

One of the source of ionization is UV light radiated by the sun. This UV light consists of different frequencies. The low frequency UV waves penetrate the atmosphere the least, therefore they produce ionized layers at higher heights. Conversely, UV light of higher frequencies penetrate deeper and produce layers at lower heights.

An important factor in determining the density of ionized layers is the elevation angle of the sun, which changes frequently. For this reason, the height and thickness of the ionized layers vary, depending on the time of the day and even the season of the year.

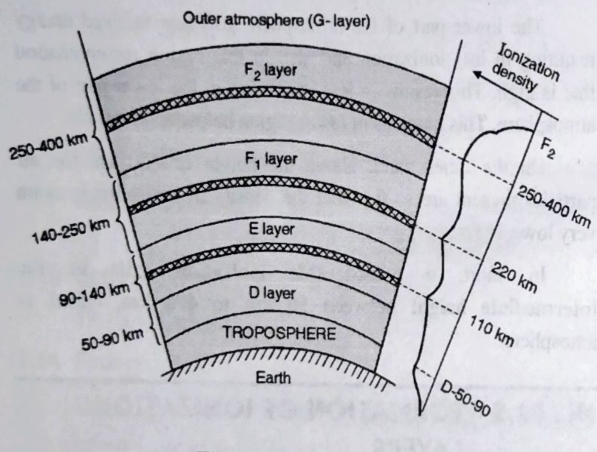
The recombination process also depends on the time of day. Between the hours of early morning and late afternoon, the rate of ionization exceeds the rate of recombination. During this period, the ionized layers reach their greatest density and exert maximum influence on radio waves.

During the late afternoon and early evening hours, however, the rate of recombination exceeds the rate of ionization, and the density of the ionized layers begins to decrease. Throughout the night, density continues to decrease, reaching a low point just before sunrise.

Since the position of the sun varies daily, monthly and yearly, with respect to a specified point on the earth, the exact position and number of layers present are extremely difficult to determine.

The ionospheric layers discussed above are named as **D, E, and F layers, from lowest level to highest level** as shown in Fig. 19.3.1.

The F-layer is further divided into two layers : F_1 (the lower layer) and F_2 (the higher layer).



aw(2.9) **Fig. 19.3.1 : Ionization layers**

These layers are the characteristics of each layer is discussed next.

19.4 CHARACTERISTICS OF DIFFERENT IONIZED REGIONS

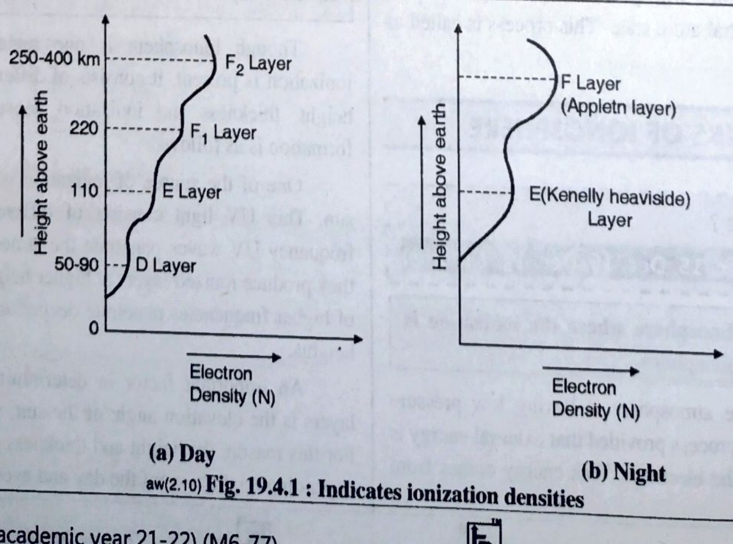
UQ. Which layers are present during day and night? Define critical frequency.

(MU - Dec. 15, Dec. 16, Dec. 17, 2 Marks)

Different regions will be discussed one by one. Refer Fig. (19.3.1 and 19.4.1).

19.4.1 D-region

- D-region is the lower-most region of the ionosphere and is located in the **height range of 50 to 90 km.**
- This layer is **present only during the day light hours** and disappears at night because recombination rate is highest. This is due to the fact that degree of ionization depends on the altitude of the sun and on sunset the recombination increases resulting vanishing of D-region all together.
- The ionization density, however is maximum at noon and its **electron density is ranging from 10^{14} to 10^{16} per cubic centimeter.**
- This D-region does **not have the well defined maximum** as in other layer.
- It is not important from the HF communication point of view but is capable of reflecting VLF signals (i.e. very long waves) and LF signals (i.e. long waves) and **absorbs to a certain extent MF and HF signals.**
- Its **critical frequency is about 100 kHz.**
- D-layer is also known as **absorbing layer for short wave signals** (i.e. HF). Since the density of electrons in this region is not sufficient to effect appreciable bending of radio waves and hence they suffer attenuation while passing.



aw(2.10) **Fig. 19.4.1 : Indicates ionization densities**

19.4.2 Normal E-region

UQ. With regard to ionosphere discuss the following :
E layer **(MU - Dec. 15, Dec. 17, 3 Marks)**

- E-region (normal) lies as narrow layer of ionization just above the D-region in the **height range of 90 to 140 km, having maximum at 110 km** from the earth surface (Fig. 19.3.1).
- This layer occurs **during day light hours** and has its **maximum density at the average height 110 km** which has appreciable effect on the direction of propagation of radio waves.
- During night hours E-region remains weakly ionized. **The electron density of E-region ranges from 10^5 to 4.5×10^5 during day and from 5×10^5 to 10^4 at night.**
- **Critical frequency** of E-layer lies in the range of **3 MHz to 5 MHz** at noon in low latitudes and it varies very little from day to day variations.
- E-region is formed by ionization of all gases by soft X-ray radiations.
- E-layer is the most **useful layer for long distance radio propagation during day light hours**, although propagation through F-region also takes place during day hours. The main function of E-layer is to reflect some HF waves in day hours.

19.4.3 Sporadic E-region (E_s)

UQ. With regard to ionosphere discuss the following :
Sporadic E layer **(MU - Dec. 15, Dec. 17, 3 Marks)**

- Besides more stable regions like D, E and F in the ionosphere there exists an anomalous ionization termed as sporadic E-region or layer and is denoted by E_s.
- Since the presence of sporadic E-region is **very much irregular**, hence it is termed as sporadic E-layer.
- It usually **occurs in the form of clouds**, varying in size from about one km to several hundred km across.
- Its presence also is **purely regional** and its occurrence and intensity of ionization has no connection with sun radiation. The occurrence of sporadic E-layer is quite unpredictable and it may be observed both in day and night hours, and in any season of the year.
- E_s is a very thin layer of high ionization density (electron density may be even 10 times to that of normal E-layer) and it may appear anywhere in the **height range of 90 km to 130 km** with normal E-layer.
- It is not important in long distance propagation but sometimes **it allows unexpectedly good reception.**

19.4.4 F₁ and F₂ and F Regions or Appleton Regions

- The region of the ionosphere **lying between 140 km to 400 km from earth surface is called as F-region or layer.**
- **Its average height is around 270 km.**
- It is the uppermost ionized region and is the only region which **always remains ionized** irrespective of hours of day or seasons of the years.
- The ionization persists throughout the dark hours of night and so the F-region is most noticeable. **Therefore F-region facilitates long distance sky wave propagation of radio signals during night hours.**
- The existence of F-layer in the night hours is due to the fact that
  - i) Being topmost layer, it is highly ionized and hence some ionizations remain even after sun set.
  - ii) Although ionization density is high, the actual air density is not much and hence most of the molecules of this layer are ionized.
- During day, sometimes after sunrise, the F-region is found to **split up into two layers called F_1 and F_2** in low latitude stations throughout the year and in high latitude stations only in summer.
- F_1-layer is the uppermost region situated height range of 140 km to 250 km with average height at 2 km.

  Its critical frequency at noon time is of the order of 5 MHz to 7 MHz and electron density ranges from 2×10^5 to 4.5×10^5.

  The main effect of F_1 layer is to provide more absorption for HF waves.
- F_2-layer is the uppermost region situated at a height range of about 250 km to 400 km in day having highest electron density of all the ionospheric layers.

  It falls to 300 km at night where it combines with F_1 layer.

  The electron density of F_2-layer is ranging from 3×10^5 to 2×10^6. Being highest in height, the air density is so low in this region that the ionization disappears very slowly.

  F_2-layer is the most important reflecting medium for high frequency radio waves.

19.4.5 Outer Atmosphere or G-Region

The upper limit of the ionosphere is not known but region further away from the 400 km is known as "G-region".

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19.4.6 Difference between E Layer and Sporadic E Layer

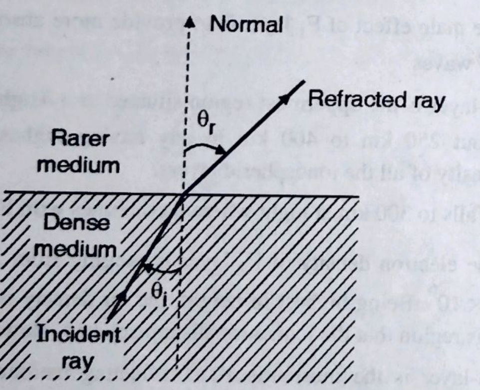
Sr. No.	E layer	Sporadic E layer
(i)	The E layer which is regular in occurrence is called as normal E-layer or simply E-layer.	The E-layer which is irregular is called as sporadic E-layer.
(ii)	It occurs in day time.	Its occurrence is unpredictable.
(iii)	Its ionization density is from 10^5 to 4.5×10^5 during day time.	Its density is higher even more than 10 times of E-layer.
(iv)	Most useful for long distance communication.	It is not important in long distance communication but sometimes results in good reception.

19.5 IONOSPHERIC OR SKY WAVE PROPAGATION (2 TO 30 MHZ)

In the ionospheric propagation radio signals take a path through ionosphere to come back to earth.

The ionosphere extends from 50 km to about 400 km from earth's surface. When the radio wave is transmitted into an ionized layer, refraction or bending of the wave occurs, which returns the wave back towards the earth. The bending of the wave is similar to bending of light in optics, which is governed by Snell's law.

19.5.1 Snell's Law in Optics



aw(2.29)**Fig. 19.5.1 : Refraction of a light ray**

Consider a light ray travelling from one media to second media having different refractive indices η_1 and η_2, as shown in Fig. 19.5.1. The light ray while travelling from medium 1 to medium 2 changes its path. This can be observed from angles θ_i and θ_r made by ray with normal to interface. The Snell's law is used for this purpose. Snell's law is,

$$\eta_1 \sin \theta_i = \eta_2 \sin \theta_r$$

or
$$\frac{\sin \theta_r}{\sin \theta_i} = \frac{\eta_1}{\eta_2} \quad ...(19.5.1)$$

Here θ_i = angle of incident ray with normal in medium 1.

θ_r = angle of refracted ray with normal in medium 2.

If η_1 is greater than η_2 ($\eta_1 > \eta_2$), we find

$$\frac{\sin \theta_r}{\sin \theta_i} > 1$$

or
$$\sin \theta_r > \sin \theta_i$$

or
$$\theta_r > \theta_i \quad \text{when } \eta_1 > \eta_2 \quad ...(19.5.2)$$

For $\eta_1 > \eta_2$, the medium 1 is said to denser medium while medium 2 is a rarer medium. So Equation (19.5.2) says;

When the ray travels from dense media to rarer media, it goes away from the normal.

Similar situation occurs in ionosphere, which is responsible for ionospheric bending of the radio wave.

This theory applies when the change in refractive index ($\eta_1 - \eta_2$) is very small. That is η_1 is closer to η_2. If not then instead of refraction we observe reflection at the interface.

19.5.2 Ionospheric Reflection and Refraction

In the above discussion we considered two media having slight change in refractive index from η_1 to η_2. In case of reflection and refraction of radio waves by the ionosphere, the mechanism is a very much function of frequency, and the above theory can be applied under some conditions.

The refractive index of the ionosphere is given by,

$$\eta = \sqrt{\epsilon_r} = \sqrt{1 - \frac{81 N}{f^2}} \quad ...(19.5.3)$$

where, N = number of electrons per cubic meter

f = frequency of radio waves in Hertz.

However, if N is expressed as number of electrons per cubic centimeter then f is expressed in kHz.

In the ionosphere, the ionization density (and hence N) increases with height from earth's surface. From Equation (19.5.3), when N increases, the refractive index η decreases. Also, it is observed that η is also a function of frequency. So it is interesting to study the effects of frequency.

(i) **Low frequency operation : (Only refraction)**

At low frequencies (high wavelength), say below 100 kHz, the change in electron and ion density (N) within a distance of wavelength is very large. So it presents abrupt change in refractive index η (according to Equation (19.5.3)), and instead of refraction we find **reflection of waves.**

In the course of electromagnetic we have studied that the reflection coefficient in this situation will depend upon the frequency, polarization, and angle of incidence of the wave. There is a total reflection provided that the angle of incidence is greater than a particular angle called as **critical angle of incidence (θ_c).**

For angles less than θ_c, the reflection coefficient is less than unity and will depend on the angle of incidence.

(ii) **High frequency operation : (Only refraction)**

At the high end of the high-frequency band, the phenomenon is exactly opposite. Here the wavelength is so small that the ionization density (and hence refractive index) changes only slightly in the course of a wavelength.

Under such conditions the ionosphere may be treated as a dielectric with continuously changing refractive index, causing **refraction not reflection.** Here the situation is governed by Snell's law of optics. Practically, this high frequency operation is important.

(iii) **Mid frequency operation : (Partial reflection and refraction)**

In previous two cases we observed that :

- At low frequencies, there is a abrupt change in refractive index making the wave totally reflected.
- At high frequencies, there is a continuous change in refractive index, resulting in refraction of waves.

But for **middle frequencies**, the ionospheric region is considered to be consists of several thin but discrete layers, each layer having a constant ionization density that differs from that of the adjacent layer. Here we find a **partial refraction and reflection.**

A partially refracted wave penetrates to the second layer where it is partially reflected and partially refracted, and so on. In this case, the resultant reflected signal may be considered as the sum of reflections form various parts of the ionized layer.

Received signal in this case will be very small as compared to incident wave, and hence practically this case is of no use.

The effect of frequency on ionospheric propagation is summarized as :

- Low frequencies are only reflected.
- Mid frequencies are partially reflected and refracted.
- High frequencies are only refracted.

19.5.3 Ionospheric Bending

UQ. Explain the mechanism of ionospheric propagation. **(MU - Q. 5(b), Dec. 19, 4 Marks)**

UQ. Explain Ray path. **(MU - May 15, 3 Marks)**

As explained above, the high frequency radio waves in ionospheric propagation is practically important. At high frequencies the ionization density changes gradually over distance of wavelength. Thus we say in the ionospheric layer at high frequency the refractive index changes gradually.

We know that ionospheric region consists of different layers like D, E, F_1 and F_2. In each layer at the center, the ionization density is maximum and decreases above and below the maximum region. In each layer at high frequency the variation of N and hence η is very smooth.

Every layer now can be visualized as consisting of small strips one above the other. The variation in η from one strip to next is so small that only refraction of radio waves will take place. In this situation the waves follow the Snell's law of optics. Refer Fig. 19.5.2.

From the base of any ionospheric layer when we go high, the value of N increases so η decreases according to the Equation (19.5.3), given as

$$\eta = \sqrt{1-\frac{81\,N}{f^2}} \qquad \ldots(19.5.4)$$

NOTES

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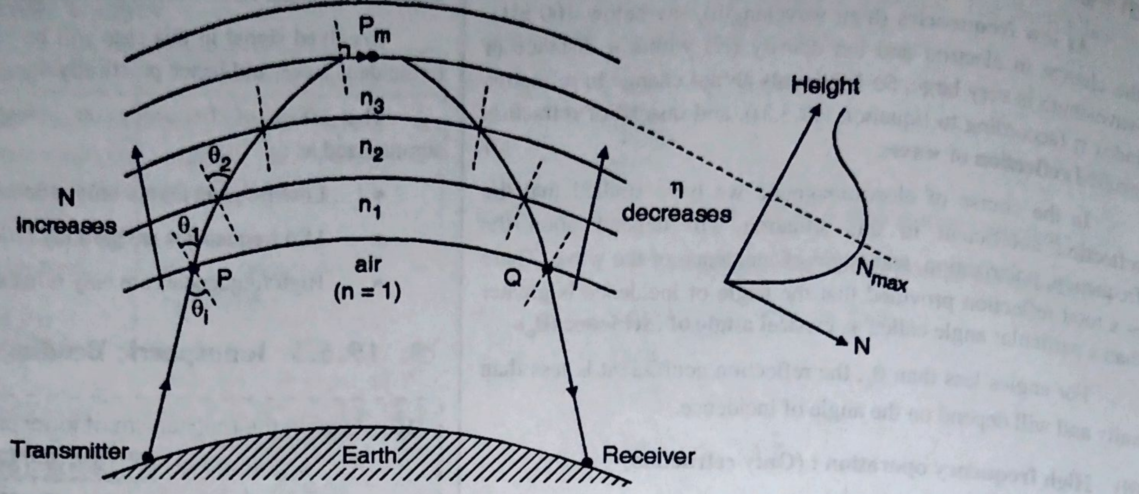
Note that due to ionization density N in the ionosphere, the value of n is always less than one in this region.



aw(2.30)**Fig. 19.5.2 : Ionospheric bending**

Let the strips in upward direction are having electron densities N_1 to N_6 then the relation between these N values are (only for simplicity few layers are shown in Fig. 19.5.2).

$$N_6 > N_5 > N_4 > N_3 > N_2 > N_1$$

Then the refractive indices are related by

$$\eta_1 > \eta_2 > \eta_3 > \eta_4 > \eta_5 > \eta_6$$

Consider the wave enters from air into the bottom strip of the layer at point P with angle of incidence θ_i. This layer is having density N_1 and refractive index η_1. According to Snell's law this wave going from dense media ($\eta = 1$ for air) to rare media ($\eta_1 < 1$), will be refracted. The angle of refraction θ_1 will be greater than θ_i. The refracted wave enters into second strip where n further decreases ($\eta_2 < \eta_1$) which causes $\theta_2 > \theta_1$ and so on.

Snell's law when applied to first strip gives

$$\eta_1 = \frac{\sin \theta_i}{\sin \theta_1}$$

or $$\sin \theta_1 = \frac{\sin \theta_i}{\eta_1} \quad \text{...(19.5.5)}$$

where η_1 is the refractive index of the first strip and θ_1 is the angle of refraction at the first strip. At the second strip the Snell's law is

$$\eta_2 \sin \theta_2 = \eta_1 \sin \theta_1 = \sin \theta_i \text{ (using Equation 19.5.5)}$$

In general at any layer, than we have

$$\sin \theta_i = \eta \sin \theta$$

or $$\sin \theta = \frac{\sin \theta_i}{\eta} \quad \text{...(19.5.6)}$$

where η is the refractive index at the point where θ is measured.

From Equation (19.5.6), it is clear that as we go higher in the layer, η decreases and so θ increases since $\sin \theta_i$ is constant for any given launching angle.

The process of increasing θ continues till the wave become parallel to the earth at point P_m. Here the angle of refraction is 90° and the point P_m is the highest point in the ionosphere reached by the radio wave. If η_m is the refractive index and N_m is the ionization density at point P_m then Equation (19.5.6) gives

$$\sin 90 = \frac{\sin \theta_i}{\eta_m}$$

or $$\eta_m = \sin \theta_i \quad \text{...(19.5.7)}$$

Any downward perturbation to the wave direction at this height (or total internal reflection) pushes the wave downward and the wave is reflected to the earth. This reflected wave from point P_m will start travelling downward through the lower strips, undergoing refraction in each strip. Note that **while the wave is coming down, it travels from low to high refractive index and thus angle of refraction decreases.**

Hence the radio wave once enter at point P, leave the ionosphere at point Q and thus reaches the receiver. In between P and Q, it follows the path in the ionosphere, hence the propagation is ionospheric propagation.

Using Equation (19.5.4), we relate this with electron density N_m as,

$$\eta_m = \sin \theta_i = \sqrt{1 - \frac{81\, N_m}{f^2}}$$

or $$\sin^2 \theta_i = 1 - \frac{81\, N_m}{f^2}$$

or $$N_m = \frac{f^2}{81}(1 - \sin^2 \theta_i)$$

or $$N_m = \frac{f^2 \cos^2 \theta_i}{81} \quad \text{...(19.5.8)}$$

This Equation says :

(i) If the electron density at some level in a layer is sufficiently great to satisfy Equation (19.5.8) then the wave will be returned to earth from that level.

(ii) If the maximum electron density in a layer is less than that given by Equation (19.5.8), the wave will penetrate the layer and it may be reflected back from a higher layer for which N is greater.

Using Equation (19.5.8) we can also explain the role of angle θ_i and frequency of wave on the ionospheric propagation.

Effect of θ_i on ionospheric propagation

Consider the radio wave with frequency f is launched at an angle θ_{i1} ($< \theta_i$).

Then
$$\cos \theta_{i1} > \cos \theta_i$$

and putting in Equation (19.5.8), the new value of ionization density is,

$$N_{m1} = \frac{f^2 \cos^2 \theta_{i1}}{81} \quad ...(19.5.9)$$

This value is greater than N_m for the previous wave in discussion. If a particular ionization layer is not having this density, then the wave is not returned from this layer. It penetrates into next ionization layer and so on till the required value of N_{m1} is obtained for the wave to be reflected to the earth.

The effect of decreasing θ_i is the wave may be reflected from higher ionization layer.

Effect of frequency on ionospheric propagation

Consider now the wave with incidence angle θ_i but the frequency is higher ($f_1 > f$). According to Equation (19.5.8), again the value of N_m is increased to some value N_{m2}, given by,

$$N_{m2} = \frac{f_1^2 \cos^2 \theta_i}{81} \quad ...(19.5.10)$$

Again to have reflection, the particular layer should have this value of ionization density otherwise the wave will enter into higher layer till this value N_{m2} is obtained. Thus the effect of decreasing θ_i or increasing f is same.

The effect of increasing frequency f is the wave may be reflected from higher ionization layer.

From the above discussion we conclude that the amount of refraction that occurs in the ionosphere depends on three main factors

(i) the density of ionisation of the layer,

(ii) the frequency of the radio wave,

(iii) the angle at which the wave enters the layer.

19.6 MEASURES OF IONOSPHERIC PROPAGATION

There are several different measures by which the ionosphere is characterized at any given time. These measures are used in making predictions of radio activity and long-distance propagation. These are :

(i) Critical frequency (f_c)

(ii) Virtual height

(iii) Maximum usable frequency (MUF)

(iv) Lowest usable frequency (LUF)

(v) Skip distance

These are the terms you will hear frequently in any discussion of ionospheric propagation.

19.7 CRITICAL FREQUENCY (fc)

UQ. Explain critical frequency. **(MU - May 15, 3 Marks)**

19.7.1 Definition

UQ. Define critical frequency. **(MU - Dec. 15, Dec. 17, Q. 5(b), Dec. 19, 2 Marks)**

UQ. Define critical frequency as a measure of ionospheric propagation. **(MU - Dec. 16, 2 Marks)**

For any given time, each ionospheric layer has a maximum frequency at which radio waves can be transmitted vertically and reflected back to earth. This frequency is known as the critical frequency.

It is denoted by f_c and it is different for different layers. Combining Equations (19.5.4) and (19.5.6) we have

$$\eta = \frac{\sin \theta_i}{\sin \theta} = \sqrt{1 - \frac{81\,N}{f^2}} \quad ...(19.7.1)$$

From the expression one can note that when the angle of incidence θ_i decrease, then refractive index η decreases which requires the term 81 N/f^2 to increase. This in turn will require the ionization density N to increase for the given frequency. If frequency is high then N has to increase more.

The maximum value of 81 N/f^2 is unity for propagation to take place. If the value exceeds unity, then η becomes imaginary which means under such condition the radio waves are attenuated at frequency f and the ionosphere is not able to transmit or bend the radio waves.

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Remember the angle of incidence θ_i is measured with respect to normal to the bottom line of the ionosphere. Then for vertical incidence, $\angle\theta_i = 0$ and according to Equation (19.8.1), the refractive index η is zero. This requires $81\ N/f^2$ to be maximum equal to unity.

By definition, the critical frequency is the maximum frequency at vertical incidence, then the ionization density N should also be maximum.

Every ionization layer is having a particular value of maximum ionization density. For the given layer let it be N_m.

19.7.2 Expression for Critical Frequency

From Equation (19.7.1), $$\eta = \frac{\sin\theta_i}{\sin\theta} = \sqrt{1-\frac{81\ N}{f^2}}$$

For vertical incidence

$$\theta_i = 0,\ \eta = 0,\ N = N_m \text{ and } f = f_c$$

Putting the values in Equation (19.8.1),

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

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

or $$f_c = 9\sqrt{N_m} \quad \text{...(19.7.2)}$$

Where f_c is expressed in Hz then N_m is in per cubic meter. If f_c is expressed in kHz then N_m is per cubic centimeter.

Thus, critical frequency for the particular ionization layer is proportional to the square root of the maximum electron density in the layer.

Knowing maximum electron density of the layer the critical frequency for each layer can be obtained. Typical values are given in Table 19.7.1.

Table 19.7.1

Ionospheric layer	Critical frequency
D	100 kHz
E	3-5 MHz
F_1	5-7 MHz
F_2	10 MHz or more

These values are typical values since the value of N_m is not same at all times of the day.

As we go to higher ionospheric layer since the value of N_m increases, the critical frequency also increases.

19.7.3 Important Points to be Remembered

i) Of course critical frequency is the highest frequency which can be refracted by a particular layer at vertical incidence but it is not the highest frequency which will get refracted for any other angle of incidence.

ii) Radio waves transmitted at frequencies higher than the critical frequency of a given layer will pass through the layer and be lost in space.

iii) But if the same waves enter an upper layer with a higher critical frequency, they will be refracted back to earth.

iv) Radio wave of frequencies lower than the critical frequency will also be refracted back to earth from the given layer unless they are absorbed or have been refracted from a lower layer.

Ex. 19.7.1 : The critical frequencies of E and F layers which are observed at a particular time are 2.5 MHz and 8.4 MHz respectively. Calculate the maximum electron density of the layers.

☑ **Soln. :**

We have $f_c = 9\sqrt{N_m}$ or $N_m = f_c^2/81$

Where f_c is in Hz then N_m is expressed per cubic meter.

i) **For E-layer :**

$$N_m = \frac{(2.5\times10^6)^2}{81} = 0.7716\times10^{11} \text{ per cubic meter.}$$

ii) **For F-layer :**

$$N_m = \frac{(8.4\times10^6)^2}{81} = 8.711\times10^{11} \text{ per cubic meter.}$$

Ex. 19.7.2 : Determine the critical frequency of EM wave for D, E and F layers. Given the maximum electron densities for

D-layer : $N_m = 400$ electrons / cm^3

E-layer : $N_m = 5\times10^5$ electrons / cm^3

F-layer : $N_m = 2\times10^6$ electrons / cm^3.

☑ **Soln. :**

We have $f_c = 9\sqrt{N_m}$

Here when N_m is expressed per cubic cm then f_c is in kHz.

i) **For D-layer :** $f_c = 9\sqrt{400} = 180$ kHz

ii) **For E-layer :**

$$f_c = 9\sqrt{5\times10^5} = 63.64\times10^2 \text{ kHz} = 6.364 \text{ MHz.}$$

iii) **For F-layer :**

$$f_c = 9\sqrt{2\times10^6} = 12.8 \text{ MHz}$$

Ex. 19.7.3 : At what frequency a wave must propagate for the D-layer to have refractive index equal to 0.5. Given : For D layer, N = 400 electrons per c.c.

☑ **Soln. :**

Since N is expressed per c.c., then frequency is in kHz.

We have,

$$\eta = \sqrt{1 - \frac{81\,N}{f^2}}$$

or

$$\eta^2 = 1 - \frac{81\,N}{f^2}$$

or

$$f = \sqrt{\frac{81\,N}{1-\eta^2}}$$

Putting the values,

$$f = \sqrt{\frac{81 \times 400}{1-(0.5)^2}} = \sqrt{\frac{81 \times 400}{0.75}} = 207.82 \text{ kHz.}$$

UEx. 19.7.4 MU - May 10, Dec. 16, 3 Marks.

Determine critical frequency for reflection at vertical incidence if the maximum value of electron density is 1.24×10^6 per CC.

☑ **Soln. :**

Given : $N_m = 1.24 \times 10^6 / cm^3$

We have $f_c = g\sqrt{N_m} = g\sqrt{1.24 \times 10^6}$

$$f_c = 10.0 \times 10^3 \text{ Hz} = 10 \text{ kHz}$$

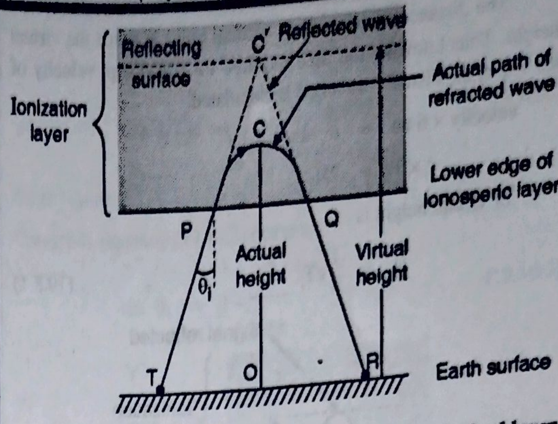
19.8 VIRTUAL HEIGHT OF THE IONOSPHERIC LAYER

UQ. What is virtual height of a layer? Why is it called so? Is it more than or less than the actual height of the layer? (MU - Dec. 15, 5 Marks)

19.8.1 Definition

The virtual height is that height from which a wave sent up at an angle appears to be reflected.

In the ionospheric propagation we studied that when the wave is launched into the ionosphere with an incidence angle θ_i, due to gradual change in refractive index there is a refraction of the wave. The path of the wave is a curve path which returns the wave back to the earth. This is shown in Fig. 19.8.1.



aw(2.32)**Fig. 19.8.1 : Actual and virtual height of an ionized layer**

The actual path of a radio wave transmitted by the transmitter (T) and received on the earth by the receiver (R) is T-P-C-Q-R

Actual path : T-P-C-Q-R

This path is a curved path in the ionosphere along P-C-Q. Instead of curved path it is convenient to consider a wave travel straight path along T-P-C′. If the mirror like reflecting surface is present at C′, then the wave gets reflected along C′-Q-R. The height of point C′ where reflecting surface is placed must be such that the refracted wave and reflected wave follow the same path in the region below ionosphere.

The height of the reflecting surface from earth's surface (OC′) is called as virtual height. It is virtual because the reflecting surface is not actually present there, it is just an imagination. The actual height is the height from earth's surface from where the wave bends down due to refraction. The actual height is the distance OC in the Fig. 19.8.1.

19.8.2 Importance of Virtual Height

The virtual height is always greater than the actual height. If virtual height of the layer is known, then it is easy to calculate the angle of incidence required for the wave to return to earth at a desired point.

19.8.3 Measurement of Virtual Height

To measure the virtual height the instrument used is ionospheric sound also called as **IONOSONDE.** The transmitter in it transmits vertically upward a pulse modulated radio wave with a pulse duration of about 150 micro-seconds.

The receiver is placed very close to the transmitter to observe both the direct wave and the reflected signal. The spacing between these signals on the time axis of CRO gives the time required for the round trip (T).

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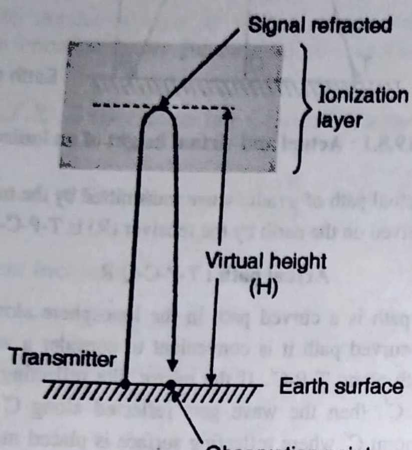
The distance travelled by a vertical pulse is twice the virtual height. Thus knowing the time required for round trip, velocity of the wave, the distance travelled is calculated.

$$\text{velocity} \times \text{time} = \text{distance}$$

$$c \times T = 2H$$

or virtual height is

$$H = \frac{1}{2} cT \quad ...(19.8.1)$$



aw(2.33)Fig. 19.8.2 : Measuring virtual height

where c is the velocity of light.

Here it is assumed that the earth is flat and ionospheric conditions are symmetrical for the incident and reflected waves.

Ex. 19.8.1 : A pulse of a given frequency transmitted vertically upward is received back after a period of 5 milli-seconds. Find the virtual height of the reflecting layer.

☑ Soln. :

The virtual height is given by,

$$H = \frac{1}{2} cT = \frac{1}{2} \times 3 \times 10^8 \times 5 \times 10^{-3}$$

$$H = 7.5 \times 10^5 \text{ m} = 7.5 \times 10^2 \text{ km.}$$

19.9 MAXIMUM USABLE FREQUENCY (MUF)

UQ. Define MUF. **(MU - Q. 5(b), Dec. 19, 2 Marks)**

19.9.1 Definition

The maximum usable frequency (MUF) is defined as the highest frequency that can be used for sky wave communication between two given points on earth.

We know that the critical frequency for any layer represents the highest frequency that will be reflected back from that layer at vertical incidence. But if it is not a vertical incidence then frequency greater than critical frequency can be returned to earth from the same layer.

We can investigate this using simple mathematics. Referring Equation (19.7.1), which is

$$\eta = \frac{\sin \theta_i}{\sin \theta} = \sqrt{1 - \frac{81 N}{f^2}} \quad ...(19.9.1)$$

Here θ is the angle of refraction and as the wave enters from one strip to next higher strip in the ionization layer its value goes on increasing. It increases to 90° and then the wave starts travelling down towards the earth. Thus at the point of highest refraction point θ = 90°. Then above equation can be written as,

$$\eta = \frac{\sin \theta_i}{\sin 90} = \sqrt{1 - \frac{81 N_m}{f^2}}$$

or

$$\eta = \sin \theta_i = \sqrt{1 - \frac{81 N_m}{f^2}} \quad ...(19.9.2)$$

Now consider two cases of angle θ_i.

i) Vertical incidence (i.e. $\theta_i = 0$)

For the vertical incidence with $N = N_m$, the frequency is nothing but critical frequency (f_c). Using Equation (19.9.2),

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

or

$$\frac{81 N_m}{f_c^2} = 1 \quad ...(19.9.3)$$

ii) Non vertical incidence ($\theta_i \neq 0$)

For wave to enter into ionosphere in upward direction the incidence angle should be

$$0° < \theta_i < 90°.$$

so

$$0 < \sin \theta_i < 1$$

so

$$0 < \eta < 1 \quad ...(19.9.4)$$

which requires

$$\frac{81 N_m}{f^2} < 1 \quad ...(19.9.5)$$

Comparing Equation (19.9.3) and Equation (19.9.5) we find

$$f > f_c \quad ...(19.9.6)$$

That is to say, $f > f_c$ will be returned to earth provided that it is non vertical incidence.

The maximum possible value of frequency for which reflection takes place for a given angle of incidence is called as the maximum usable frequency (MUF) for that angle and for the given ionospheric layer.

If the frequency is higher than this then the wave penetrates the ionized layer and does not reflect back to earth.

For flat earth, if the distance between the transmitter and receiver is (d) and knowing the virtual height of the ionospheric layer (H), the relation between θ_i and d can be very easily determined as shown in Fig. 19.9.1. In the figure

$$\beta = 90 - \theta_i$$

Using the triangle TMO,

$$\tan\beta = \frac{MO}{TO} = \frac{H}{d/2}$$

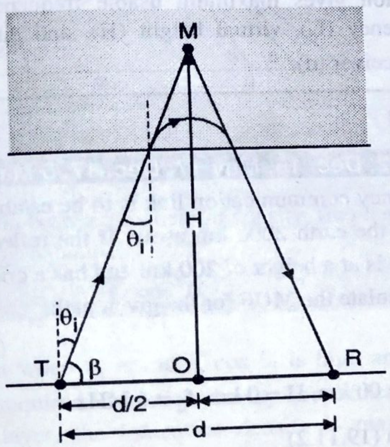
i.e.

$$\tan(90 - \theta_i) = \frac{2H}{d} \quad ...(19.9.7)$$

Thus knowing virtual height (H) and distance between transmitter and receiver (d), we can determine angle θ_i.

However, the angle of incidence is not of prime importance, since it is determined by the distance between the points on earth that are to be joined by a sky-wave link. Thus MUF is now defined in terms of two such points, rather than in terms of angle of incidence.

There is a different value of MUF for each pair of points on the earth.



aw(2.34)Fig. 19.9.1 : Relation between θ_i and d

19.10 SECANT LAW

Using this law we can determine the highest frequency that will be returned to earth for non vertical incidence. We have from Equation (19.9.1),

$$\eta = \frac{\sin\theta_i}{\sin\theta} = \sqrt{1 - \frac{81\,N}{f^2}} \quad ...(19.10.1)$$

At highest refraction point

$$\theta = 90°, \quad N = N_m \text{ and}$$

For f greater than f_c, let us denote it by f_{MUF}. Putting the values in Equation (19.10.1),

$$\eta = \frac{\sin\theta_i}{\sin 90} = \sqrt{1 - \frac{81\,N_m}{f_{MUF}^2}}$$

or

$$\sin\theta_i = \sqrt{1 - \frac{81\,N_m}{f_{MUF}^2}} \quad ...(19.10.2)$$

From equation $f_c = 9\sqrt{N_m}$ or $f_c^2 = 81\,N_m$

Using this Equation (19.10.2) becomes

$$\sin^2\theta_i = 1 - \frac{f_c^2}{f_{MUF}^2} \quad ...(19.10.3)$$

or

$$\frac{f_c^2}{f_{MUF}^2} = 1 - \sin^2\theta_i = \cos^2\theta_i$$

or

$$f_{MUF}^2 = f_c^2 \sec^2\theta_i$$

or

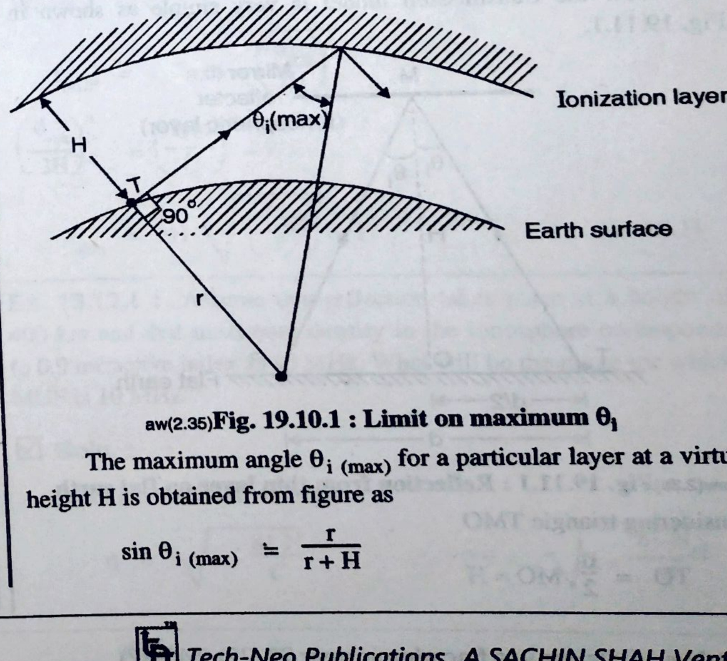
$$\boxed{f_{MUF} = f_c \sec\theta_i} \quad ...(19.10.4)$$

This equation says that maximum usable frequency (f_{MUF}) is greater that critical frequency (f_c) by a factor sec θ_i. This is known as **SECANT LAW.**

This formula is applicable only to a flat earth and flat reflecting layer. According to this equation, as angle θ_i increases, the frequency f_{MUF} increases. But the curvature of the earth and the ionospheric layer limits the maximum value of θ_i.

19.10.1 Effect of Curvature of Earth

The above equation can be applied safely upto a distance of 1000 km. However, as the distance between transmitter and receiver is increased a limit occurs due to the curvature of the earth and ionospheric layer, where the wave becomes tangent to the earth surface at these two points on the earth. This is indicated in Fig. 19.10.1. The largest angle of incidence θ_i can be obtained in F-layer reflection is of the order of 74 degrees.



aw(2.35)Fig. 19.10.1 : Limit on maximum θ_i

The maximum angle $\theta_{i\,(max)}$ for a particular layer at a virtual height H is obtained from figure as

$$\sin\theta_{i\,(max)} = \frac{r}{r + H}$$

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or $\boxed{\theta_{i\,(max)} = \sin^{-1}\left(\frac{r}{r+H}\right)}$ ...(19.10.5)

Where r = radius of the earth

H = virtual height of the layer

In practice the highest working frequency between a given pair of points is set less than MUF. This is because due to atmospheric variation MUF may show small daily variations about the monthly average of up to 15 percent.

19.11 MUF IN TERMS OF D, H AND fc

UQ. Derive relation between MUF and skip distance. **(MU - May 15, May 17, May 18, 5 Marks)**

UQ. Obtain an expression for MUF in terms of d, H and f_c. **(MU - Dec. 16, Dec. 17, 5 Marks)**

Many times we require to calculate MUF knowing d, H and f_c. The terms are having usual meaning, where

d = Distance between the transmitter and receiver

H = Virtual height

f_c = Critical frequency.

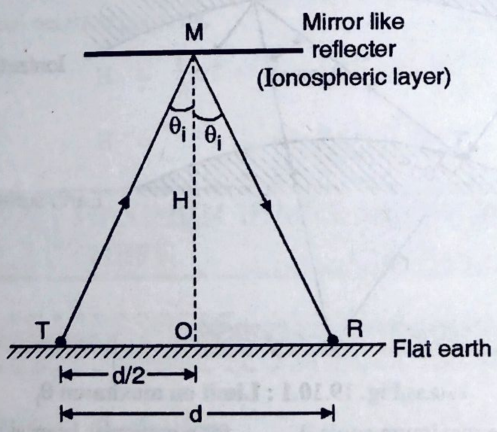
A simple relation can be obtained making some assumptions.

Assumptions

i) Ionization layer is very thin with sharp ionization density gradient so that it can be treated as mirror like reflector for radio waves.

ii) The distance d is so small that earth curvature is neglected and can be considered to be flat.

Now the transmission model is very simple as shown in Fig. 19.11.1.



aw(2.36)**Fig. 19.11.1 : Reflection from thin layer on flat earth**

Considering triangle TMO

$$TO = \frac{d}{2},\ MO = H$$

$$\therefore \quad TM = \sqrt{MO^2 + TO^2} = \sqrt{H^2 + (d/2)^2}$$

$$\text{Also, } \cos\theta_i = \frac{MO}{TM} = \frac{H}{\sqrt{H^2+(d/2)^2}} = \frac{2H}{\sqrt{4H^2+d^2}} \quad ...(19.11.1)$$

We have Equation (19.10.3)

$$\sin^2\theta_i = 1 - \frac{f_c^2}{f_{MUF}^2}$$

or

$$\frac{f_c^2}{f_{MUF}^2} = 1 - \sin^2\theta_i = \cos^2\theta_i$$

Putting value of cos θ_i from Equation (19.11.1).

$$\frac{f_c^2}{f_{MUF}^2} = \frac{4H}{4H^2+d^2}$$

or

$$\frac{f_{MUF}^2}{f_c^2} = \frac{4H^2+d^2}{4H} = 1 + \frac{d^2}{4H^2} = 1 + \left(\frac{d}{2H}\right)^2$$

i.e.

$$f_{MUF} = f_c\sqrt{1+\left(\frac{d}{2H}\right)^2} \quad ...(19.11.2)$$

This expression gives maximum usable frequency in terms of critical frequency (f_c), virtual height (H), and distance between transmitter-receiver (d).

UEx. 19.11.1

MU - Dec. 12, Dec. 16, May 17, Dec. 17, 5 Marks

A high frequency communication link is to be established between two points on the earth 2000 km away. If the reflection region of the ionosphere is at a height of 200 km and has a critical frequency of 5 MHz, calculate the MUF for the given path.

Soln. :

Given : d = 00 km, H = 0 km, f_c = 6 MHz.

Using Equation (19.11.2)

$$f_{MUF} = f_c\sqrt{1+\left(\frac{d}{2H}\right)^2}$$

$$f_{MUF} = 5\times10^6\sqrt{1+\left(\frac{2000\times10^3}{2\times200\times10^3}\right)^2}$$

$$f_{MUF} = 25.495\times10^6 \text{ Hz} = 25.495 \text{ MHz.}$$

19.12 SKIP DISTANCE

19.12.1 Definition

The skip distance is the shortest distance from a transmitter measured along earth's surface at which a sky wave of fixed frequency (more than f_c) will be returned to earth.

19.12.2 Effect of Changing θ_i

We know that the critical frequency is the highest frequency signal returned to earth at vertical incidence. But for non vertical incidence, the frequency greater than f_c will be returned to earth, we call this frequency as maximum usable frequency (MUF).

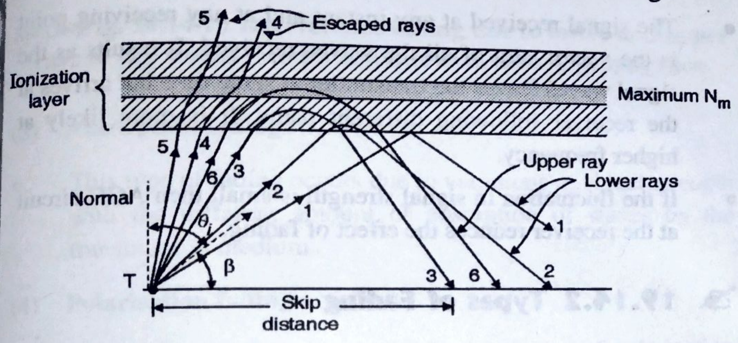
$$f_{MUF} = f_c \sec \theta_i$$

Now let us consider the frequency is greater than f_c and the wave is transmitted at different incidence angle θ_i.

In the Fig. 19.12.1 two angles are shown, the relation between them is

$$\theta_i = 90° - \beta$$

Where β = radiation angle ; θ_i = incidence angle.



aw(2.37)**Fig. 19.12.1 : Effect of varying θ_i on ionospheric rays**

The relation between ionization density, frequency, and angle of incidence is by Equation (19.5.8),

$$N_m = \frac{f^2 \cos^2 \theta_i}{81}$$

In this equation when θ_i is more, $\cos \theta_i$ is high and for a fixed frequency, the required ionization density for reflection is less. In the ionization layer, the ionization density is maximum at the center of the layer and it decreases both in downward and upward direction. The wave with high θ_i is returned to the earth from the lower region of the ionization layer. This is true for ray 1 and ray 2 in the Fig. 19.12.1. These rays are referred as **lower rays.**

As this angle is slowly reduced, naturally the wave returns closer and closer to the transmitter as in case of ray 2 and 3.

If the angle of incidence is now made significantly less than that of ray 3, as for ray 4, or only slightly, as for ray 5. For these rays high value of N_m is required, if not present in the given ionization layer, the wave penetrates through the ionization layer with very little refraction. These rays will not return to the earth, and hence called as **escaped rays.**

Finally, if the angle of incidence is only just smaller than that of ray 3, the wave penetrates more into the ionization layer as compared to ray 3 due to more ionization density is required. This ray is refracted rather slowly. A ray such as this is ray 6 which returns to earth but at a distance farther than the return point of ray 3.

Observing rays 1 to 6 we conclude that :

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. According to definition this distance is called as the **skip distance.**

It is called as skip distance because in this region sky wave communication fails and so should be skipped for communication. Any higher frequency beamed up at the angle of ray 3 will not be returned to ground.

Thus the frequency which makes a given distance correspond to the skip distance is the MUF for that pair of points.

19.12.3 Expression for Skip Distance

UQ. Derive relation between MUF and skip distance. **(MU - May 15, May 17, 5 Marks)**

UQ. Derive an expression for the Maximum Usable Frequency (MUF) in terms of the skip distance and virtual height. **(MU - May 18, 5 Marks)**

The frequency which makes a given distance corresponds to the skip distance it the maximum usable frequency for those two points.

For the given frequency, $f = f_{MUF}$, the skip distance is calculated using Equation (19.11.2)

$$f_{MUF} = f_c \sqrt{1 + \left(\frac{d}{2H}\right)^2}$$

Where $d = d_{skip}$

$$f_{MUF} = f_c \sqrt{1 + \left(\frac{d_{skip}}{2H}\right)^2}$$

$$\left(\frac{d_{skip}}{2H}\right)^2 = \left(\frac{f_{MUF}}{f_c}\right)^2 - 1$$

$$d_{skip} = 2H \sqrt{\left(\frac{f_{MUF}}{f_c}\right)^2 - 1} \quad \text{...(19.12.1)}$$

Ex. 19.12.1 : Assume that reflection takes place at a height of 400 km and that maximum density in the ionosphere corresponds to 0.9 refractive index at 10 MHz. What will be the range for which MUF is 10 MHz ?

☑ **Soln. :**

We have refractive index

$$\eta = \sqrt{1 - \frac{81 N}{f^2}} \qquad \therefore \; 0.9 = \sqrt{1 - \frac{81 N_m}{f^2}}$$

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i.e. $0.81 = 1 - \frac{81 N_m}{(10 \times 10^6)^2}$ i.e. $N_m = 23.456 \times 10^{10} \ m^{-3}$

The critical frequency is given by

$$f_c = 9\sqrt{N_m} = 9\sqrt{23.456 \times 10^{10}} = 4.359 \times 10^6 \text{ Hz.}$$

For a flat earth, the skip distance is

$$D_{skip} = \sqrt{\left(\frac{f_{MUF}}{f_c}\right)^2 - 1} = 2 \times 400$$

$$\sqrt{\left(\frac{10 \times 10^6}{4.359 \times 10^6}\right)^2 - 1} = 1651.76 \text{ km.}$$

19.13 OPTIMUM WORKING FREQUENCY (OWF)

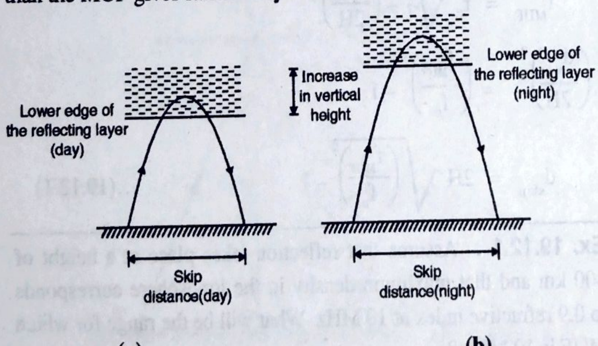
19.13.1 Definition

The frequency normally used for ionospheric propagation is called as optimum working frequency (OWF). It is 15% less than MUF.

As we know, the attenuation at the lower layers of ionosphere is inversely proportional to square of the frequency. Thus it is desirable to use the frequency as high as possible. The highest frequency is of course the Maximum Usable Frequency (MUF).

Due to irregularities in the ionosphere, the MUF for a particular location varies from time to time, from season to season and from months to months. If we consider only day variation, the virtual height of the ionospheric layer varies considerably. In the night time it increases than the day time and so the skip distance increases as shown in Fig. 19.13.1.

In practice it is not possible to change MUF from time to time. Practically it is found that the frequency about 15% lower than the MUF gives satisfactory communication.



aw(2.40)**Fig. 19.13.1 : Variation in lower edge of the reflecting layer during (a) day, (b) night**

19.14 FADING

UQ. Describe the Fading. (MU - May 16, 5 Marks)

19.14.1 What is Fading ?

- **Fading is the fluctuation in the received signal strength at the receiver or it is the undesirable variation in the intensity of the waves received at the receiver.**
- It is caused by variation in heights and density of ionization in the different layers of the ionosphere.
- Fading may be slow, rapid, frequency selective or caused due to interference between two waves of different path length.
- The signal received at any instant and at any receiving point is the vector sum of all the waves received. It results as the signal waves leaves the transmitter at same time but arrives at the receiver following different paths. It is more likely at higher frequency.
- If the fluctuation in signal strength is small then AGC circuit at the receiver reduces the effect of fading.

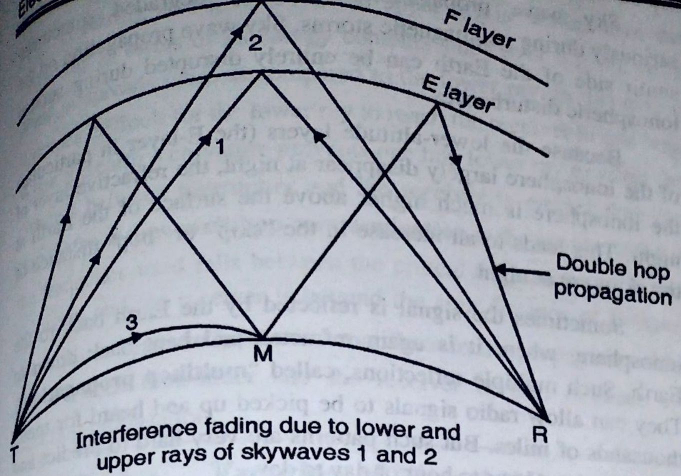
19.14.2 Types of Fading

(1) Selective fading

- Produces serious distortion of modulated signal.
- Since the fading is frequency selective, it is possible for adjacent portion of a signal to fade independently, although their frequency separation is only a few dozen Hz.
- Selective fading is more prevalent at high frequencies for which sky wave propagation is used. AM signals are more distorted by selective fading rather than SSB signals.
- It can be reduced by using high carrier reception and also single side band system.

(2) Interference fading

- Interference fading is the most serious type of fading and it is produced by the interference between upper and lower rays of a sky wave, between sky waves reaching the receiver by different number of hops or different paths and even between a ground wave a sky wave, particularly at the lower end of the HF band as shown in Fig. 19.14.1.
- Interference fading also occurs because of the fluctuations of height or ionic density in the ionospheric layer if a single sky wave frequency is in use.
- It can be minimized by space diversity or frequency diversity reception.



aw(2.44)**Fig. 19.14.1 : Interference fading due to lower and upper rays of sky waves 1 and 2 and due to multihop propagation**

(3) Absorption fading

- This type of fading occurs due to variations of signal strength with the different amount of absorption of waves by the transmission medium.

(4) Polarisation fading

- This type of fading occurs due to the change of polarization of the down coming sky waves. The state of polarization of a down coming sky wave is constantly changing.
- This is caused by a superposition of the ordinary and extra-ordinary waves which are oppositely polarized. The polarization w.r.t. antenna is constantly changing, giving rise to changes of amplitudes in the receiver and producing polarization fading.

(5) Skip fading

- This type of fading occurs at distances near the skip distance. Any variation in the height or density of an ionized layer may move the receiving point in-out the skip zone.
- The most common method to minimize fading is to use an automatic volume control AVC or AGC in the receiver.
- The best method is to employ diversity reception system.

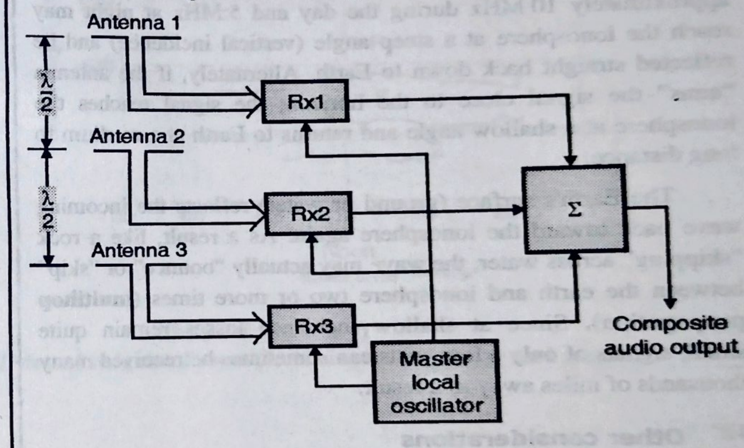
19.14.3 Diversity Reception (Minimizing Fading)

- Diversity reception is used for minimizing signal fading. While the AGC helps in minimizing the fading effect it becomes ineffective when the signal fades below the noise level.
- The use of diversity reception can eliminate this problem.
- **Two types of diversity reception system are in common use :**

i) Space diversity and
ii) Frequency diversity.

i) Space diversity

- **It takes the advantage of the fact that signals, received at different locations, do not fade out at the same time.**
- **In the short-wave range antennas spaced three to ten wave lengths apart will receive signals that are independent to one another.**
- **Several antennas, used in space diversity systems are provided with separate receivers. These receivers are connected to a common output so that a signal is always obtained as long as the signal intensity from at least one of the antennas is acceptable.**
- **The different receivers are operated from a common AGC system derived from the sum of the AGC output voltages of the receivers. Thus only the signal, from the strongest receiver is passed on to the common output stage, with other contributing little or nothing to the output.**



aw(2.45)**Fig. 19.14.2**

ii) Frequency diversity

- **Signals at different frequency, do not fade at the same time or synchronously. This fact is used in minimising fading in radio telegraph circuits.**
- **The same antenna is used for the receiver which work with simultaneous transmission at two or more frequencies.**
- **Since frequency diversity is more wasteful of frequency spectrum, it is used only when space diversity cannot be used for want of space as in ship-to-ship communication.**

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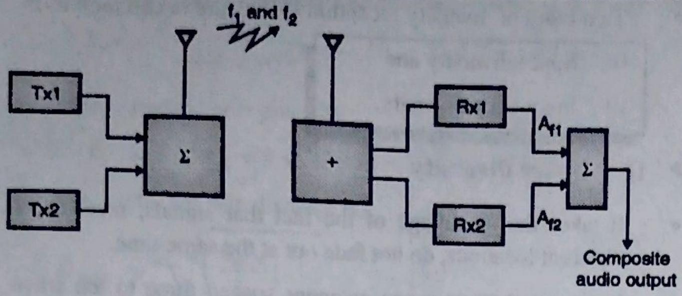


aw(2.46)**Fig. 19.14.3**

Applications

(1) Used in data transmission, such as telegraph transmission.

(2) Voice transmission, using PCM techniques.

19.15 MULTIHOP PROPAGATION

The multi hop propagation in ionosphere is similar to troposphere.

Depending on the transmitting antenna, signals below approximately 10 MHz during the day and 5 MHz at night may reach the ionosphere at a steep angle (vertical incidence) and be reflected straight back down to Earth. Alternately, if the antenna "aims" the signal close to the horizon; the signal reaches the ionosphere at a shallow angle and returns to Earth at a medium to long distance.

The Earth's surface (ground or water) reflects the incoming wave back toward the ionosphere again. As a result, like a rock "skipping" across water, the wave may actually "bounce" or "skip" between the earth and ionosphere two or more times (**multihop propagation**). Since at shallow incidence losses remain quite small, signals of only a few watts can sometimes be received many thousands of miles away as a result.

Other considerations

VHF signals with frequencies above about 30 MHz usually penetrate the ionosphere and are not returned to the Earth's surface. E-skip is a notable exception, where VHF signals including FM broadcast and VHF TV signals are frequently reflected to the Earth during late Spring and early Summer. E-skip rarely affects UHF frequencies, except for very rare occurrences below 500 MHz.

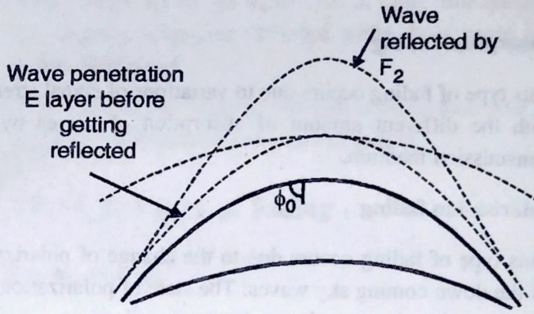
Frequencies below approximately 10 MHz (wavelengths longer than 30 meters), including broadcasts in the medium wave and shortwave bands (and to some extent long wave), propagate most efficiently by sky wave at night. Frequencies above 10 MHz (wavelengths shorter than 30 meters) typically propagate most efficiently during the day. Frequencies lower than 3 kHz have a wavelength longer than the distance between the Earth and the ionosphere. The maximum usable frequency for skywave propagation is strongly influenced by sunspot number.

Sky wave propagation is usually degraded sometimes seriously during geomagnetic storms. Sky wave propagation on the sunlit side of the Earth can be entirely disrupted during sudden ionospheric disturbances.

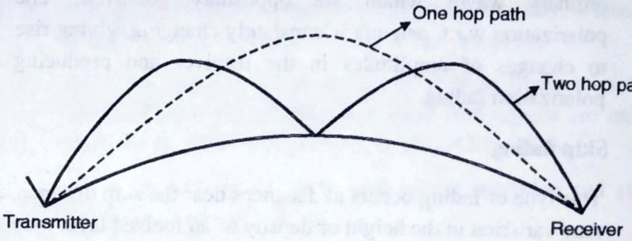
Because the lower-altitude layers (the E-layer in particular) of the ionosphere largely disappear at night, the refractive layer of the ionosphere is much higher above the surface of the Earth at night. This leads to an increase in the "skip" or "hop" distance of the skywave at night.

Sometimes the signal is reflected by the Earth back to the ionosphere, where it is again refracted and bent back down to Earth. Such multiple reflections, called "**multihop propagation**". They can allow radio signals to be picked up and heard for many thousands of miles. But such patterns are very hard to predict and may vary from hour to hour or day to day.

The multi hop multilayer propagation as shown in the Fig. 19.15.1(a).



aw(2.41)**Fig. 19.15.1(a) : One hop multilayer propagation**



aw(2.41)**Fig. 19.15.1(b) : Distance of receiver greater than one hop distance**

When the wave originating from transmitter reaches the receiver without touching the ground in between, it is known as one hop distance. When the receiver is beyond one hop distance, multihop communication is the solution. The link between transmitter and receiver is maintained in four ways namely :

1. Single hop single layer.
2. Single hop multilayers of atmosphere.
3. Multihop single layer.
4. Multihop multilayers of atmosphere.

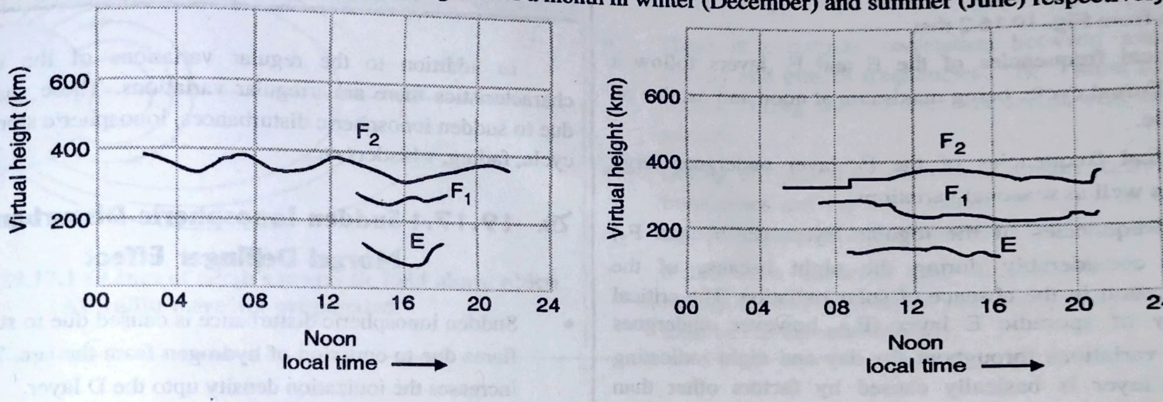
Referring to Fig. 19.14.1, the upper ray is weaker than the lower ray in terms of its energy contents since over a given solid angle, it spreads more as compared to the lower ray. In this case it becomes difficult for the lower ray to reach the receiver in one hop. When the earth's curvature prevents one hop lower ray or when the distance between transmitter and the receiver is greater than the skip distance then **multihop communication** is the answer. Also if the frequency used falls between the critical frequencies of E and F_1 layers and the receiver is beyond the skip distance of E layer, two or three separate layers can contribute to the propagation. The link between transmitter and the receiver is then obtained by multihop propagation.

19.16 REGULAR VARIATIONS OF THE IONOSPHERE

- Conditions in the ionosphere varying throughout the day with the angle of Sun's rays and regularly with the season. The effect of it will be directly on critical frequencies and virtual heights.
- A picture of critical frequencies and virtual heights gives a good understanding of the ionospheric variations.

19.16.1 Variation of Virtual Height

- The virtual heights of E, F_1 and F_2 layers undergo diurnal and seasonal variation shown in Fig. 19.16.1(a) and (b) the nature of diurnal (daily) variations of virtual heights averaged over a month in winter (December) and summer (June) respectively.



aw(2.47)**Fig. 19.16.1 : Monthly average diurnal variation of virtual heights of ionospheric layers in winter and summer**

- It may be seen from Fig. 19.16.1(a) that **during winter.**
  (i) The virtual height of F_2 layer does not undergo wide diurnal variations.
  (ii) The virtual heights of E and F_1 layer suffer inappreciable diurnal variation.
  (iii) The F_1 layer lasts only for about 10 to 12 hours during day time and then merges with F_2 layer.
- From Fig. 19.16.1(b) we see that **during summer.**
  (i) The virtual heights of F_2 layer undergoes large variation, the maximum height occurring sometimes in the afternoon.
  (ii) Virtual height of both E and F_1 layers vary only slightly during the day. Figs. 19.16.2(a) and (b) show the nature of the diurnal variation of the critical frequencies of ionospheric layers averaged over a month in winter (December) and summer (June) respectively for a specific location in temperature climate.

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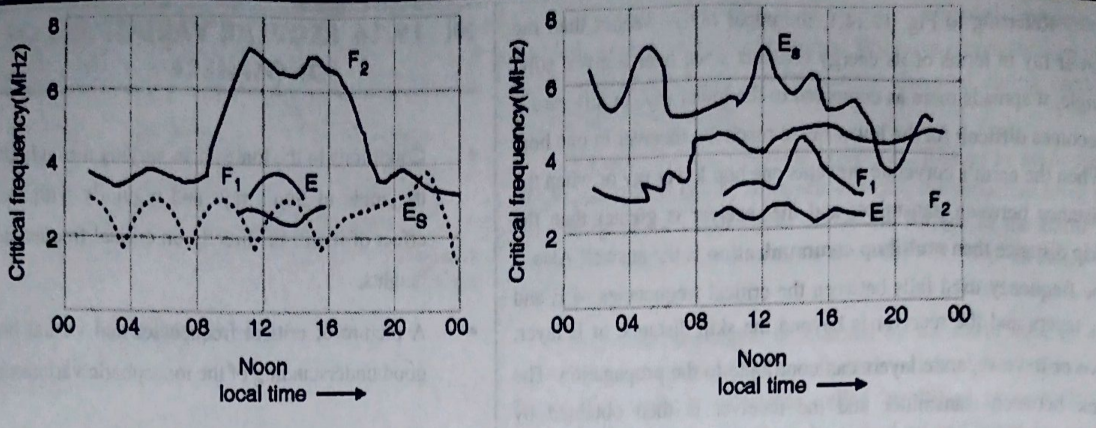


(a) December (b) June

aw(2.48)**Fig. 19.16.2 : Monthly average diurnal variation of critical frequencies of ionospheric layers in winter and summer**

19.16.2 Variation of Critical Frequencies

It may be seen from Fig. 19.16.2 that

(i) The critical frequencies of the E and F_1 layers follow a regular diurnal cycle, being maximum at noon and decline on either side.

(ii) The critical frequencies of the F_2 layer undergoes large diurnal as well as seasonal variations.

(iii) Critical frequencies of the regular layers (E, F_1 and F_2) decrease considerably during the night because of the recombination in the absence of solar radiation. The critical frequency of sporadic E layer (E_s), however, undergoes irregular variations throughout the day and night indicating that this layer is basically caused by factors other than radiations.

- The critical frequency increases with the altitude of the sun. It is maximum on a summer day. The critical frequency of an E layer is given as,

$$f_E = K \sqrt[4]{\cos \psi}$$

where ψ = zenith angle of the sun.

K = depends on intensity of radiation from sun.

The virtual height measurement is done using the relation

$$N = \frac{\omega^2 m \epsilon_v}{e^2}$$

The maximum value of N for any layer is given as,

$$N_{max} = \frac{\omega^2 m \epsilon_v}{e^2}$$

where f_c = critical frequency for layer ;

N = number of electrons per cubic meter.

19.17 IRREGULAR VARIATIONS OF THE IONOSPHERE

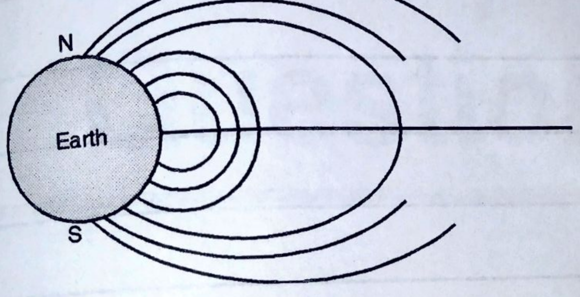
In addition to the regular variations of the ionospheric characteristics there are irregular variations. These variations are due to sudden ionospheric disturbances, ionospheric storm, sunspot cycle, fading, whistlers etc.

19.17.1 Sudden Ionospheric Disturbances : Morgel Dellinger Effect

- Sudden ionospheric disturbance is caused due to sudden solar flares due to emission of hydrogen from the sun. The X rays increases the ionization density upto the D layer.
- Due to this there is an increase in the absorption of short wave i.e. high frequency signals and increased reflection of atmospheric noise.
- Consequently, the value of lowest usable frequency increases beyond maximum usable frequency (MUF), resulting in complete black out of all high frequency sky wave communication via ionosphere.
- This type of sudden ionospheric disturbance may last from a few minutes to about an hour and takes place simultaneously everywhere on the sunlit portions of the globe.
- The phenomenon of complete black out is known as sudden ionospheric disturbance and was first noticed by scientist Morgel and Dellinger and is named after their name.
- It is noted that during sudden ionospheric disturbance the VLF propagation improves.
- The frequency of occurrence increases as the sun spot cycle advances and it rarely occurs during the sun spot minimum.

19.17.2 Whistlers

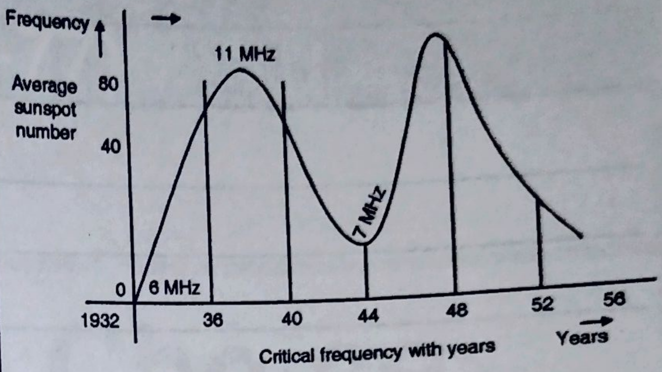
- Naturally occurring transient electromagnetic disturbances in receivers are called **whistlers.** These are associated with electromagnetic pulses of audio frequency radiation propagation along the lines of the earth's magnetic field between conjugate points in the northern hemisphere and southern hemisphere.
- The lightening discharges generate the pulses which may "bounce" back and forth before several times before disappearing, between the two hemispheres.
- These whistlers may be long whistlers, short whistlers and noise whistlers.
- Fig. 19.17.1 shows that audio-frequency waves generated by lightning flashes in the polar area may well travel through the ionosphere.



aw(2.49)**Fig. 19.17.1 : Lines of earth's magnetic field along which AF radio wave are propagated**

19.17.3 Sunspot Cycle

- Sun has 11 years cycle over which its output varies tremendously.
- Solar disturbances are measured by sun spot counting.



aw(2.50)**Fig. 19.17.2 : Sunspot cycle**

- There is a definite correlation between average sunspot activity and critical frequencies. The critical frequencies are highest during sunspot maxima and lowest during sunspot minima.
- During the period of minimum sunspot activity, the lower frequencies are the only usable at night, as such time the higher frequencies are seldom used for long distance work.
- It has been observed that all ionospheric characteristics closely follow, the eleven year sunspot cycle and therefore must be considered seriously.

Chapter Ends...

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