11.4. MODES OF PROPAGATION

(AMIETE, Dec. 1992)

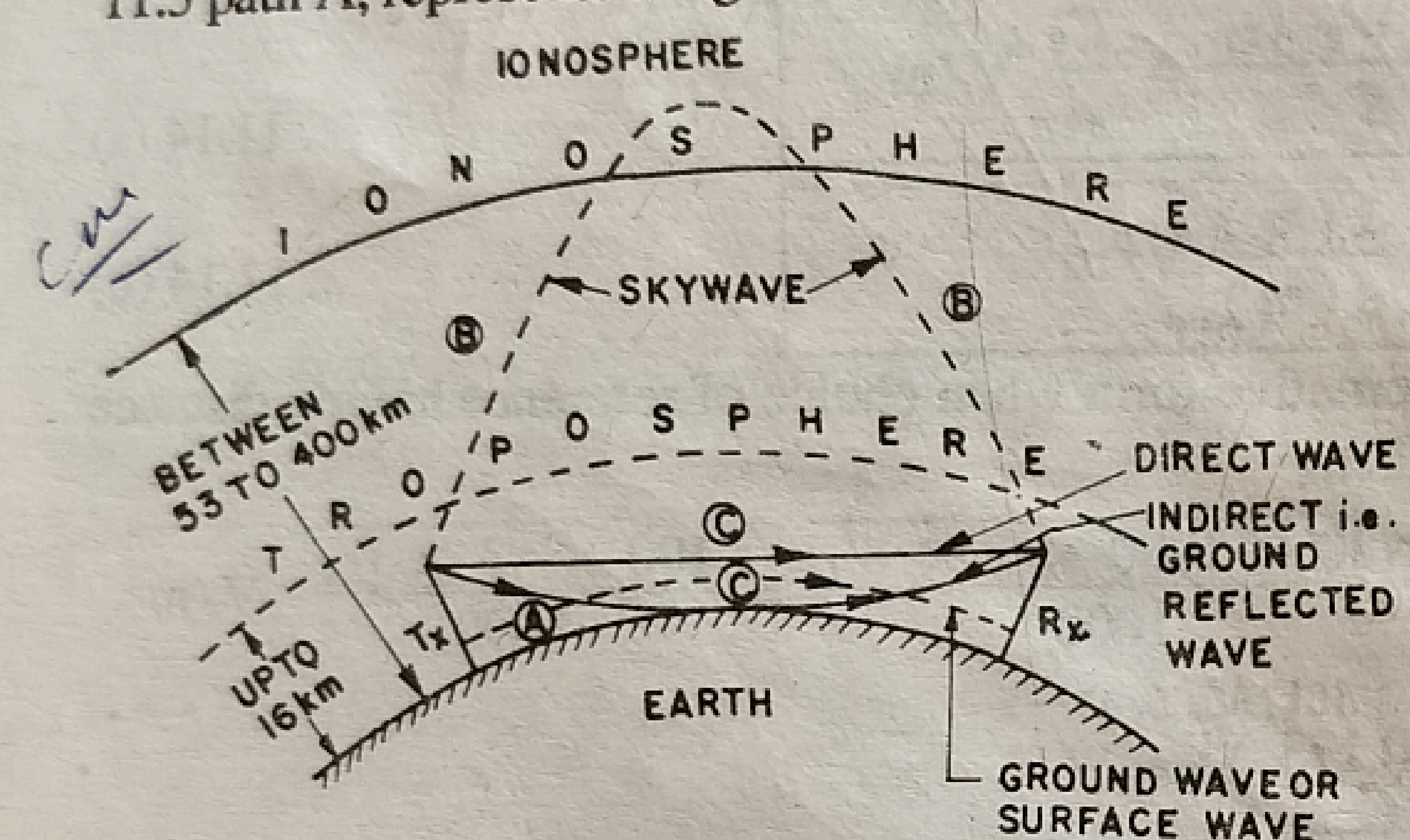
The radio waves from the transmitting antenna may reach to the receiving antenna following any of the following modes of propagations depending upon several factors like frequency of operation, distance between transmitting and receiving antennas etc.

11.4.1. *Ground Wave or Surface Wave Propagation (Upto 2 MHz)* 2MHz . 3MHz

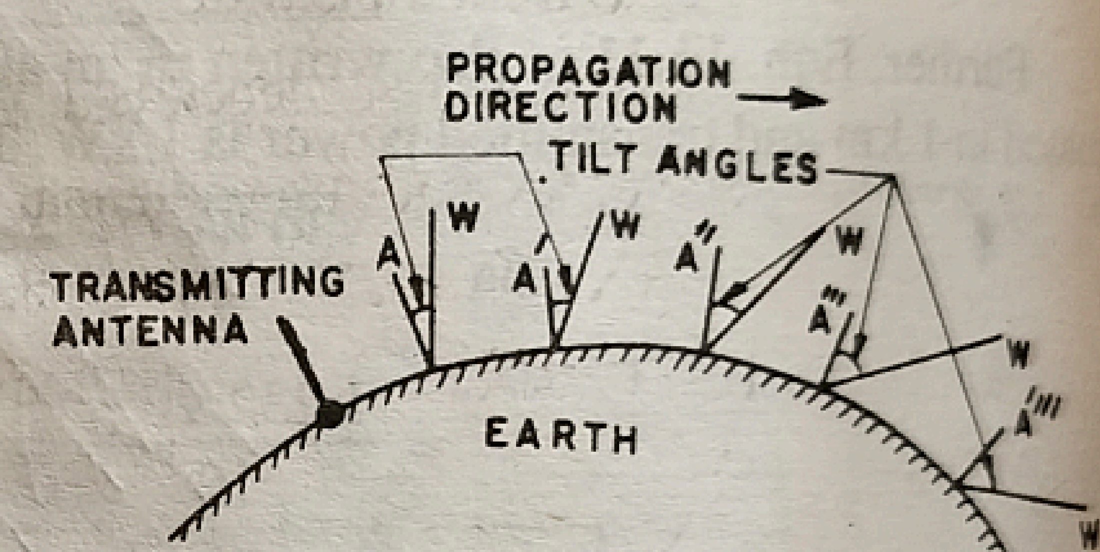
(AMIETE, May 1976, ~~77, 78~~, 79, 93, Nov. 1977, 78, 1985, 1992)

The ground wave or surface wave (sometimes also called as Norton's surface wave) is of practical importance at broadcast and lower frequencies *i.e.* for medium waves, long waves and very long waves. The ground wave is a wave that is guided along the surface of the earth just as an electromagnetic wave is guided by a waveguide or transmission line. Surface wave permits the propagation around the curvature of the earth. This mode of propagations exist when the transmitting and receiving antennas are close to the surface of earth and is supported at its lower edge by the presence of the ground. The ground wave as being produced usually, by vertical antennas, is vertically polarized *i.e.* Electric field vectors of e.m. waves are vertical w.r.t. to ground as shown in Fig. 11.1. Any horizontal component of electric field in contact with the earth is short circuited by the earth. The ground wave propagation along the surface of the wave, induce charges in the earth, which travel with the wave and hence constitute a current. While carrying this induce current the earth behaves just as a leaky capacitor and, therefore, the earth can be represented as a resistance in shunt with a capacitor. This behaviour of earth as a conductor may be described in terms of conductivity and dielectric constant *k*.

When the surface wave glides over the surface of the earth energy is abstracted from the surface wave to supply the losses in the earth. *Thus while passing over the surface of the earth, the surface wave looses some of its energy by absorption.* Energy lost so, is, however, replenished to a certain extent, by the energy diffracted downward from the upper portion of the wave front present some what above the immediate surface of the earth. The ground wave, therefore, suffers varying amount of attenuation while propagating along the curvature of the earth, depending upon frequency, surface irregularities, permittivity and conductivity. Earth's attenuation increases as the frequency increases and hence the mode of propagation is suitable for low and medium frequency *i.e.* upto 2 MHz only. At higher frequency, wave attenuation by ground is much more than at low frequency over the same ground. It is also called as medium wave propagation and is used invariably in local broadcasting. All the broadcast signals received during day time is due to ground wave propagation. In Fig. 11.5 path A, represents the ground or surface wave propagation.



Tx = Transmitting antenna.
Rx = Receiving antenna.
Path A = Ground wave propagation.
Path B = Sky or ionospheric propagation.
Path C = Space wave propagation.
Fig. 11.5. Possible propagation paths from transmitting antenna to receiving antenna



W = Successive wave fronts
A, A, A'', A''', A' = Tilt angles in increasing order
Fig. 11.6. Tilting wave wave fronts in ground wave progagation.

Besides ground attenuation, there is still another way in which surface wave is attenuated *i.e.* due to diffraction and tilt in the wave front as illustrated in Fig. 11.6. As the wave progress over the curvature of the earth, the wave fronts start gradually tilting more and more. This increase in the tilt of wave causes more short circuit of the electric field component and hence the field strength goes on reducing. Ultimately, at some appreciable distance from the transmitting antenna in wavelength, the surface wave dies because of the losses mentioned above.

It may be noted that maximum range of surface wave propagation depends not only on the frequency but power as well. Hence range of transmission can be increased by increasing the power of the transmitter in the VLF band but this method can not be effective at the MF band (higher side) where the tilting due to diffraction is more effective.

The field strength at a distance from the transmitting antenna due to ground wave has been calculated from the Maxwell eqns. as

$$E = \frac{120\,\pi\, h_t \cdot h_r I_s}{\lambda\, d} \text{ Volt/meter} \quad \text{... (11.16)}$$

where $120\,\pi \simeq 377\,\Omega$ = Intrinsic impedance of free space.

h_t, h_r = Effective heights of transmitting and receiving antennas.

I_s = Antenna currents.

λ = wavelength.

d = distance between transmitting and receiving points.

If, however, the distance d is fairly large, the reduction in the field strength due to ground attenuation and atmospheric absorption increases and thus the actual voltage received at receiving point decreases. This results in less field strength than that shown by eqn. 11.16.

According to Sommerfeld, the field strength for ground wave propagation for a flat earth is given by

$$E_g = \frac{E_0 A}{d} \quad \text{.... (11.17)}$$

where E_0 = Ground wave field strength at the surface of earth, at unit distance from the transmitting antenna. Earth losses not accounted.

E_g = Ground wave field strength.

A = Factor accounting for earth losses called attenuation factor.

d = Distance from transmitting antenna expressed in the same unit as E_0.

Unit distance field strength E_0 depends upon

(i) Power radiation of transmitting antenna.

(ii) Directivity in vertical and horizontal planes.

If the antenna is non-directional in the horizontal plane, producing a radiated field which is proportional to the cosine of the angle of elevation (as in case of short vertical antenna), then the field at unit distance (i.e. 1 km) for a radiated power of 1 kW is given by the general formula

$$E_0 = \frac{300\sqrt{P}}{d} \text{ V/m} = \frac{300\sqrt{1}}{1000} \text{ V/m} = 300 \text{ mV/m} \quad \text{.... 11.17 (a)}$$

where P = radiated power in kiloWatts and d = distance in kilometers.

This is because, for a short vertical unipole antenna (grounded antenna), the field strength E_0 at a distance of d on a hypothetical flat perfectly conducting earth is

$$E_0 = \frac{\sqrt{90\,P}}{d} \text{ volts/metres} \quad \text{... 11.18 (a)}$$

where P = radiated power in Watts

and d = distance in metres.

when P is expressed in kilowatts (kW) and d in kilometres (km), then eqn. 11.18 (a) reduced to

$$E_0 = \frac{\sqrt{90 \times P \times 1000}}{d} \text{ V/m}$$

Since P = 1 kW = 1000 Watts and d = 1 km = 1000 m

$$E_0 = \frac{300\sqrt{P}}{d} \text{ V/m}$$

If d is expressed in miles, then

$$E_0 = \frac{300\sqrt{P}}{1.609} \text{ mV/miles} = 186.45 \text{ mV/miles} \quad \text{... 11.18 (b)}$$

Thus for radiated power of 1 kW, E_0 = 300 mV/m at a distance of 1 km and E_0 = 186.45 mV/m at a distance of 1 mile. For other values of radiated power, E_0 will be proportional to the square root of the power P and will accordingly be modified in accordance with the directivity in horizontal plane, and for any added directivity when the field is not proportional to the cosine of the angle of elevation.

P being effective power radiated in kiloWatt and d, the distance in kilometers. The reduction factor A in eqn. 11.17, accounting for earth losses too, depends on :

(i) frequency (ii) dielectric constant

(iii) conductivity of the earth

A is a complicated function of above factors, expressed in terms of two auxiliary variables, the numerical distance p and phase constant b.

These two constants p and b are determined by the frequency, distance and dielectric characteristics of ground considered as a conductor of radio frequency currents and are given as follows.

(i) ***For Vertically polarised wave.*** The reduction factor A is expressed in terms of two auxiliary parameters p and b.

The parameter p and b are related as

$$p = \frac{\pi}{x} \cdot \frac{d}{\lambda} \cos b \quad \text{... 11.19 (a)}$$

and

$$b = \tan^{-1}\left(\frac{\varepsilon_r + 1}{x}\right) = 2b_2 - b_1 \quad \text{... 11.19 (b)}$$

and

$$x = \frac{1.8 \times 10^{12}\,\sigma}{f(\text{Hz})} \text{ mhos/cm} = \frac{1.8 \times 10^{4}\,\sigma}{f(\text{MHz})} \text{ mhos/m} \quad \text{... (11.20)}$$

(ii) ***For horizontally polarized wave :*** The parameters p and b are given by

$$p = \frac{\pi d}{\lambda} \cdot \frac{x}{\cos b}$$

$$b = 180° - b_1 \quad \text{... (11.21)}$$

and

$$b_1 = \tan^{-1}\left(\frac{\varepsilon_r - 1}{x}\right) \quad \text{... (11.22)}$$

$$b_2 = \tan^{-1}\frac{\varepsilon_r}{x} \quad \text{... (11.23)}$$

where b_2 = Power factor angle of the impedance offered by the earth to the flow of current.

f = frequency, in Hz.

σ = the conductivity of the earth, in mhos/cm.

ε_r = dielectric constant of the earth relative to air.

λ = wavelength in same unit as d.

11.4.2. *The Ground wave Attenuation factor A.* The relation between numerical distance p and phase constant b is shown in Fig. 11.7. The numerical distance p depends upon the frequency and the ground constants and the actual distance to the transmitter. It is proportional to the distance and the square of the frequency and varies almost inversely with the ground conductivity. The phase constant b is a measure of the power- factor angle of the earth. The attenuation factor A may be represented by following empirical formula

For $b < 5°$

$$\boxed{A \cong \frac{2 + 0.3\,p}{2 + p + 0.6\,p^2}} \quad \text{... (11.24)}$$

and $$p = \frac{0.582\, d_{km}\, f^2_{(MHz)}}{\sigma\,(mS/m)}$$ (11.25)

The auxiliary parameter p is called the numerical distance. For all values of b, the value of A is given by

$$A = \frac{2 + 0.3\,p}{2 + p + 0.6\,p^2} - \sin b \sqrt{\frac{p}{2}} \cdot e^{-\frac{5}{8}p} \quad \text{... (11.26)}$$

Earth offers a resistive impedance to the flow of radio frequency currents when $b = 0$ for vertical polarization and $b = 180°$ for horizontal polarization and offers a capacitive impedance when $b = 90°$ for either polarization. The study of Fig.11.8 shows that

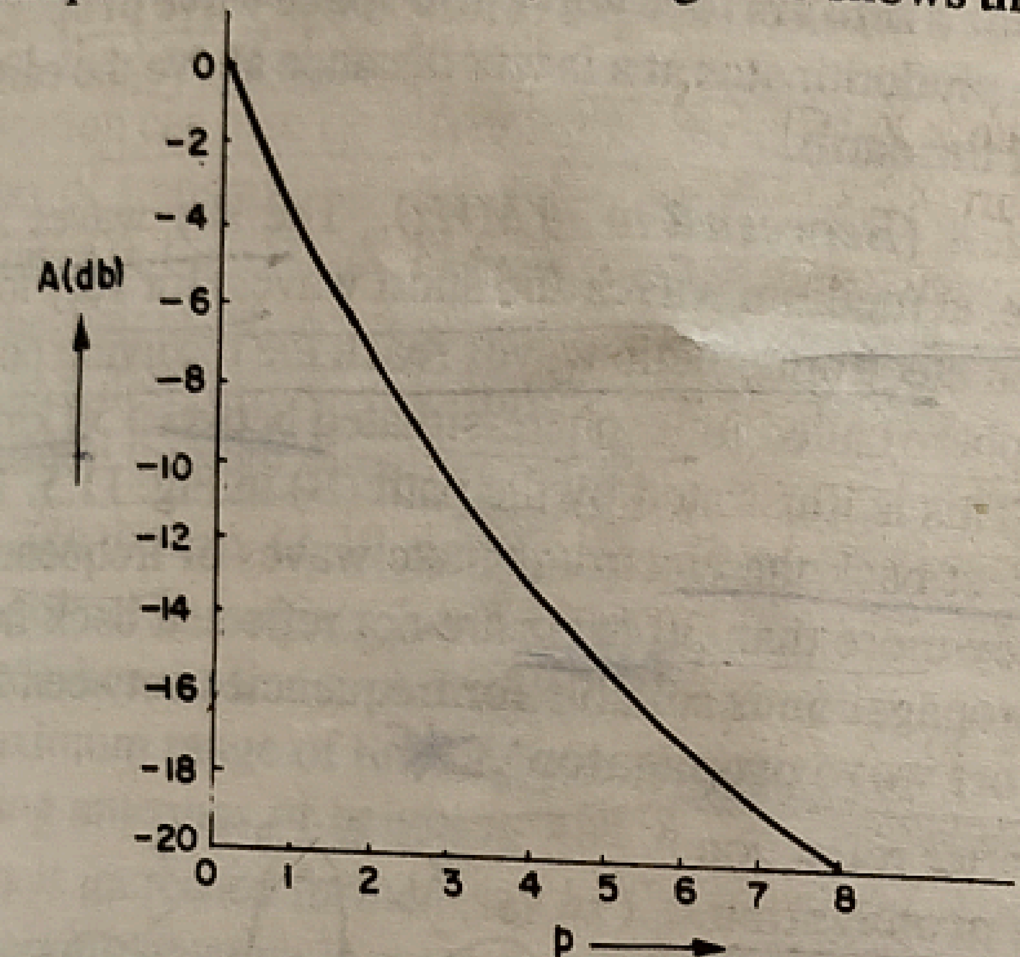


Fig. 11.7. Shows graph of the approximate values of ground wave attenuation factor A against numerical distance p based on eqn. 11.24.

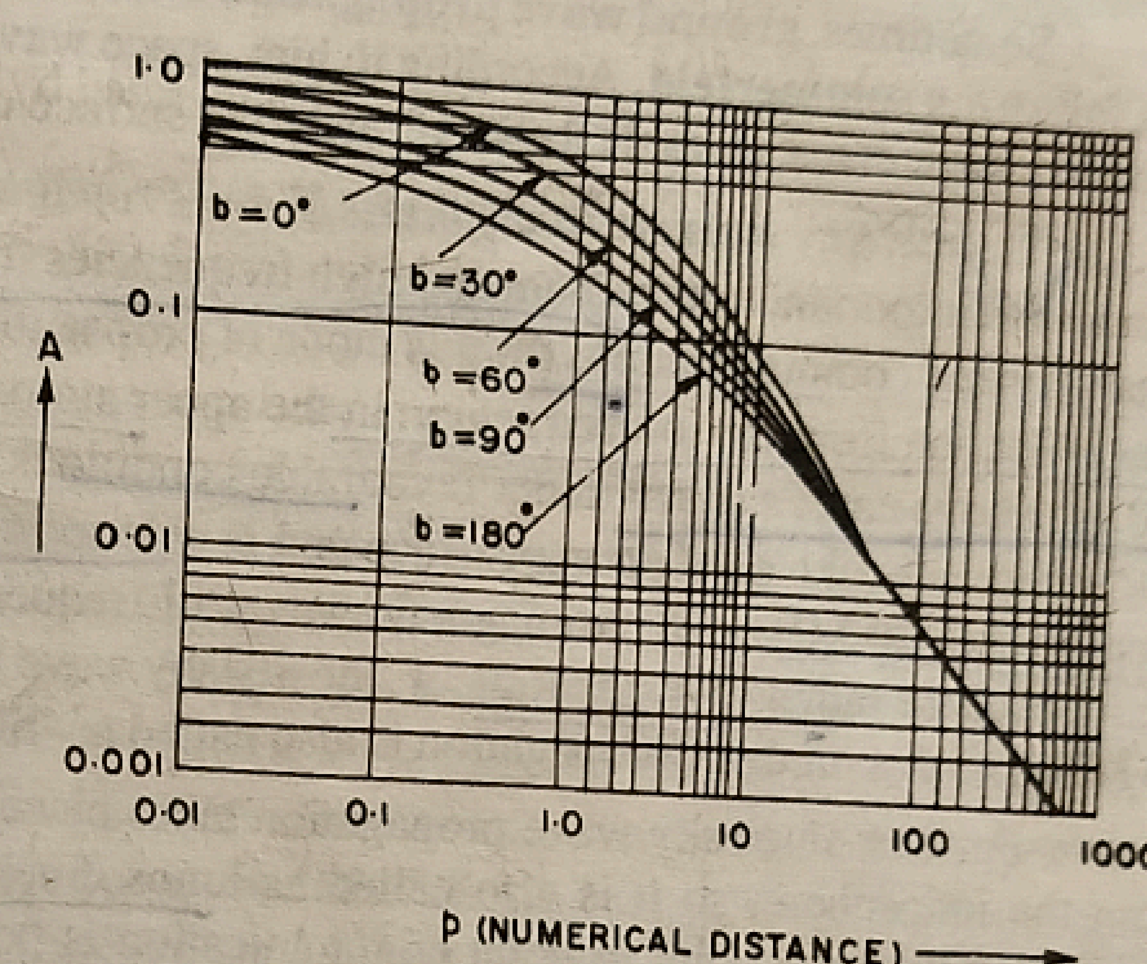


Fig. 11.8. Variation of ground attenuation factor A with numerical distance p for different values of b.

(i) For $p < 1$. The ground attenuation factor A differs only slightly from unity and reduces slowly with the increase of p. The ground losses are then not significant. From eqn. 11.17 it can be seen that the field strength of the ground wave varies inversely with the distance.

(ii) For $p > 1$. As the numerical distance p becomes greater than unity, the attenuation factor A decreases rapidly.

(iii) For $p > 10$. The attenuation factor A is almost exactly inversely proportional to actual physical distance. Hence for $p > 10$, the field strength of the ground wave is inversely proportional to the square of the distance.

The value of numerical distance p of the plane earth (eqn.11..25) ground wave attenuation factor ignores the effect of diffraction and ground permittivity. The variation of p and ground attenuation factor A is shown in Fig. 11.7. This gives realistic answers for the distance less than d_{max} where

$$d_{max} = \frac{100}{f^{1/3}} = \frac{100}{\sqrt[3]{f}} \text{ km} \quad \text{... (11.27)}$$

$\frac{100}{(6)^{1/3}}$

where d_{max} is in km and f is in MHz. Typical value of the maximum distance is 125 km to 90 km corresponding to a frequency range of $f = 0.5$ MHz to 1.5 MHz.

A slightly more accurate solution is obtained within the same limit of distance by incorporating the relative permittivity ε_r of the ground path. This is achieved through yet another auxiliary parameter b^* defined by

$$\tan b^\circ = \frac{(\varepsilon_r - 1)f}{18\,\sigma} \quad \ldots (11.28)$$

with the auxiliary parameter for numerical distance reduced to

$$p = \frac{0.582\, d \cdot f^2 \cos b^\circ}{\sigma} \quad \ldots (11.29)$$

where d is in km, f is in MHz and σ is in mS/m.

The expression for A is then changed to eqn. 11.26. These assumptions assume a plane earth, a vertical polarization and distances restricted to d_{max}. The difference in above equations and equations shown earlier is only of units.

Sometimes, ground wave propagation is sub-divided into surface wave and space wave propagation following sommerfeld. According to him, space wave predominates at a larger distance above the earth, where as, the surface wave is the larger near the surface of the earth.

11.4.3. *Sky wave or Ionospheric Wave Propagation. (Between 2 to 30 MHz).* The sky waves are of practical importance at medium and high frequencies (*i.e.* at medium waves and short waves) for very long distance radio communications. In this mode of propagation electromagnetic waves reach the receiving point after reflection from the ionized region in the upper atmosphere called ionosphere-situated between 50 km to 400 km above earth surface-under favourable conditions. This is illustrated by the path (B) in Fig. 11.5. The ionosphere acts like a reflecting surface and is able to reflect back the electromagnetc waves of frequencies between 2 to 30 MHz. Electromagnetic waves of frequency more than 30 MHz are not reflected back from the ionosphere rather they penetrate it. Mostly sky wave propagation is suitable for frequencies between 2 to 30 MHz, so this mode of propagation is also called as **'Short wave propagaton'.**

Further, since sky wave propagation takes place after reflection from the ionosphere, so it is also called as **ionospheric propagation.** Since long distance point to point communication is possible with sky wave propagation, so it is also called as **point to point propagation or communication** by engineers and scientists. Extremely long distance *i.e.* round the globe communication is also possible with the multiple reflections of sky waves as shown in Fig 11.9. In a single reflection from the ionosphere the radio waves cover a distance not more than 4000 km.

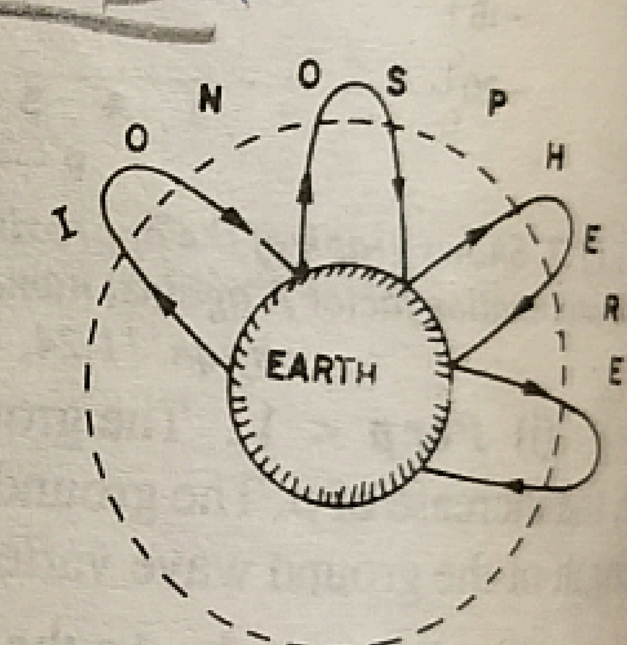


Fig. 11.9. Shows multiple reflections of radio waves from ionosphere.

The signals received due to sky wave propagation are, however, subjected to fading in which signal strength varies with time. It is because at the receiving point a large number of waves follow a different number of paths. Hence provision has to be made to overcome the fading.

11.4.4 *Space wave propagation (above 30 MHz).* The space wave propagation of practical importance at VHF bands (between to 30 MHz to 300 MHz), U.H.F. and microwaves and communications like televisions, radar, frequency modulations etc.. utilize this mode of propagation. In this mode of propagation, electromagnetic waves from the transmitting antenna reach the receiving antenna either directly or after reflections from ground in the earth's **troposphere region.** Troposphere is that portion of the atmosphere which extends upto 16 km from the earth surface (Fig. 11.5, path C). Space wave consists, of at least two components *e.g.* direct component and indirect *i.e.* ground reflected components. It means in the former, wave reaches directly from the transmitting antenna to receiving antenna and in latter, the wave reaches the receiving antenna after reflection from the ground, where the phase change of 180° is also introduced due to reflection at the ground, in the ground reflected wave. Although both the waves (direct and indirect) leave the transmitting antenna at the same time with the same phase but may reach the receiving antenna either in phase or out of phase, because the two waves travel different path lengths. The strength of the resultant waves, thus, at the receiving point may be stronger or weaker than the direct path alone depending upon whether the two waves are adding or opposing in phase. At receiving point the signal strength is the vector addition of direct and indirect waves. Space wave propagation is also called as *Tropospheric propagation* because space wave propagates through troposphere.

Space wave propagation is mainly in VHF, and higher frequencies because at such frequencies sky wave and ground wave propagations both fail. Beyond 30 MHz sky wave fails as the wavelength becomes too shorts to be reflected from the ionosphere and ground waves are propagating close to the antenna only, as attenuation ~~is very high~~. Therefore just after few hundred feet ground waves too die due to attenuation and wave tilt. Space wave propagation is also called as *line of sight* propagation because at VHF, UHF and microwave frequencies, this mode of propagation is limited to the line of sight distance and is also limited by the curvature of the earth. Although in actual practice space waves propagate even slightly beyond the line of sight distance due to refraction in the atmosphere of the earth. In line of sight distance transmitting antenna and receiving antenna can usually "see" each other.

In fact, the line of sight distance i.e. range of communication can also be increased by increasing the heights of transmitting and receiving antennas as illustrated in Fig. 11.10. The curvature of the earth and the height of the transmitting and receiving antennas determines maximum range of communication through direct waves.

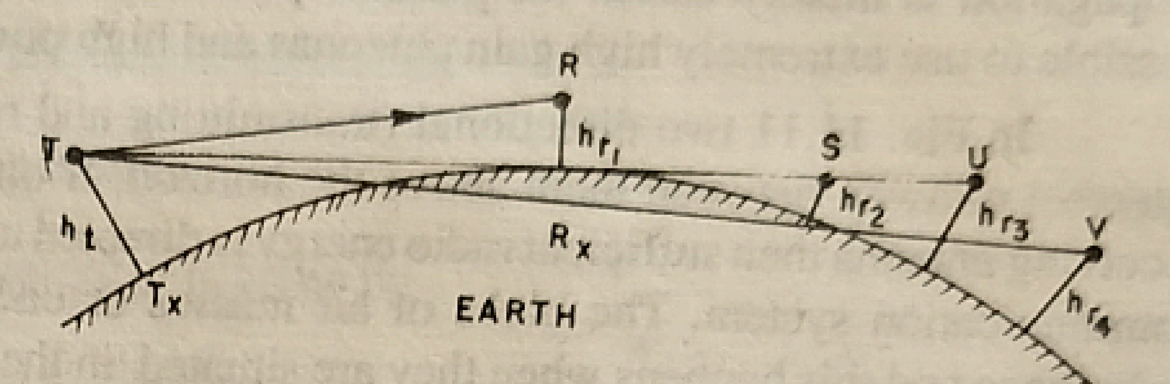


Fig. 11.10. Direct ray propagation..

In the Fig. 11.10, with the height of transmitting antenna, h_t and receiving antenna h_{r_1}, the direct wave communication range is *TR*. As the range is increased *i.e.* receiving antenna is moved away from *R*, a point is reached when the line of sight distance from *T* to *S* will just graze over the surface of earth. Then *TS* represents the maximum range of line of sight distance upto which communication is possible with the transmitting and receiving antennas of height h_t and h_{r_2}. This line of sight distance can still be increased if heights of either antenna is increased further (say h_3) point *U* which means the range has increased from *TS* to *TU*. Lastly, if the receiving antenna is moved to a distance which is not in the line of sight distance just like point *V* of the same height h_{r_3}, then no direct wave signal reception is possible.

In fact, the line of sight distance has now been extended by what is known as *Space Communication or specially Satellite Communication* which has facilitated trans-oceanic propagation of microwaves with the potentiality of large bandwidth. By space communication we mean the radio traffic between a ground station and satellite or space probe, between satellites or space probes and also between ground stations itself via man made communication satellites or natural space body (e.g. the sun, the moon, the venus etc.)

11.4.5. *Tropospheric Scatter Propagation or Forward Scatter Propagation (UHF and Microwaves i.e. above 300 MHz)*

(AMIETE, June 1974, 80, 91, 92, 93, Dec. 87, 89, 82)

Forward scatter propagation or simply scatter propagation is of practical importance at VHF, UHF and microwaves. UHF and microwaves signals were found to be propagated much beyond the line of sight propagation through the forward scattering in the tropospheric irregularities. It uses certain properties of troposphere and is also known as *Troposcatter* as illustrated in Fig. 11.11. This has also lead to the discovery of ionosphere scatter propagation for signal frequencies in the lower end of VHF band. Therefore, in the recent years, it has been established that it is possible to achieve a very reliable communication over communication range of 160 km to 1600 km by using high power transmitter and high gain antennas *i.e.* reliable scatter propagation is possible in the VHF and UHF bans. The name scatter propagation (beyond the horizon propagation) is given to it due to mechanism involved in the phenomenon.

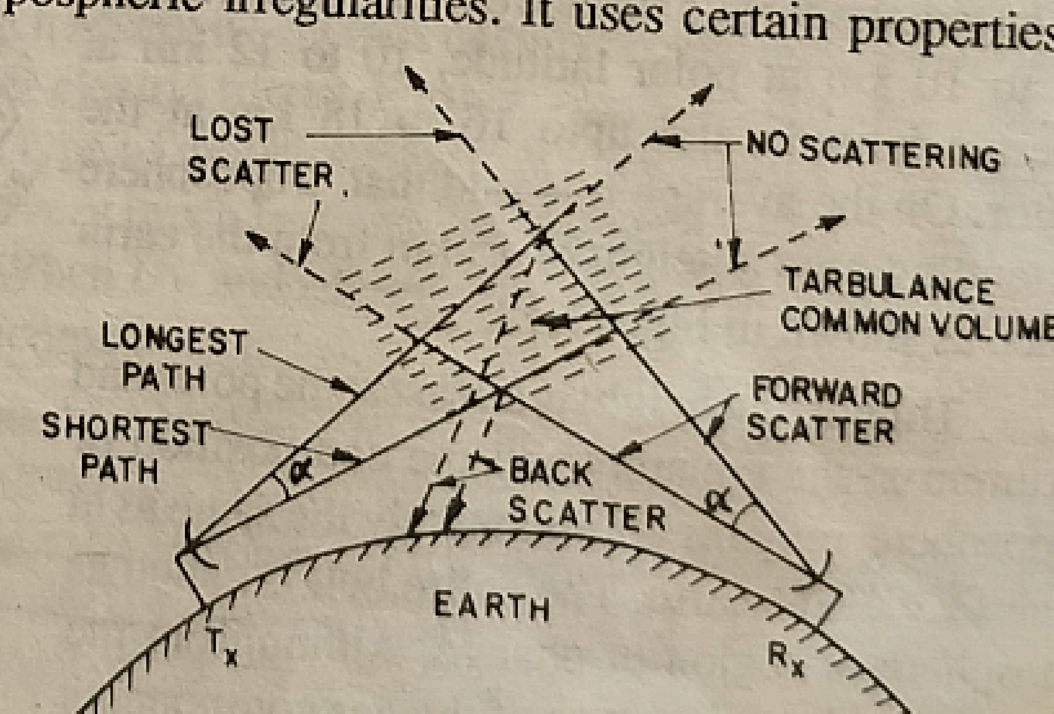


Fig. 11.11. Tropospheric scatter propagation.

Infact, the physical mechanism is not yet completely known but there are two different theories involved in forward scatter propagation. *The first mode is ionospheric and is believed to be resulted from the scattering of radio waves from the Lower E layer of the ionosphere. The second mode is Tropospheric and is thought to be result of scattering from either blobs or fine layers in the troposphere.*

It is suggested that ionospheric scatter might be due to blobs or fine layers at the lower edge of the E layer or it could be from the ionized trails of myriads of small meteors which bombard the earth from the outer space. Ionospheric scatter permits communication in the communication range of about 1000 km to 2000 km at about 25 MHz to 60 MHz. However, the importance of ionospheric scatter propagation decreases beyond 60 MHz, but at the same time tropospheric scatter propagation appears to be effective starting from 100 MHz to atleast 10 GHz *i.e.* 10,000 MHz. Due to the greater attenuation of signals along the path, forward scatter propagation is mainly useful for point to point communication, radio or television relay links where it is possible to use extremely high gain antennas and high power transmitters.

In Fig. 11.11 two directional (transmitting and receiving) antennas are so pointed that their beams intersect midway between them above the horizon. If one is UHF transmitting antenna and the other UHF receiving antenna then sufficient radio energy is directed towards in the receiving antenna to make this a useful communication system. The blobs of air masses or eddies in the troposphere scatter radio waves due to turbulence and this happens when they are situated in the common volume facing transmitting and receiving antennas beams. When the wavelength is more (frequency low) than the eddies, the scattering may occur in all directions even some back scattering too. On the other hand, when the wavelength is small (frequency high) than the eddies, forward scattering dominates into the cone of angle α (Fig. 11.11). The angle α should be as small as possible. The best and typical used frequencies are centered on 900 MHz, 2000 MHz, 5000 MHz.

Both ionospheric and tropospheric scatters sometimes, produce undesirable noise and fading which may be minimized to certain extent by diversity reception.

Besides these four modes of propagation, sometimes there is formation of inversion layers in the troposphere under certain tropospheric conditions. Propagation in these layers is called **'duct propagation'** or **Super-refraction** and long distance communication with relatively less attenuation is possible in frequency range of 300 MHz to 30,000 MHz *i.e.* UHF and SHF bands.

11.5. STRUCTURE OF ATMOSPHERE

Since the medium between transmitting and receiving antennas plays an important role, therefore, it is necessary to study the medium above earth, through which the radio waves propagate before further study on modes of propagation is taken. We shall be restricting ourselves to (a) structure of troposphere, (b) structure of ionosphere and (c) outer atmosphere.

11.5.1. *Structure of Troposphere.* Troposphere is that portion of the earth atmosphere which from the earth's surface extends 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 it is said that troposphere is extending upto a height of 15 km from the earth surface as shown in Fig. 11.12.

Thus actual height is atleast at the poles and maximum at the equators and the composition of Troposphere remains approximately the same as at the surface of the earth. The entire belt is called as troposphere or region of change. Although in the troposphere, the percentage of the gas components remains almost constant with increase of height, yet

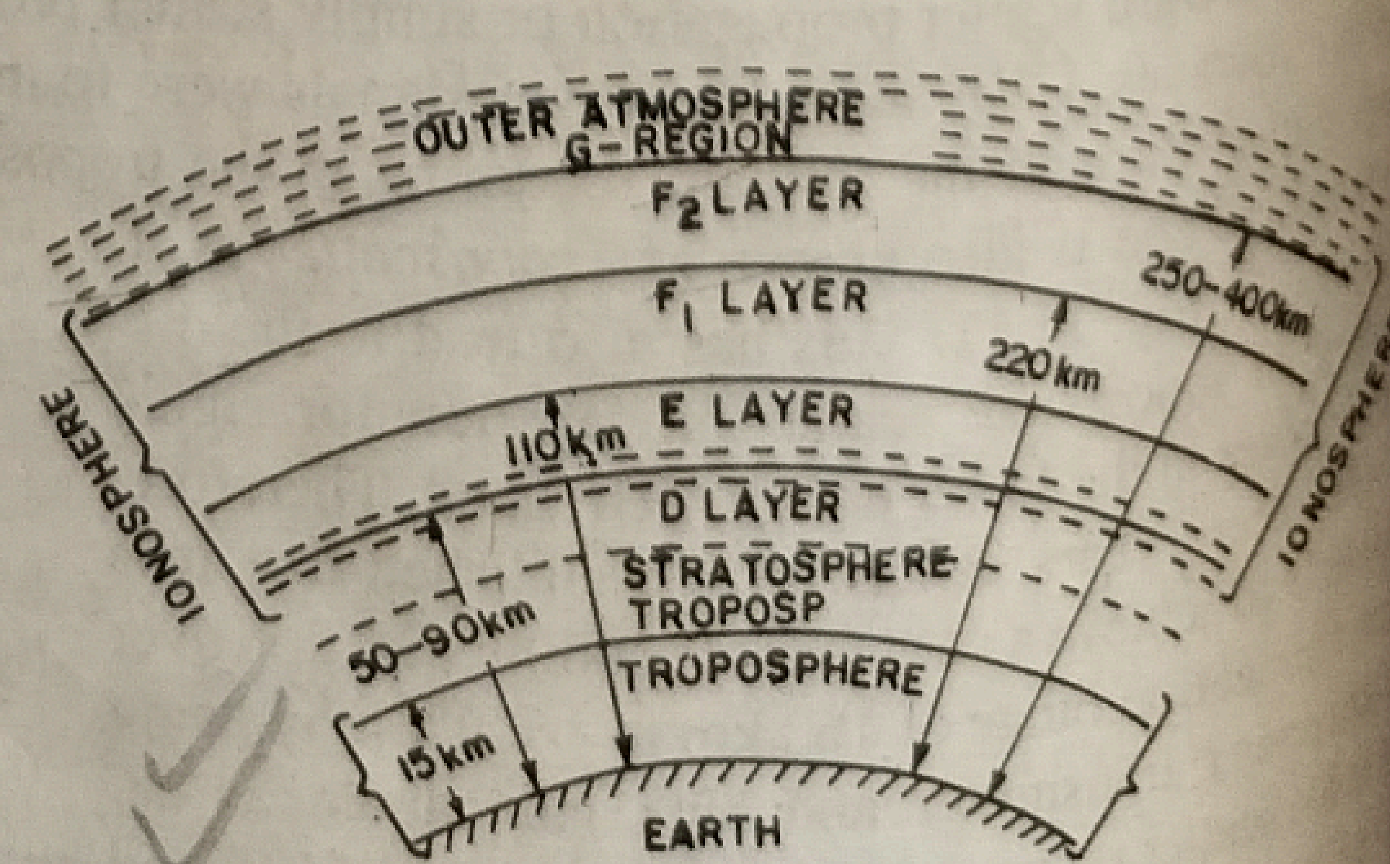


Fig. 11.12. Medium above earth surface.
(a) Troposphere upto 15 km.
(b) Ionosphere—50—400 km.
(c) outer atmosphere above 400 km.

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 formed by the ionization of UV, X-rays and probably Corpuscular radiations. *Its critical frequency is 10 MHz or still more at low altitude stations.* It ranges from 5 MHz to 12 MHz. The ionization in the F_2-layer is effected largely by earth's magnetic field, atmospheric (*i.e.* ionospheric tides and winds), ionospheric storms and other geomagnetic disturbances. Its ionization density shows large changes with solar activity and the change from sun spot minimum to sun spot maximum is highest for this layer. *F_2 -layer does not follow Chapman's law and shows a number of irregularities as located at the highest.* Splitting up of F_1 and F_2 is produced by tidal effects and increasing temperature with increasing height. F_2 -layer is the most important reflecting medium for high frequency radio waves.

11.6.5. *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*". The outer-region of the ionosphere is occupied by the radiation belts girdling the earth and consisting of the charged particles trapped by the terrestrial magnetic field, having the shape of magnetic lines of force.

11.7 SKY WAVE PROPAGATION

As mentioned already, the propagation of space and ground waves are limited by the curvature of the earth and hence these modes of propagations fail for communication over large distances. Therefore, propagation over long distance of thousand kilometer or more are almost exclusively performed by the sky waves or ionospheric waves. The sky waves are reflected from some of the ionized layers of ionosphere and return back to earth either in single hop or in multiple-hops of reflections Fig. 11.16. Thus for a sky wave of suitable frequency it is possible to cover any distance round the earth. Radio wave of frequency 2 MHz to 30 MHz (*i.e.* H.F. signals or short waves) is reflected from the ionosphere but in the day time the lower frequencies of 2-30 MHz are highly attenuated and hence efficient long distance communication or broadcasting is perfomed in the frequency range of 10 MHz to 30 MHz. Since in night higher frequencies around 30 MHz is not at all reflected back to earth, so during night some what lower frequency is utilized for long distance or broadcasting. Further sky waves follows different paths in the ionosphere and at receiving point, the received signal is the vector sum of all, so fading occurs which is minimized by A.V.C. or Diversity reception.

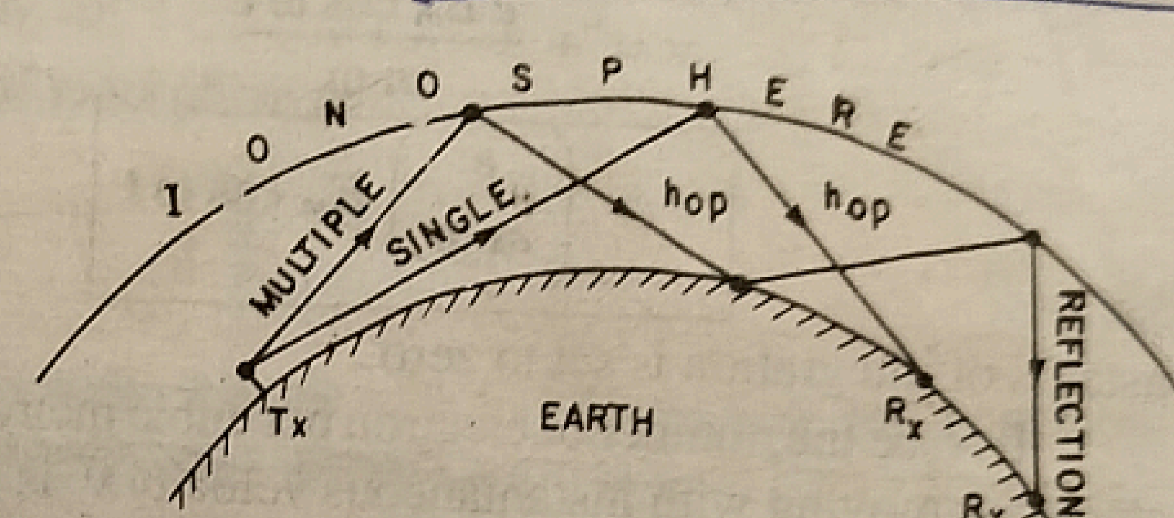


Fig. 11.16. Single and multiple-hops reflections for long distance communications.

Now the sky wave propagation, by neglecting earth's magnetic field first and then by considering it will be discussed. Besides, the various terminology grown up around ionosphere and sky wave propagation *e.g.* **the virtual height,** *critical frequency, MUF skip distance, fading and also various ionospheric variation terms etc.* would be studied.

11.7.1. *Propagation of Radio Waves through the Ionosphere (Neglecting Earth's Magnetic Field-Theory of Eccles and Larmor) or Expression for the Refractive Index of the Ionosphere.*

(AMIETE, Dec. 1979, 78, 1988, June 87, Agra Univ. M.Sc. Phy. 1986, Ghy. Univ. 1971)

In an ionized medium having free electrons, and ions when the radio waves passes through, it set these charged particles in motion. Since the mass of the ions are much heavier than the electrons so their motions are negligibly small and neglected for all practical purposes. The radio wave passing through the ionsophere is influenced by the electrons only and the electric field of radio waves set electrons of the ionosphere in motion. These electrons then vibrate simultaneously along paths parallel to the electric field of the radio waves and the vibrating electrons represent an a.c. current proportional in the velocity of vibration. Here the effect of earth's magnetic field on the vibrations of ionospheric electrons lags behind the electric field of the wave, thus resulting electron current is inductive. The actual current flowing through a volume of the space in the ionosphere consists of the components *e.g.* the usual capacitive current which leads the voltage by 90^0 and the electron current which lags the voltage by 90° and hence subtracted from the capacitive current. Thus free electrons in space decrease the current and so the dielectric constant of the space is also reduced below the value that would be in the absence of electron. The reduction in the dielectric constant due to presence of the electrons in the ionosphere causes the path of radio waves to bent towards earth *i.e.* from high electron density to lower electron density.

Let an electric field of value

$$E = E_m \sin \omega t \text{ volts/metre} \qquad \text{... (11.33)}$$

is acting across *a cubic metre of space in the ionosphere*, where ω is the angular velocity and E_m, the maximum amplitude. Force exerted by electric field on each electron is given by

$$F = -eE \text{ Newton} \quad \Big| \quad e = \text{charge of an electron in coulomb} \qquad \text{... 11.34 (a)}$$

Let us assume that there is no collision, then the electron will have an instantaneous velocity v meters/sec in the direction opposite to the field.

Force = Mass × Acceleration

$$-Ee = m\frac{dv}{dt} \quad \Big| \quad m = \text{mass of electron in kg}; \ \frac{dv}{dt} = \text{Acceleration} \qquad \text{... 11.34 (b)}$$

or $$\frac{dv}{dt} = -\frac{Ee}{m} \quad \text{or} \quad dv = -\frac{Ee}{m}dt$$

Integrating both sides

$$\int dv = -\int \frac{eE}{m}dt; \ v = -\frac{e}{m}\int E_m \sin \omega t \, dt \quad \Big| \text{ by eqn. 11.33}$$

$$v = +\frac{e E_m \cos \omega t}{m\omega}$$

or $$\boxed{v = \left(\frac{e}{m\omega}\right) E_m \cos \omega t} \qquad \text{... (11.35)}$$

constants of integration is set to zero.

If N be the number of electron per cubic metre, then instantaneous electric current constituted by these N electrons moving with instantaneous velocity v is

$$i_e = -Nev \text{ amp/m}^2 = -Ne \cdot \left(\frac{e}{m\omega}\right) E_m \cos \omega t \qquad \text{... (11.36)}$$

or $$\boxed{i_e = -\left(\frac{Ne^2}{m\omega}\right) E_m \cos \omega t} \qquad \text{... (11.37)}$$

which shows current i_e lags behind the electric field $E = (E_m \sin \omega t)$ by 90°.

Besides this inductive current (or conduction current component obtained by ionization of air *i.e.* presence of electron and its motion), there is usual capacitive current (i_c) (or displacement current exists in an un-ionized air). The capacitance of unit volume is

$$k_0 = 8.854 \times 10^{-12} \text{ F/m}$$

Hence the capacitive or displacement current through this capacitance is

$$i_c = \frac{dD}{dt} = \frac{d}{dt}(k_0 E) = k_0 \frac{d}{dt}(E_m \sin \omega t) \qquad \text{by eqn. 11.34}$$

Since $D = \varepsilon_0 E = k_0 E$; k_0 = constant

$$i_c = k_0 E_m \cos \omega t \, \omega \quad \text{... (11.38)}$$

Thus total current i that flows through a cubic metre of ionized medium is

$$i = i_c + i_e = k_0 E_m \omega \cdot \cos \omega t - \frac{N e^2}{m \omega} E_m \cos \omega t$$

$$= E_m \cos \omega t \, \omega \left[k_0 - \frac{N e^2}{m \omega^2} \right] \quad \text{... (11.39)}$$

Comparing eqn. 11.39 and eqn. 11.38, the effective dielectric constant k of the ionosphere (*i.e.* ionized space)

$$k = k_0 - \frac{N e^2}{m \omega^2} = k_0 \left[1 - \frac{N e^2}{m \omega^2 k_0} \right]$$

Hence the relative dielectric constant w.r.t. vacuum or air

$$k_r = \frac{k}{k_0} = 1 - \frac{N e^2}{m \omega^2 k_0}$$

Thus relative refractive index (μ) of the ionosphere w.r.t. vacuum or air (*i.e.* un-ionized air)

$$\mu = \sqrt{k_r} = \sqrt{\frac{k}{k_0}} = \sqrt{1 - \frac{N e^2}{m \omega^2 k_0}} \quad \Big| \because v = \frac{c}{\sqrt{k_r}} = \frac{c}{\mu} \ \therefore \mu = \sqrt{k_r} \quad \text{... 11.40 (a)}$$

If we put the values *i.e.*

$$m = 9.107 \times 10^{-31} \text{ kg} ; \ e = 1.602 \times 10^{-18} \text{ coulombs}$$

$$k_0 = 8.854 \times 10^{-12} = \frac{1}{36 \pi \times 10^9} \text{ F/m. and } \omega = 2 \pi f \text{ (vide Ex. 11.1)}$$

we get the desired expression for the refractive index of ionosphere as

$$\boxed{\mu = \sqrt{1 - \frac{81 N}{f^2}}} \qquad 9\sqrt{N} = f_c \quad \text{... 11.40 (b)}$$

where N = Number of electrons per cubic metre or ionic density and f = frequency in Hz. If N is in per cubic cm, then frequency is in kHz, then this relation still holds good.

Eqn. 11.40 shows that refractive index of ionosphere is less than one where that of un-ionized, medium is one. Thus presence of electrons in ionosphere reduces the refractive index of the air and reduction is higher if electrons are more. While deriving this eqn., it is assumed that the electrons do not undergo any in-elastic collision during their motion and there is no dissipative loss of energy.

11.7.2 *Mechanism of Radio Wave bending by the ionosphere* (AMIETE, Dec. 1978)

The bending of radio waves at the ionosphere can readily be understood with the help of refractive index formula of the ionized medium 11.40 *i.e.*

$$\mu = \sqrt{k_r} = \sqrt{1 - \frac{81 N}{f^2}} \quad \text{... (11.40)}$$

where N = ionic density, in m^{-3} and f = frequency, in Hz

if N is expressed in per cubic c.c. then f will be in kHz. Eqn 11.40 shows that real values of refractive index of the ionosphere is always less than unity and the deviation of μ from the unity becomes greater, if *the ionic density is higher and frequency is lower. If $f^2 < 81 N$, then the refractive index becomes imaginary which means under such condition the radio waves are attenuated at this frequency and ionosphere is not able to transmit or bend the radio waves.*

The bending of radio waves by the ionosphere is governed by the ordinary optical laws. By Snell's law, the angle of incidence (i) and refraction (r) at any point is given by

$$\mu = \frac{\sin i}{\sin r} \quad \text{... (11.41)}$$

Since $\mu < 1$ for the ionosphere, so $\sin i < \sin r$ *i.e.* angle of refraction will go on deviating from the normal as the wave will encounter rarer medium as illustrated in Fig. 11.17. If successive layers of the ionosphere are of higher electron density *i.e.* $N_6 > N_5 > N_4 > N_3 > N_2 > N_1$ it means by eqn. 11.40, μ

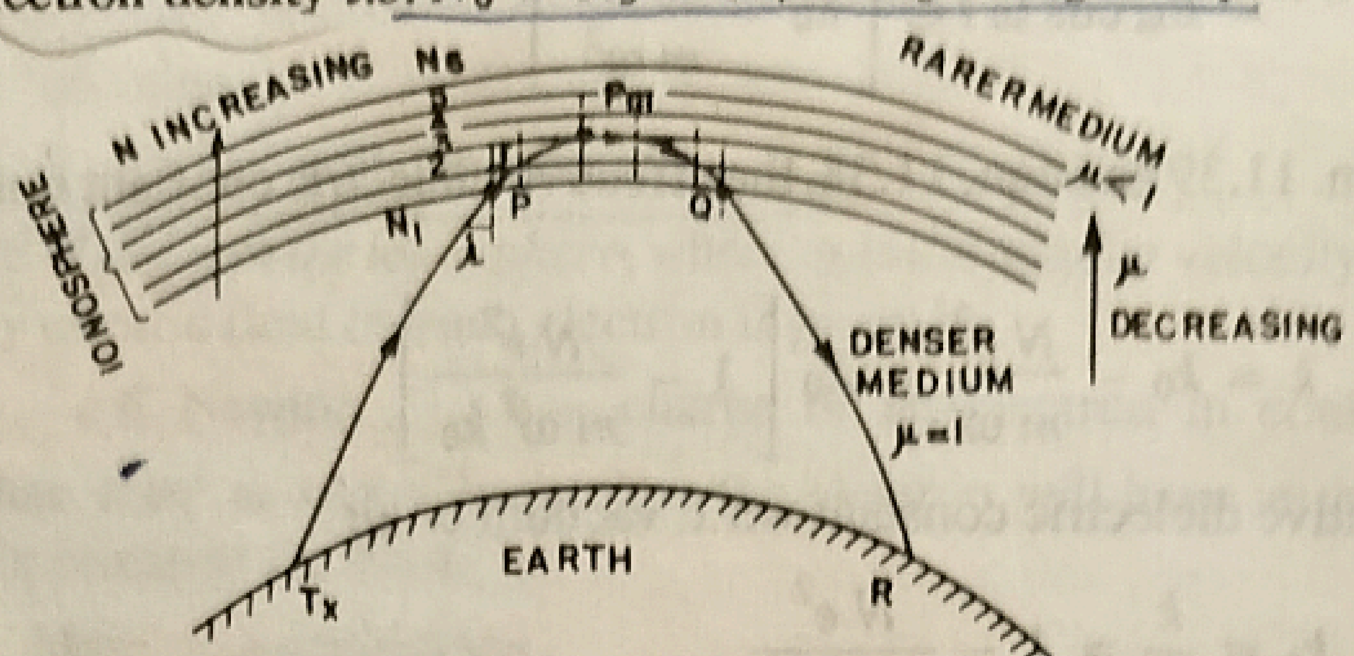


Fig. 11.17. Refraction of radio waves in the ionosphere.

will go on decreasing and decreasing *i.e.* $\mu_1 > \mu_2 > \mu_3 > \mu_4 > \mu_5 > \mu_6$. Thus a wave enters at say point P will be deviating more and more and a point will reach where it travels parallel to earth (at 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 μ_m, be refractive index and N_m be the maximum electron density at the point P_m then eqn. 11.41 will become

$$\boxed{\mu_m = \sin i_m} \qquad \because \sin r = \sin 90° = 1 \quad \text{... (11.42)}$$

The point P_m, is usually called as point of reflection although it is actually a point of refraction. At this point total internal reflection takes place and the wave gets bent earthward and ultimately returns to earth. *Hence the radio waves once enter at point P, leave the ionosphere at point Q after slight penetration in to the ionosphere and thus radio waves are reflected back to earth after successive refraction in the ionosphere.*

Eqn. 11.42 suggests that smaller the angle of incidence ($\angle i$), the smaller the refractive index μ_m which implies higher should be the electron density needed to return the radio wave towards the earth. Further, if angle of incidence reduces to zero *i.e.* for vertical incidence ($\angle i = 0$), then the refractive index also becomes zero for reflection to take place and this corresponds to maximum electron density of the layer and the frequency corresponds to critical frequency — the maximum frequency which can be reflected by a layer at vertical incidence.

11.7.3. *Critical Frequency.*

(AMIETE, Dec. 1990, 84, 93, 1991, 1980, 72, 71, May 1978, 76, 70, 69, 91, UPSC IES 1969)

The critical frequency of an ionized layer of the ionosphere is defined as *the highest frequency which can be reflected by a particular layer at vertical incidence. This highest frequency is called critical frequency for that particular layer and it is different for different layers. It is usually denoted by f_0 or f_c.* Critical frequency for the particular regular layer is proportional to the square root of the maximum electron density in the layer as shown below. From eqn. 11.40 and 11.41 we can write

$$\mu = \frac{\sin i}{\sin r} = \sqrt{1 - \frac{81\,N}{f^2}} \quad \text{... (11.43)}$$

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

By definition, at vertical incidence

Angle of incidence $\angle i = 0$; $N = N_{max}$ and $f = f_c$.

As the angle of incidence go on decreasing and reaches to zero, (*i.e.* vertical incidence) the electron density go on increasing and reaches to maximum electron density (N_m). Then the highest frequency that can be reflected back by the ionosphere is one for which refractive index μ becomes zero.

$$\therefore \qquad \mu = \frac{\sin\theta}{\sin r} = \sqrt{1 - \frac{81\,N_m}{f_c^{\,2}}} = 0$$

$$\text{or} \qquad 1 = \frac{81\,N_m}{f_c^{\,2}} \quad \text{or } f_c = \sqrt{81\,(N_m)} \qquad \text{... 11.44 (a)}$$

$$\text{or} \qquad \boxed{f_c = 9\sqrt{N_m}}$$

where f_c is expressed in MHz and N_m in per cubic metre. Thus if the maximum electron density N_m is known, the critical frequency can be calculated by eqn. 11.44. Of course critical frequency is the highest frequency which can be reflected by a particular layer *at vertical incidence but it is, not the highest frequency which will get reflected for any other angle of incidence.* The frequency that can be reflected from a layer is a function of angle of incidence (i) and is called maximum usable frequency MUF (to be seen next).

Thus critical frequency gives an idea that radio waves of frequency equal to or less than the critical frequency will certainly be reflected back by the ionospheric layer irrespective of the angle of incidence. Radio waves of frequency greater than critical frequency will also be returned to earth only when the angle of incidence (i) is sufficiently glancing so that eqn. 11.42 is satisfied at the frequency involved, otherwise the wave will penetrate the layer concerned. However, it may be reflected back by a still higher layer. Thus for a wave of frequency greater than critical frequency to be reflected, the condition is

$$\sin i > \mu_m \qquad \text{from eqn. 11.42}$$

$$> \sqrt{1 - \frac{81\,N_m}{f^2}} \qquad \text{... (11.45)}$$

$$\sin i > \sqrt{1 - \frac{f_c^2}{f^2}}$$

$$f_c = \frac{81\,N_m}{f^2} = \frac{N_m\,e^2}{m\,4\,\pi^2 f^2\,k_0} \qquad \text{... (11.46)}$$

FECT OF THE EARTH'S MAGNETIC FIELD ON IONOSPHERIC RADIO WAVE PROPAGATION

(AMIETE, May 1970, 76, 80, Dec. 1971, 76, 73, 1993)

A radio wave propagating in an atmosphere which is not ionized is not affected by the earths magnetic eld. However, in the ionized medium *i.e.* ionosphere the electrons are set in motion by the electric field of the radio wave and the earth's magnetic field, then, exerts a force on the vibrating electrons producing twisting effect on their paths. This reacts on the incident radio waves.

Thus the earth magnetic field splits up the incident radio waves into two components *e.g. the ordinary and the extra-ordinary waves.* The properties of the ordinary wave are same as the waves withouts superim-posed magnetic field. The extra-ordinary wave is distinguishable from the ordinary wave only in the upper region of F_2 layer or F layer. The two rays bend different amounts by the ionosphere and hence travel through it along slightly different paths. The rates of energy absorption and velocities also differ. There is also double refractions. The two waves (ordinary and extra-ordinary) have elliptical polarization and rotate in opposite direction. *The phenomenon of splitting of wave into two different components by the earth's magnetic field is called as "Magneto ionic splitting".* The amplitude of extra- ordinary wave relative to ordinary wave depend on the magnitude of the magnetic effects. The critical frequency (f_x) of extra-ordinay wave is always higher the (f_c) by an amount approximately half the gyro frequency.

Besides, splitting of incident wave into ordinary and extra-ordinary wave components the earth's magnetic field is also effecting the polarization of the incident radio wave. The electrons set in simple harmonic

11.12. DEFINITIONS

The terminology around ionosphere and sky wave propagation which has developed will be discussed now. The important being virtual height, MUF, skip distance, L.U.F., O.W.F. etc.

11.12.1. *Virtual Height.* (AMIETE, June 1983 92, De.c 1987, 91, UPSC IES 1969)

Can be understood with help of diagram drawn in Fig. 11.20. Fig. shows that as the wave is refracted from the layer, it is bent down gradually rather sharply. The actual path of the wave in the ionized layer is a curve and is due to the refraction of the wave, as happens in case of refraction from the prism. Since it is more

8-10/

transm
symme
Fig. 11

convenient to think of the wave being reflected rather than refracted therefore, the path can be assumed to be straight lines *TD* and *RD* as shown in figure. This assumption is made in the measurements of the height of a layer. The height *OD* is called the virtual height of the ionized layer as it is not the true height. The true height is the height shown in figure. *Virtual height is always greater than the actual height.* If virtual height of 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.

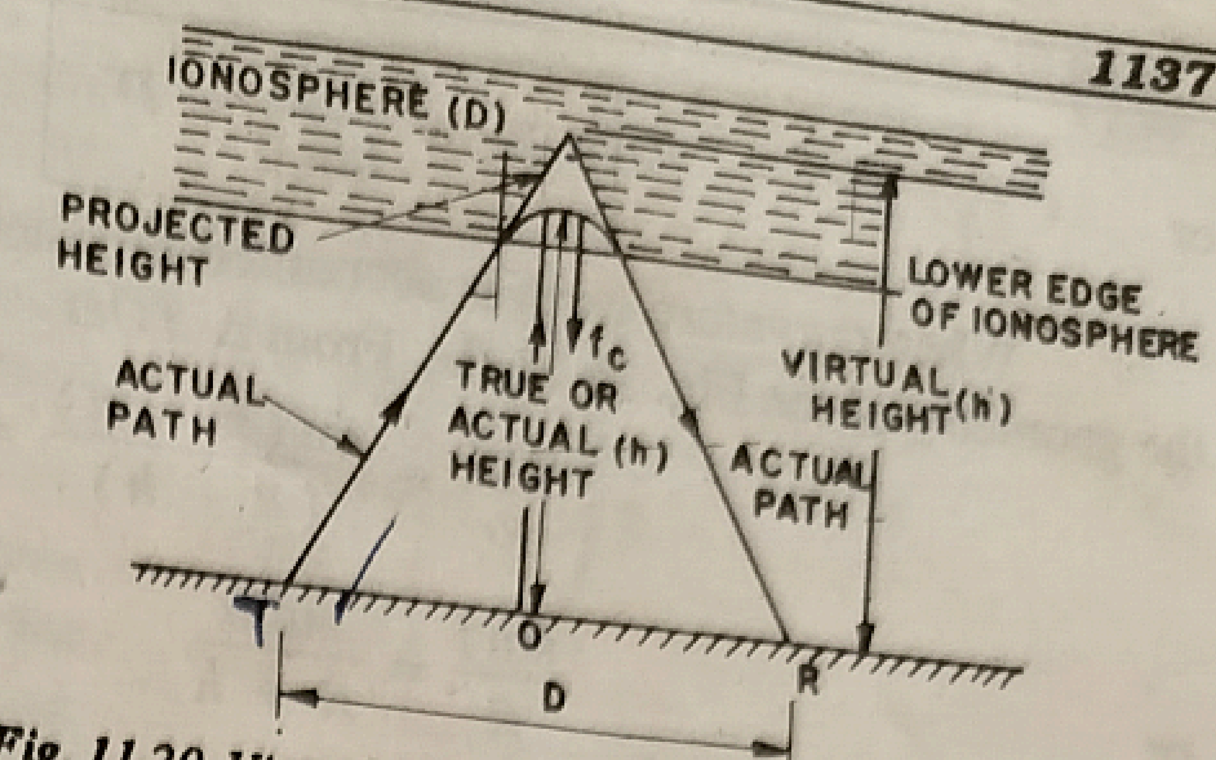
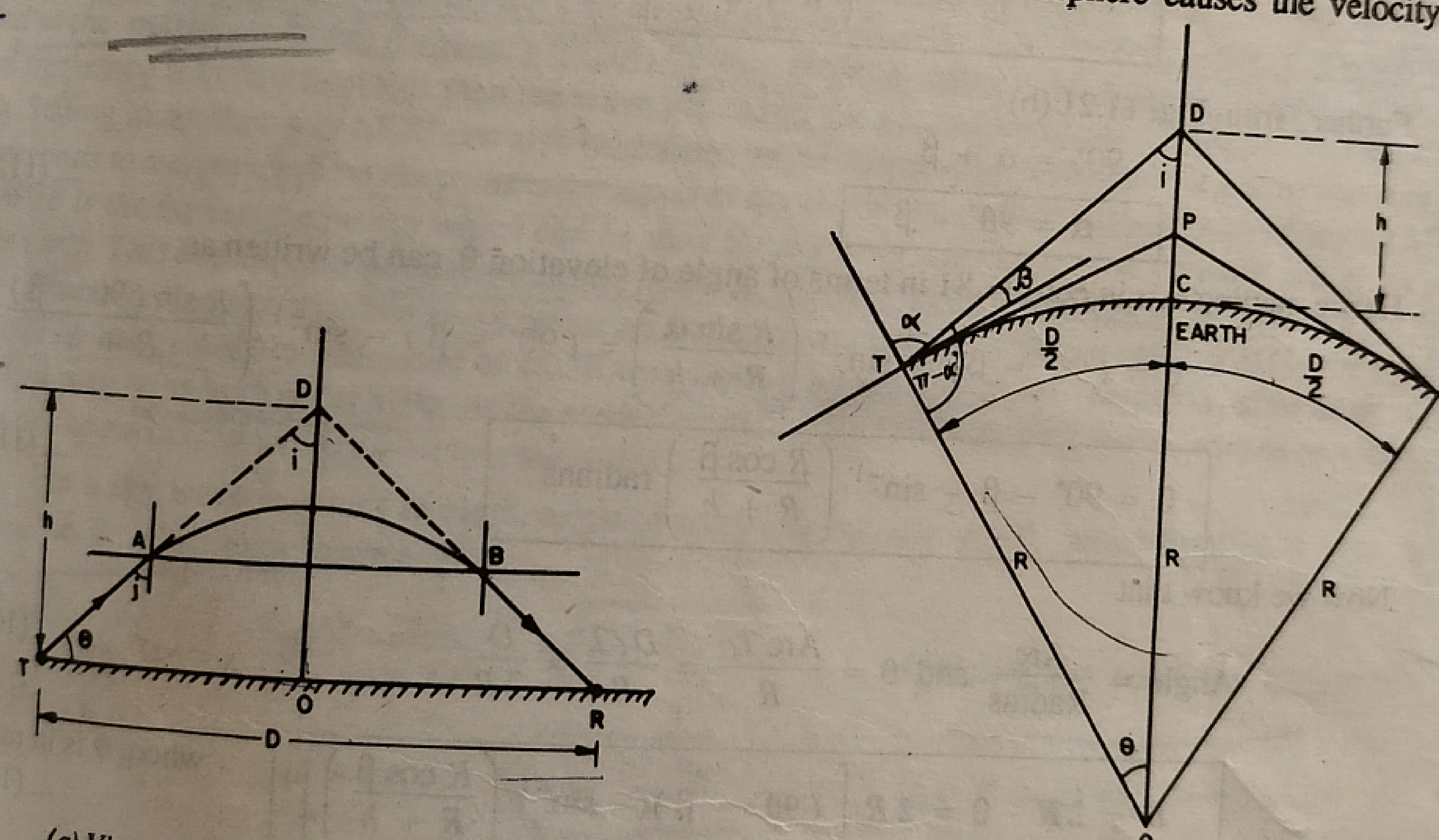


Fig. 11.20. Virtual and actual heights of an ionized layer.

Virtual height of an ionospheric layer may be defined as *the height to which a short pulse of energy sent vertically upward and travelling with the speed of light would reach taking the same two ways travel time as does the actual pulse reflected from the layer.* In the measurement of virtual heights the transmitting point (*T*) and receiving point (*R*) are usually placed very close together so that the wave sent nearly vertically upward.

The commonest method of virtual height measurement is that in which the transmitted signal consists of pulses of *RF* energy of short duration. The receiver which is located close to the transmitter, picks up both the direct and the reflected signals. The spacing between these signals on the time axis of C.R.O. gives a measurement of the height of the layer. The actual height (*h*) is less than virtual height because the interchange of energy takes place between the wave and the electrons of the ionosphere causes the velocity of the propagation to be reduced.



(a) Virtual height determination for flat earth. *(b) Virtual height determination for curved earth.*

Fig. 11.21.

The virtual height has the greatest advantage of being easily measured, and it is very useful in transmission-path-calculations. For flat earth assumption and assuming that the ionospheric conditions are symmetrical for the incident and reflected waves, the transmission-path distance *TR* is obtained from the Fig. 11.21 (a)

$$\tan\beta = \frac{Do}{To} = \frac{h}{TR/2} \quad \text{or} \quad \frac{TR}{2} = \frac{h}{\tan\beta} \qquad \because To = \frac{TR}{2}$$

$$T_R = \frac{2h}{\tan\beta} = D \quad \text{...(11.79)}$$

or

When curvature earth is accounted for, then the transmission-path distance may be calculated from the geometry of the Fig. 11.21 (b). From $\Delta\ TOD$

$$\frac{\sin i}{R} = \frac{\sin(\pi - \alpha)}{(R+h)} = \frac{\sin\alpha}{R+h}$$

or

$$\frac{\sin i}{R} = \frac{\sin\alpha}{R+h} \qquad \because \sin(\pi-\alpha) = \sin\alpha; \quad R = \text{Radius of the earth} = 6370 \text{ km}$$

But

$$\angle OTD = \pi - \angle(i+\theta) \text{ or } \pi - \alpha = \pi - (i+\theta)$$

or

$$\boxed{i = \alpha - \theta} \quad \text{...(11.80)}$$

Hence, putting this in above eqn., we get

$$\frac{\sin(\alpha-\theta)}{R} = \frac{\sin\alpha}{(R+h)} \text{ or } \sin(\alpha-\theta) = \left(\frac{R\cdot\sin\alpha}{R+h}\right)$$

or

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

or

$$\boxed{\theta = \alpha - \sin^{-1}\left(\frac{R\sin\alpha}{R+h}\right)} \quad \text{...(11.81)}$$

Further, from Fig. 11.21 (b)

$$90^\circ = \alpha + \beta$$

or

$$\boxed{\alpha = 90^\circ - \beta} \quad \text{...(11.82)}$$

Hence, putting this in eqn. 11.81 in terms of angle of elevation θ, can be written as

$$\theta = (90^\circ - \beta) - \sin^{-1}\left(\frac{R\sin\alpha}{R+h}\right) = (90^\circ - \beta) - \sin^{-1}\left(\frac{R\sin(90-\beta)}{R+h}\right)$$

$$\boxed{\theta = 90^\circ - \beta - \sin^{-1}\left(\frac{R\cos\beta}{R+h}\right) \text{ radians}} \quad \text{...(11.83)}$$

$T_R = D$

Now we know that

$$\text{Angle} = \frac{\text{Arc}}{\text{Radius}} \text{ and } \theta = \frac{\text{Arc } T_C}{R} = \frac{D/2}{R} = \frac{D}{2R} \quad \text{...(11.84)}$$

or

$$\boxed{D = 2R\cdot\theta = 2R\left[(90^\circ - \beta) - \sin^{-1}\left(\frac{R\cos\beta}{R+h}\right)\right]} \quad \text{where } \theta \text{ is in radians} \quad \text{...(11.85)}$$

Measurement of virtual height is normally carried out by means of an instrument known as an IONOSONDE. The basic method is to transmit vertically upward a pulse--modulated radio wave with a pulse duration of about 150 micro-seconds. The reflected signal is received close to the transmission point, and the time T required for the round trip is measured. The virtual height is then given by

$$\boxed{h = \frac{cT}{2} = \text{Virtual height}} \quad \text{...(11.91)}$$

$cT/2 = 2D$

where c = velocity of light, in m/s = 3×10^8 metres/sec

$cT/2$ unless $2h/\tan\beta$

The ionosonde will have facilities for sweeping over the radio frequency range, typically, it will sweep from 1 MHz to 20 MHz in 3 minutes. It will also have facilities of automatic plotting of virtual height against frequency. The resultant graph is known as an IONOGRAM shown in Fig. 11.22.

The ionogram shows two critical frequencies $f_o F_2$ and $f_x F_2$. These two critical frequencies are for ordinary ray denoted by $f_o F_2$ and for the extra-ordinary ray denoted by $f_x F_2$. The development of two components of the relative permittivity of the ionized layer is due to earth's magnetic field. The occurrence of two critical frequencies are only for F_2 layer.

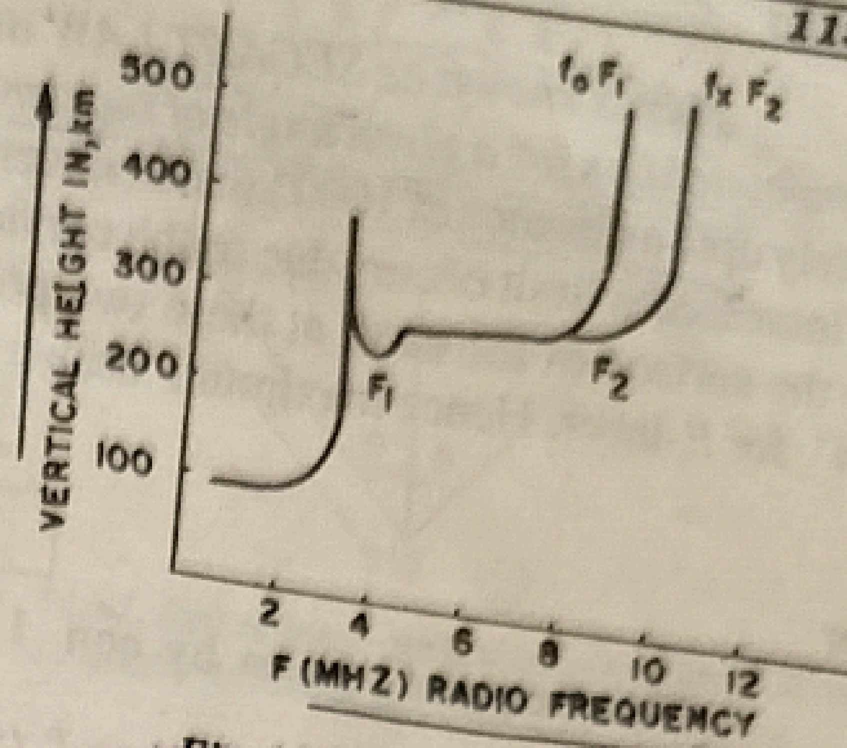


Fig. 11.22. Ionogram

11.12.2 Maximum Usable Frequency (MUF)

(AMIETE, May 1993, 92, 78, 77, 76, 75, 68, Nov. 1966, 68 69, 87, 89, 91, 92)

Critical frequency is the maximum frequency of the radio wave which is returned from a ionized layer at *vertical incidence*. However, when the frequency of radio wave exceeds the critical frequency, then the influence of the ionospheric layer on the path of propagation (*i.e.* communication) depends on the angle of incidence at the ionosphere. Thus *the maximum usable frequency (MUF) is also a limiting frequency which can be reflected back to earth but this time for some specific angle of incidence rather than the vertical*. The *maximum possible value of frequency for which reflection takes place for a given distance of propagation, is called as the maximum usable frequency (MUF) for that distance, and for the given ionospheric layer*. If the wave frequency is higher than this then the wave penetrates the ionized layer and does not reflect back to the earth. Stating in another way MUF can also be defined as *the frequency which makes a given receiving point corresponds to a distance from the transmitter equal to the skip distance*. Still another way of saying MUF is that *MUF is the highest frequency which can be used for sky wave communication between two given points on the earth. This implies that maximum usable frequency is the highest frequency which can be used for sky wave communication between two given points on the earth and there is different value of MUF for each pair of points on the globe*. Normal value of MUF vary from 8 MHz to 35 MHz. However, after unusual solar activity it may be as high as 50 MHz. *At the same time the highest working frequency between two particular points on the earth is obviously a bit less that MUF*.

For a sky wave to return to earth, angle of refraction *i.e.* $\angle r = 90°$, which implies $N = N_{max}$ and $f = f_{max}$ *i.e.* the maximum frequency

$$\therefore \quad \mu = \frac{\sin i}{\sin 90^0} = \sqrt{1 - \frac{81 N_m}{f_{muf}^2}} \qquad | \text{ Applying the condition of MUF}$$

$$\text{or} \quad \mu = \sin i = \sqrt{1 - \frac{81 N_m}{f_{muf}^2}} \qquad | \text{ But } f_c^2 = 81 N_m$$

$$\therefore \quad \sin i = \sqrt{1 - \frac{f_c^2}{f_{muf}^2}} \text{ or } \sin^2 i = 1 - \frac{f_c^2}{f_{muf}^2} \qquad \text{... (11.86)}$$

$$\text{or} \quad \frac{f_c^2}{f_{muf}^2} = 1 - \sin^2 i = \cos^2 i \qquad \text{... 11.87 (a)}$$

$$\text{or} \quad f_{muf}^2 = f_c^2 \cdot \sec^2 i$$

$$\boxed{f_{muf} = \sec i \cdot f_c} \qquad \text{... 11.87 (b)}$$

This shows that *muf* for a layer is greater than f_c by a factor sec i.

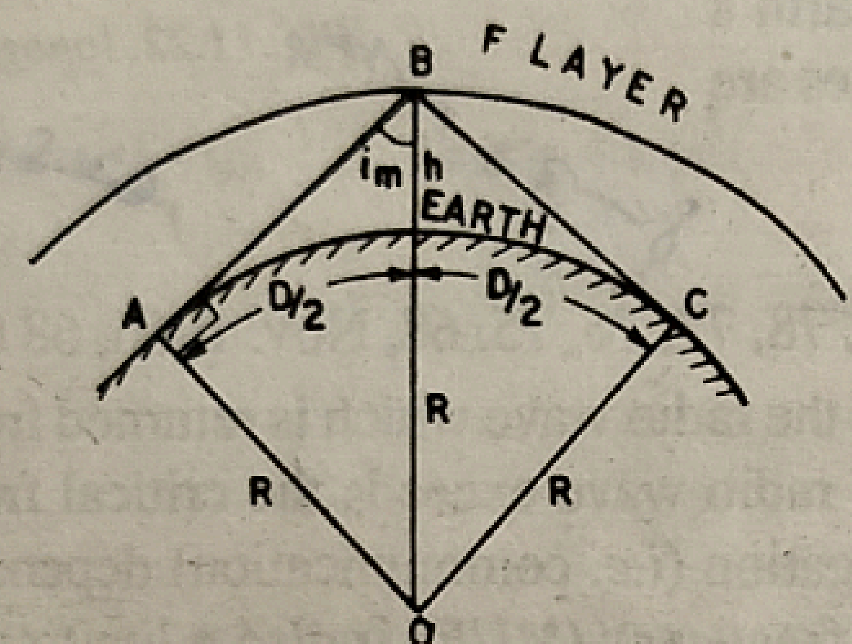
This is known as SECANT LAW and gives the maximum frequency which can be used for sky wave communication for a given angle of incidence (i) between two points on the earth. This equation can be applied safely upto a distance of 1000 km. However, as the distance between two points (i.e. transmitting and receiving) is increased a limit occurs due to the curvature of the earth (Fig. 11.23) where the path of the wave is tangent to the surface of the earth at these two points. The angle (i) corresponding to this limiting distance is about 74° for *F*-layer. Hence maximum usable frequency for this case is given by

$$f_{muf} = \sec 74 \cdot f_c$$

or

$$\boxed{f_{muf} = 3.6 f_c} \qquad \text{... (11.88)}$$

The frequency given by eqn. 11.88 is the maximum frequency which can be reflected from the ionosphere.



$i_m = i_{max}$

and $\sin i_{max} = \dfrac{R}{R+h}$

Fig. 11.23. Max. angle of incidence of a wave on the

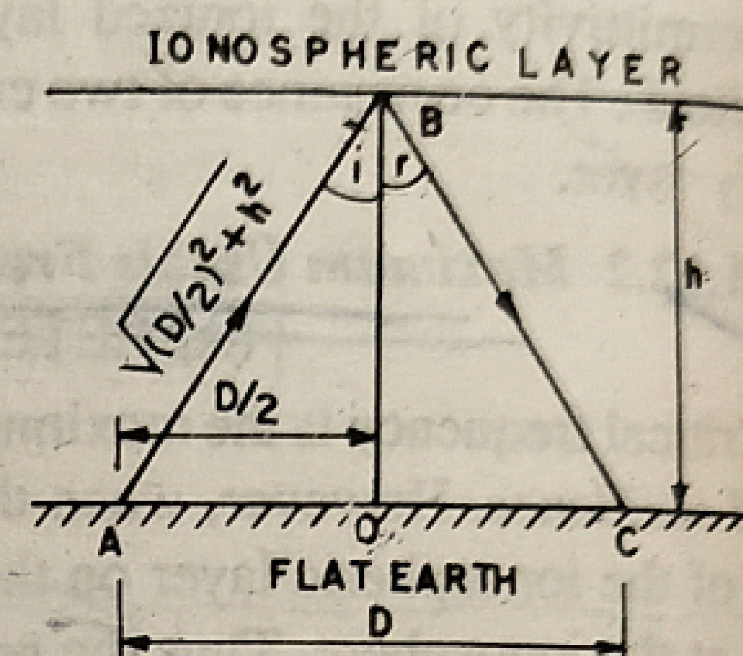


Fig. 11.24. Reflection from a thin layer on flat earth

11.12.3. *Calculation of MUF.*

Case I. ***Thin Layer (or Flat Earth).*** The ionized layer may be assumed to be thin layer with sharp ionization density gradient, which gives mirror like reflection of radio waves as shown in Fig. 11.24. For the shorter distance of communication (Say upto 500 km) the earth can be assumed to be flat.

From the Fig. 11.24,

or
$$\cos i = \frac{BO}{AB} = \frac{h}{\sqrt{h^2 + \dfrac{D^2}{4}}} = \frac{2h}{\sqrt{4h^2 + D^2}} \qquad \text{... (11.89)}$$

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

The maximum usable frequency for which the wave is to be reflected from the layer for returning to earth, $f = f_m$, $\sin r = 90°$ and $N = N_m$. Hence from eqn. 11.89

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

where f_c = critical frequency and f_{muf} = *muf* Putting $\cos^2 i$

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

from eqn. 11.87 (a) and eqn. 11.89 ... 11.90 (a)

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

by cross multiplying or reversing

or
$$\frac{f_{muf}}{f_c} = \sqrt{\left(1 + \frac{D^2}{4h^2}\right)}$$

$$\boxed{f_{muf} = f_c \sqrt{1 + \left(\frac{D}{2h}\right)^2}} \qquad \text{... 11.90 (b)}$$

$f_c \sqrt{1 + (D/2h)^2}$

$= \dfrac{f_c}{\cos i}$

This is the expression for maximum usable frequency in terms of critical frequency (f_c), propagation distance D and height of layer h and can be evaluated, if these terms are known.

Case II. *Thin Layer (Curved Earth)*

(AMIETE, May 1975, Nov. 1969)

If the curvature of earth is taken into account, the reflecting region is considered to be concentric with earth as illustrated in Fig. 11.25 where transmitted wave leaves the transmitter tangentially to the earth. Let 2θ be the angle substended by the transmission distance D at the centre of the earth O.

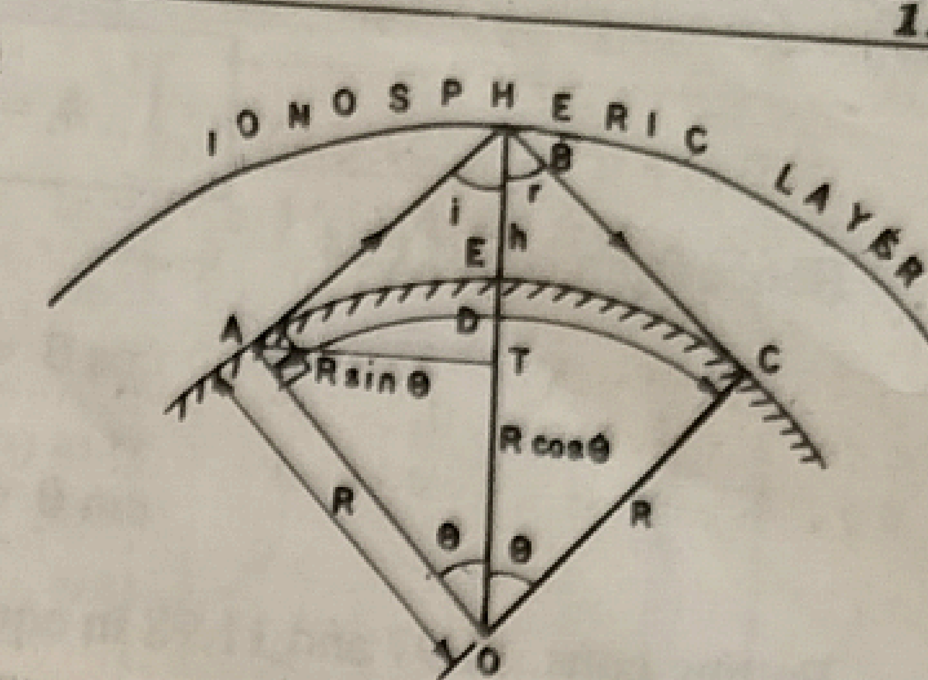


Fig. 11.25. Reflection from a thin ionospheric layer but on curved earth accouting its curvature.

Then

$\because$ $$\text{Angle} = \frac{\text{Arc}}{\text{Radius}} \quad \therefore \quad 2\theta = \frac{D}{R}$$

or $$\boxed{D = 2R\theta}$$

Now $$AT = R\sin\theta\,; \quad OT = R\cos\theta \qquad \text{... (11.91)}$$

$\therefore$ $$BT = OE + EB - OT = h + R - R\cos\theta$$

and $$AB = \sqrt{AT^2 + BT^2} = \sqrt{(R\sin\theta)^2 + (h + R - R\cos\theta)^2}$$

Hence $$\cos i = \frac{BT}{AB} = \frac{h + R - R\cos\theta}{\sqrt{(R\sin\theta)^2 + (h + R - R\cos\theta)^2}}$$

or $$\cos^2 i = \frac{(h + R - R\cos\theta)^2}{(R\sin\theta)^2 + (h + R - R\cos\theta)^2} \qquad \text{... (11.92)}$$

By eqn. 11.87 (a)

$$\cos^2 i = \frac{f_c^2}{f_{muf}^2} = \frac{(h + R - R\cos\theta)^2}{(R\sin\theta)^2 + (h + R - R\cos\theta)^2} \qquad \text{... (11.92)}$$

The curvature of earth limits both the MUF and the skip distance D and the limit is obtained when waves leave the transmitter at grazing angle (implies $\angle OAB = 90°$).

Thus when D is maximum, (*i.e.* max. skip distance to be seen next), θ is maximum, given by

$$\cos\theta = \frac{OA}{OB} = \frac{R}{R + h} \qquad \text{... (11.93)}$$

However actual value of θ is very small, so eqn. 11.93 can be expanded

$$\cos\theta = \frac{R}{R\left(1 + \frac{h}{R}\right)} = \left(1 + \frac{h}{R}\right)^{-1}$$

$$\cos\theta = \left(1 - \frac{h}{R} + \ldots\right) \qquad \because \frac{h}{R} \ll 1 \qquad \text{... (11.94)}$$

$\cos^2\theta = 1 - \sin^2\theta$

$\cos\theta = \sqrt{1 - \sin^2\theta}$

$\theta = \sqrt{1 - \theta^2}$

or $$1 - \frac{\theta^2}{2} = 1 - \frac{h}{R} \quad \text{or} \quad \theta^2 = \frac{2h}{R} \qquad \text{... (11.95)}$$

Hence from eqn. 11.91

$$D^2 = 4R^2\theta^2 = 4R^2 \cdot \frac{2h}{R} = 8hR \qquad \text{from eqn. 11.95}$$

$$\boxed{h = \frac{D^2}{8R}} \quad \text{...(11.96)}$$

Hence from eqn. 11.94

$$\cos\theta = \left(1 - \frac{D^2}{8R^2}\right) \text{ and as } \theta \text{ is small} \quad \text{...(11.97)}$$

and

$$\sin\theta \simeq \theta = \frac{D}{2R} \quad \text{from eqn. 11.91} \quad \text{...(11.98)}$$

Putting eqns. 11.97 and 11.98 in eqn. 11.92, we get

$$\frac{f_c^2}{(f_{muf}^{\;2})_{max}} = \frac{\left\{h + R - R\left(1 - \frac{D^2}{8R^2}\right)\right\}^2}{\left\{R^2 \cdot \frac{D^2}{4R^2} + \left[h + R - R\left(1 - \frac{D^2}{8R^2}\right)\right]^2\right\}} = \frac{\left(h + \frac{D^2}{8R}\right)^2}{\frac{D^2}{4} + \left\{h + \frac{D^2}{8R}\right\}^2}$$

or

$$\frac{(f_{muf})_{max}}{f_c} = \frac{\sqrt{\frac{D^2}{4} + \left\{h + \frac{D^2}{8R}\right\}^2}}{\sqrt{\left(h + \frac{D^2}{8R}\right)^2}}$$

$$\boxed{(f_{muf})_{max} = f_c \frac{\sqrt{\frac{D^2}{4} + \left(h + \frac{D^2}{8R}\right)^2}}{\sqrt{\left(h + \frac{D^2}{8R}\right)^2}}} \quad \text{...(11.99)}$$

$f_{muf} = R\sqrt{H}\left(\frac{R}{2h}\right)^2$

and from eqn. 11.96

$$\boxed{(D_{skip})_{max} = \sqrt{8\,h\,R}} \quad \text{... 11.100 (a)}$$

As D is nothing but skip distance

or

$$D = 2\left(h + \frac{D^2}{8R}\right)\sqrt{\left(\frac{f_m}{f_c}\right)^2 - 1} \quad \text{... 11.100 (b)}$$

11.12.4. *Transmission Curve Method of determination of MUF* (AMIETE, Nov. 1968)

This method is a graphical method utilized by Central Radio Propagation Laboratory (CRPL) National Burea of Standards (America) and hence also known as CRPL method. In this experimental ($h' - f$) curve is utilized for determination of MUF, in terms of virtual height h' rather than actual or true height h. $h' - f$ curve is also known as "**Transmission Curve**".

If h is replaced h' in equations of thin layer formulae, (say Eqn. 11.90), then it is equally applicable for thick layer case also in which gradual bending of radio wave in the ionospheric layer is involved (Fig. 11.24). Thus from Eqns. 11.89 and 11.87 (b), we have

$$\cos i = \frac{h'}{\sqrt{h'^2 + \left(\frac{D}{2}\right)^2}} \quad \text{... (11.101)}$$

and

$$f_{muf} = \sec i \cdot f_c \quad \text{... 11.87 (b)}$$

where h' = virtual or apparent height ; i = Angle of incidence and f_c = Critical frequency.

Now with the help of Eqn. 11.101, a curve between virtual height h' and $\cos i$, for a given value of D can be plotted. The curve is generally plotted on a transparent sheet with $\cos i$ along x-axis on a logarithmic scale and h' along y-axes with linear scale and curve so obtained is given name transmission curve for given value of skip distance D as shown in Fig. 11.26 (dotted). The scale of plot of this transmission curve is made identical with experimentally obtained $h' - f$ curve. In order to determine the MUF of a particular given path for a given time, *an experimental ($h' - f$) plot for that time at the place of reflection is taken*. Now the transmission curve drawn on transparent sheet for the given distance is placed over this experimentally obtained ($h' - f$) curve with their axes coinciding and then slided towards right until the transmission curve just touches the experimental ($h' - f$) curve as in Fig. 11.26. Then the value of MUF is read from the frequency axis corresponding to $\cos i$ = 1.. Experimental ($h' - f$) curve is shown with solid lines and the transmission curve with dotted line.

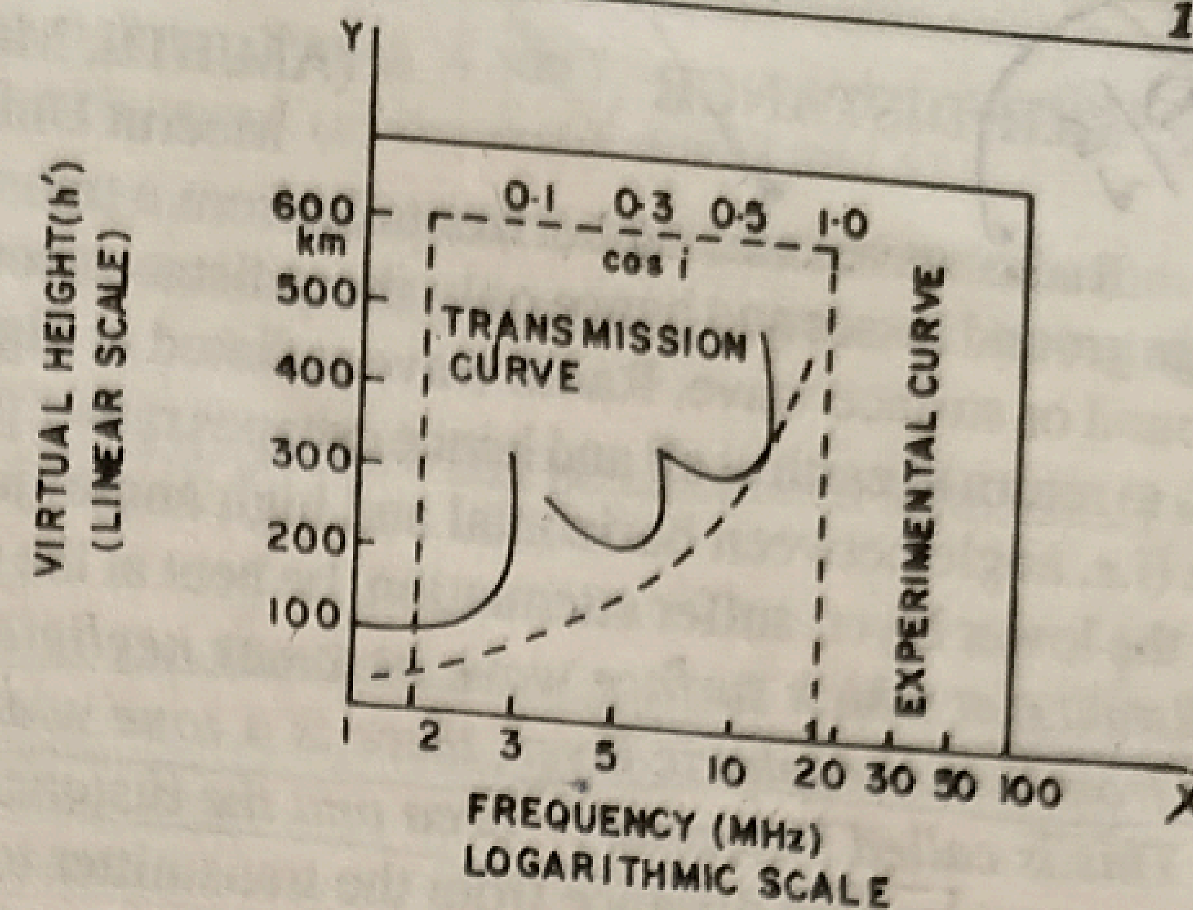


Fig. 11.26. Determination of MUF by graphical (CRPL) method.

11.13. LOWEST USABLE FREQUENCY (L.U.H.F. OR L.U.F. SIMPLY)

The absorption of an High frequency (HF) radio wave in the *D*-region of the ionosphere is proportional to the inverse square of the frequency. The sensitivity of an HF receiver is normally limited by external noise which increases as the frequency is reduced. Hence there is a frequency limit below which the signal to noise ratio fails to reach an acceptable value for the service required. *Therefore, Lowest Usable Frequency (LUF), is dependent upon the engineering characteristics of the link viz. transmitted power.* In addition to absorption limitations, the signal can loose energy after it has been transmitted by several other mechanism for example,

(i) Free space propagation loss *i.e.* spatial spreading of the energy.

(ii) Polarization change caused by the earth's magnetic field.

(iii) Scatter processes.

(iv) Focusing and defocusing caused by ionospheric curvature.

These processes complicate the evaluation of the expected performance of the circuit.

For a given distance of transmission and limited transmitter power, *the lowest usable high frequency* for sky wave propagation is limited mainly due to following two phenomena :

(a) Sky wave absorption increases with decreasing frequency and hence reducing the received field intensity for the lower frequencies.

(b) The atmospheric noise as also most of the man-made electrical noises increases with decreasing frequency in the short wave or high frequency range. As a result, with lowering of transmitter frequency a situation arises where the received noise field is stronger than the desired signal intensity.

As the MUF limits the highest permissible frequency for sky wave propagation in a given path, the LUF gives the lowest permissible frequency. For a lower frequency of transmission the received sky wave signal gets lost in the background noise and no communication is possible. The LUF is limited by absorption in the D-layer during day light hours. Whereas at night, it is primarily limited by increased noise at lower frequencies. The value of day time LUF is normally much higher than the night time and further increases during SID's. The value of LUF is calculated from the measurement of noise level at the receiving site and the estimated value of sky wave absorption in the given propagation path.

11.14. SKIP DISTANCE

(AMIETE, May 1974, 1975, 1992, 1994, Nov. 1975, 82, 89, 90, 91, Meerut Univ. M.Sc. Phy. (F) 1983, Agra Univ. M.Sc. Phy. 1984)

Radio wave radiated horizontally from a transmitter near the earth's surface is quickly absorbed due to large ground losses and hence only short distance communication is carried out by this horizontal radiations of ground or surface wave. Radio wave radiated at high angle may not be bent sufficiently at the ionospheric layers to return to earth at all and hence escapes rather penetrates the layer. Thus radio wave radiated at shallow angle (*i.e.* angle between horizontal and high angle) just great enough to escape absorption by the earth, will enter the lower layer, suffer attenuation, be bent at the upper layer and return to earth. In other words between, *the distance at which surface wave becomes negligible and the distance at which the first wave returns to earth from the ionospheric layer, there is a zone which is not covered by any wave (i.e. neither ground nor sky). This is called skip zone or area and the distance across it is the 'skip distance.'* Although, it is more usual to consider skip distance from the transmitter to the point where first sky wave is received, as range of surface wave is always small.

Hence skip distance may be defined as

(i) The minimum distance from the transmitter at which a sky wave of given frequency is returned to earth by the ionosphere. It is represented by D as in the Fig. 11.27, or

(ii) The minimum distance from the transmitter to a point where sky wave of a given frequency is first received, or

(iii) The minimum distance within which a sky wave of given frequency fails to be reflected back, or

(iv) The minimum distance for which sky wave propagation just takes place and no sky wave propagation is possible for points nearer than this distance.

The higher the frequency, the higher the skip distance and for a frequency less than critical frequency of a layer skip distance is zero. As the frequency of a wave exceeds the critical frequency, the effect of the ionosphere depends upon the angle of incidence at the ionosphere as shown in Fig. 11.27 in which waves of different angle of incidence is shown.

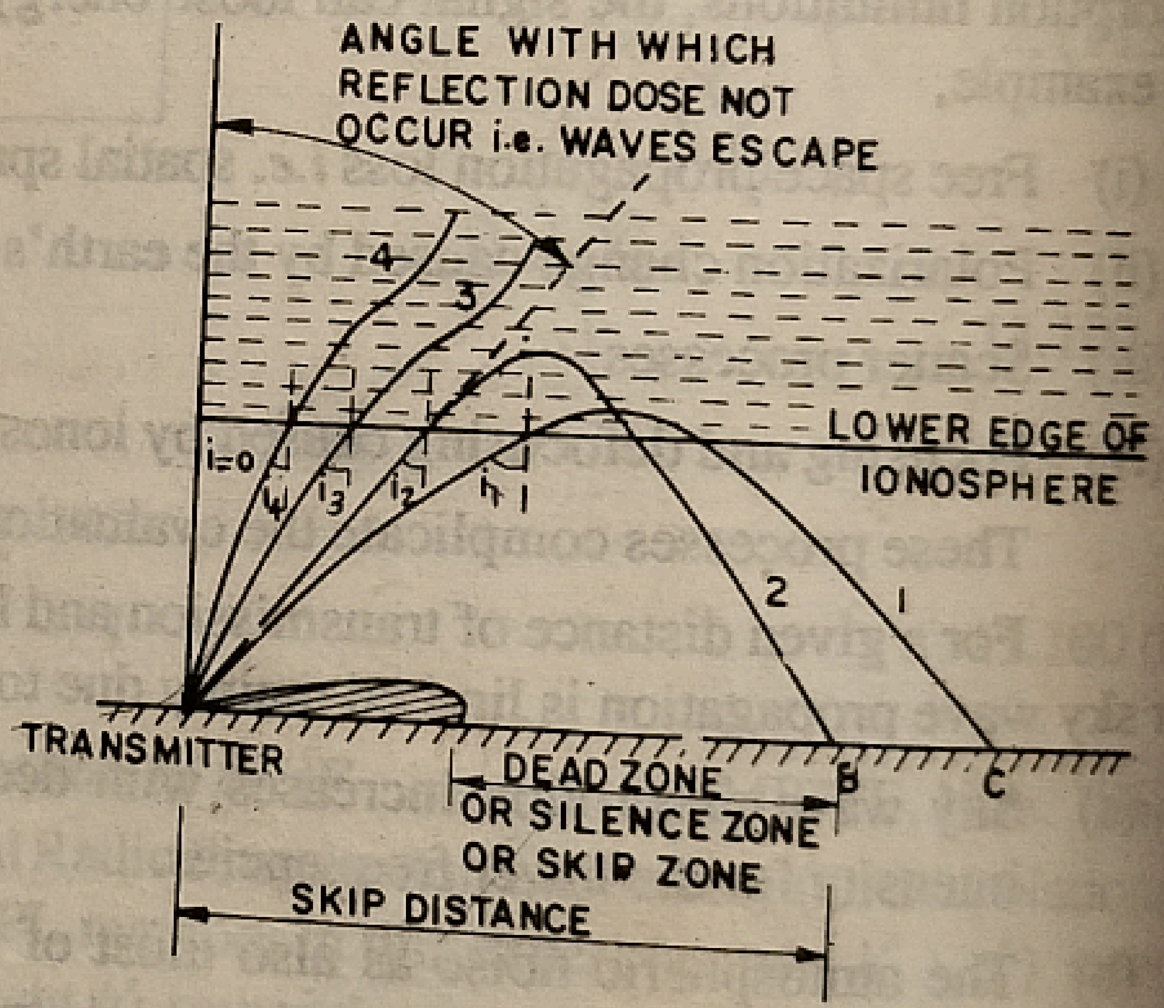


Fig. 11.27. Skip distance explantation.

As the angle of incidence at the ionosphere decreases, the distance from the transmitter, at which the ray returns to ground first decreases. This behaviour continues until eventually an angle of incidence is reached at which the distance becomes minimum. The minimum distance is called skip distance D (as with wave no. 2). With further decrease in angle of incidence, the wave penetrates the layer (as wave nos. 3 and 4) and does not return to earth. *Infact, skip distance is the distance skipped over by the sky wave.*

This happens because

(1) As the angle of incidence i is large (say for wave no. 1), the eqn.

$$\mu = \sin i = \sqrt{1 - \frac{81 N}{f^2}}$$

is satisfied with small electron density. This means μ is slightly less than unity and hence wave returns after slight penetration into the layer.

As the angle of incidence is further decreased (As in wave no. 2) $\sin i$ decrease still more and so also the μ, as N becomes comparatively more. Hence the wave penetrates still more before it reaches to earth.

Lastly when angle of incidence is small enough so that $\mu = \sin i$ can not be satisfied even by maximum electron density of the layer, then the wave penetrates (as the wave nos. 3 and 4).

The frequency which makes a given distance corresponds to the skip distance is the maximum usable frequency for those two points. If a receiver is placed with the skip distance no signals would be heard unless of course ground wave is strong enough as at *A*.

For a given frequency of propagation $f = f_{muf}$ the skip distance can be calculated from Eqn. 11.90 (b) in which *D* is the skip distance. Thus,

$$\frac{f_{muf}}{f_c} = \sqrt{1 + \left(\frac{D}{2h}\right)^2} \quad \text{or} \quad \left(\frac{f_{muf}}{f_c}\right)^2 - 1 = \left(\frac{D_{skip}}{2h}\right)^2$$

or

$$\boxed{D_{skip} = 2h\sqrt{\left(\frac{f_{muf}}{f_c}\right)^2 - 1}} \quad \text{... (11.102)}$$

11.15. OPTIMUM WORKING FREQUENCY (OWF) (AND DAY AND NIGHT FREQUENCY)

(AMIETE, May, 1971, Dec. 1992)

In practical radio communication, for satisfactory reception of signals at the receiving points, it is essential that the frequency should be less than MUF and absorption of waves by the ionosphere be small. Due to presence of electrons (free) which give rise to certain conductivity and this effect is important at lower edge of the ionosphere. The absorption is dependent on the inverse square of the frequency. Thus highest possible frequency gives the strongest sky wave signal at the receiver and hence it is preferred to work as closely as possible to the MUF.

Optimum frequencies are selected from the predication of MUF based on a monthly average and in practice there is daily variations about 15% from this mean value. Hence, it is normal to use a frequency 85% of the predicated MUF. *Therefore there is a frequency called optimum working frequency (O.W.F.) or optimum traffic frequency (O.T.F.) which is 50% to 85% of MUF is used to accommodate a number of channels i.e OWF = 85% MUF.*

Since MUF for a particular location varies considerably with time of the day, from season to season and from months to months and accordingly the optimum working frequency also follow similar variations. However, in practice it is not possible to change the frequency of communication from hour to hour. Therefore, *for continuous communication, it is necessary to use atleast two frequencies, one for day and the other for night. Even, sometimes a third frequency for transition period is also used. In the night the vertical height of the ionospheric layer increases than in the day time and so the skip distance too increases as illustrated in Fig. 11.28.*

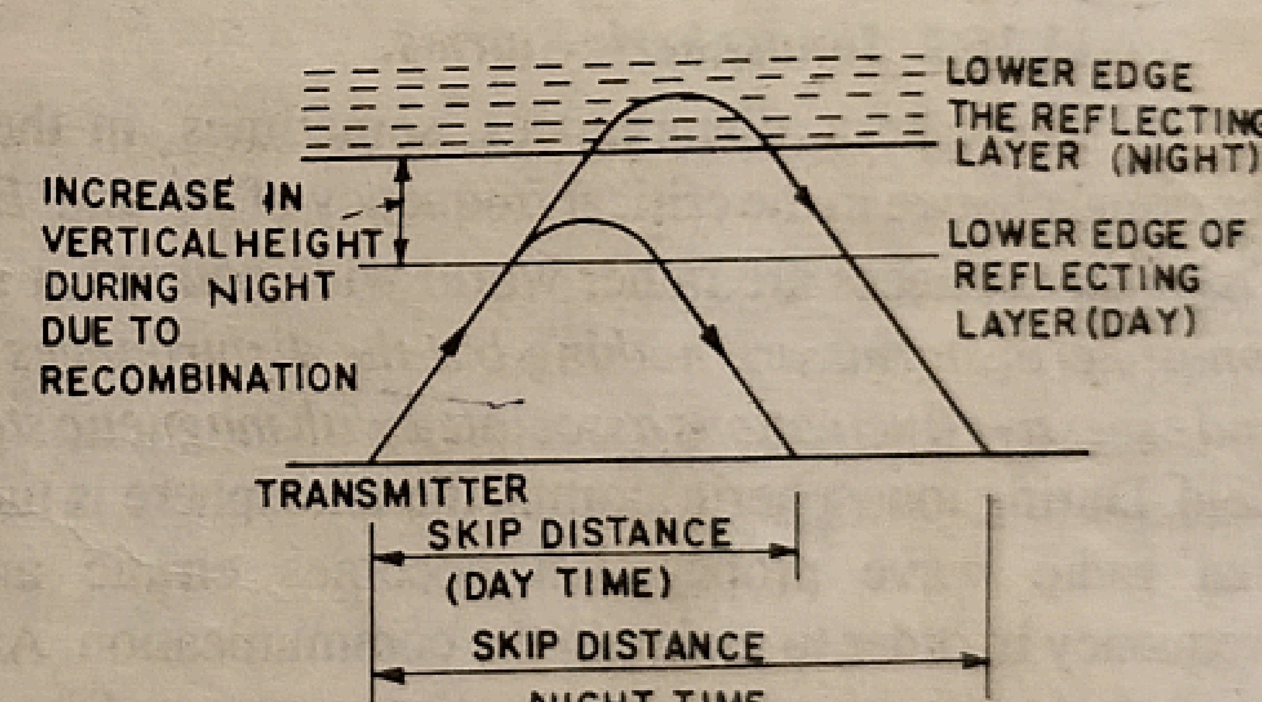


Fig. 11.28. Increase in height of layer during night and hence the need of day and night frequency.

10 - 30 MH

Since the wave of lower frequency is bent round more quickly than wave of higher frequency and accordingly different frequencies are used for day (higher frequency) and night (lower frequency) working. The increase in skip distance in the night due to increase in the vertical height of the layer in the night, is cancelled by use of lower frequency. Typical frequencies for day and night are 6.450 MHz and 5000 MHz respectively. The practical frequency for day time is selected 15% to 20% lower than the average of optimum frequency for entire of the day time. Practical frequencies for night and transition hours are also selected on similar basis.

appreciable energy to the receiver...

Fig. 11.32. (c) Illustration of day and night.

11.19. SPACE WAVE PROPAGATION

As already mentioned, the space wave or line of sight propagation is chiefly useful at higher frequencies *i.e.* VHF, UHF and microwaves because the sky wave and surface wave propagations both fail at such frequencies. The space wave propagation is practically limited to line of sight distance and is also limited by the curvature of the earth.

Line of sight distance is that distance between the transmitter and receiver, in which if a direct ray passes from the transmitter to the receiver without being intercepted by the bulge in the earth's surface, considering variation of refractive index (μ) of earth's atmosphere with height, the transmitting antenna must 'see' atleast the top of the receiving antenna. Line of sight propagation is limited to about few tens of kilometres and the propagation occurs in the troposphere — a region 16 km above earth's surface. Now the various aspects of space wave propagation will be described, *i.e.* line of sight communication range, effective earth's radius, Field strength etc.

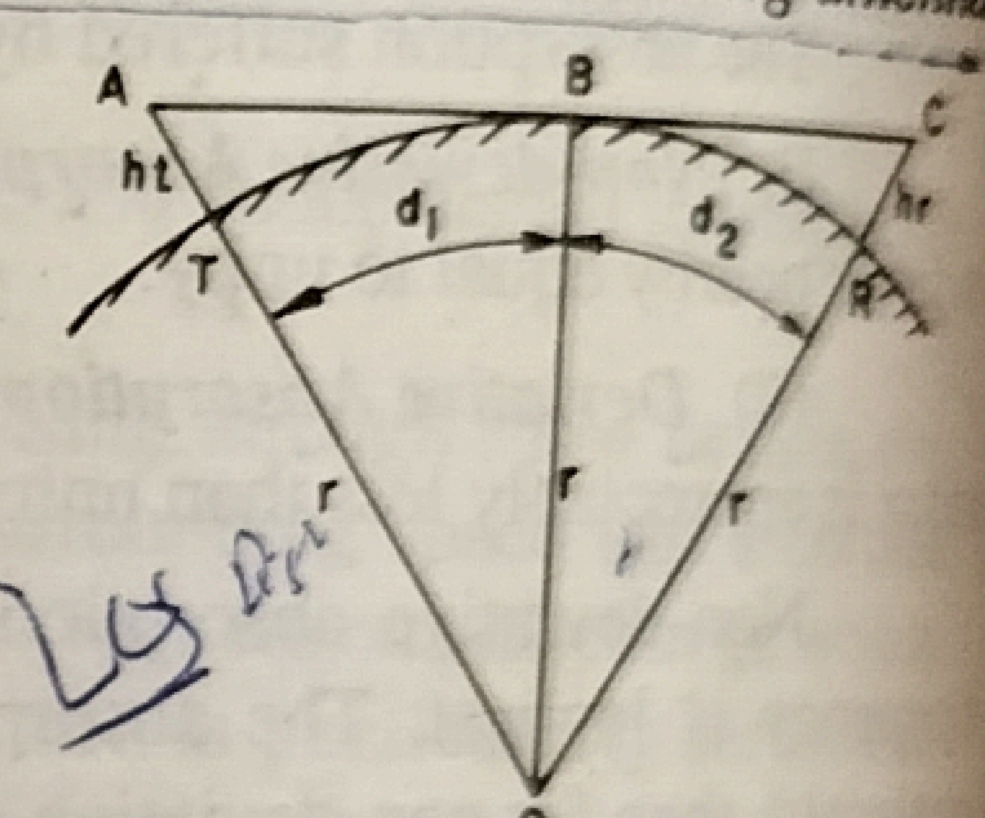


Fig. 11.33. Optical range of line of sight (LOS) propagation.

11.19.1. *Range of Space Wave Propagation or Line of Sight Distance (LOS).* In general, space wave communication is possible only upto or slightly beyond line of sight distance and this distance is determined mainly by the heights of transmitting and receiving antennas as derived below.

Let d be the distance between transmitter and the receiver, and heights of the transmitting and receiving antennas are h_t and h_r respectively above ground. Now from Fig. 11.33, the line of sight distance

$$d = d_1 + d_2 \qquad \ldots (11.104)$$

If r be the radius of earth (equal to 6370 km) then from $\Delta\, ABO$ and $\Delta\, CBO$,

$$d_1 = \sqrt{(h_t + r)^2 - r^2} = \sqrt{h_t^2 + r^2 + 2\, h_t \cdot r - r^2} \simeq \sqrt{2\, r\, h_t} \text{ metres} \qquad \Big|\ \because h_t^2 << 2\, r\, h_t$$

Similarly, $d_2 = \sqrt{(h_r + r)^2 - r^2} = \sqrt{h_r^2 + r^2 + 2\, h_r \cdot r - r^2} = \sqrt{2\, r \cdot h_r}$ metres $\quad \because h_r^2 \le 2\, r\, h_r$

Thus putting the values of d_1 and d_2 in eqn. 11.104, we get

$$d = [\sqrt{2\, r \cdot h_t} + \sqrt{2\, r\, h_r}\,] \text{ metres} = \sqrt{2\, r}\, [\sqrt{h_r} + \sqrt{h_r}\,] \text{ metres} \qquad \ldots (11.104\ a)$$

$$= \sqrt{2 \times 6370 \times 10^3}\, [\sqrt{h_t} + \sqrt{h_t}\,] \text{ metres} \qquad \Big|\ \because r = 6370 \text{ km} = 6370 \times 10^3 \text{ metres}$$

$$= \sqrt{12.74 \times 10^6}\, [\sqrt{h_t} + \sqrt{h_r}\,] \text{ metres}$$

$$= 10^3\, \sqrt{12.74}\, [\sqrt{h_t} + \sqrt{h_r}\,] \text{ metres} = 10^3 \times 3.570\, [\sqrt{h_t} + \sqrt{h_r}\,] \text{ metres}$$

$$\boxed{d = 3.57\, [\sqrt{h_t} + \sqrt{h_r}\,] \text{ km}} \qquad \ldots (11.105)$$

Where h_t, h_r are heights of transmitting and receiving antennas in metres and the maximum line of sight distance covered by space wave propagation d is in km. Eqn. 11.105 shows that service area 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. As an example if h_t and h_r are 100 metres each, the value of d is 71.4 km only.

11.19.2. *Effective Earth's Radius* (AMIETE, June 1980, Dec. 92, PLE 84, UPSC, CES 76)

A radio wave travelling horizontally in the earth's atmosphere follows a path which has a slight downward curvature due to the refraction of the wave in the atmosphere. This curvature of path tends to overcome partially the loss of signal due to the curvature of the earth and permits the diret ray to reach point slightly beyond the horizon as found by the straight line or line of slight path. In making computations the effect of refraction is accounted for by using *an effective radius of curvature of the earth* which is a bit greater than the actual radius, and then assuming straight line path (i.e. without refraction) in the atmosphere. As the dielectric constant *i.e.* refractive index of the atmosphere changes with the height above ground and hence the refraction of a radio wave takes place. The dielectric constant of the atmosphere near the surface of earth is greater than unity but decreases to unity at greater height where air density approaches zero. *This decrease in refractive index with height causes refraction of the radio wave which results in the bending of radio wave towards the region of higher dielectric constant or refractive index i.e. towards the earth.*

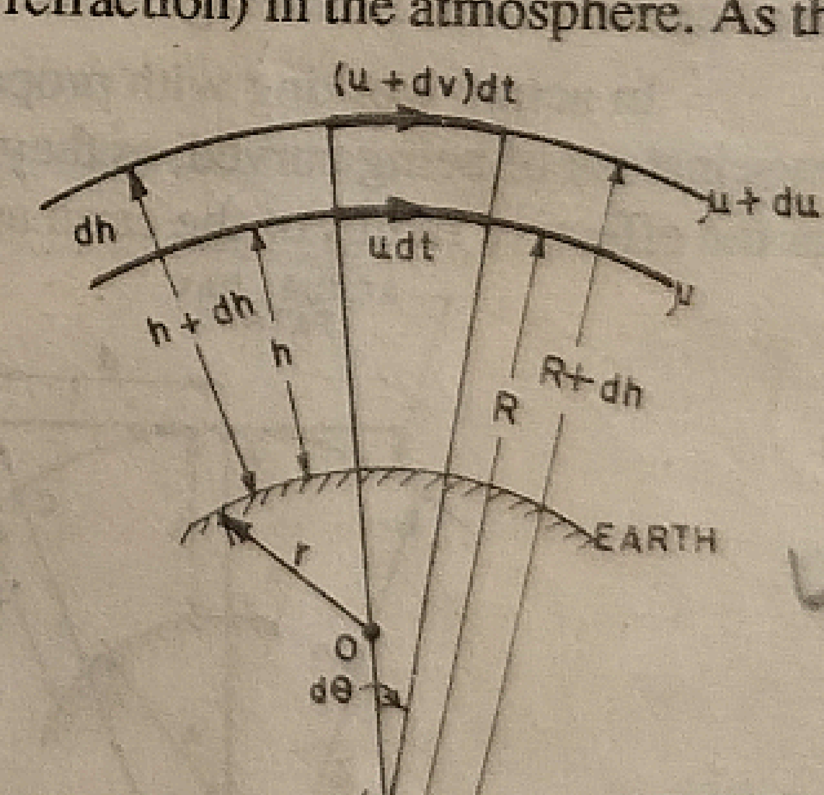


Fig. 11.34. Refraction of radio wave in the troposphere.

Let us now derive a relation between the radius of curvature of the ray path in the troposphere and change of refractive index with height by assuming the curvature of the earth (assumption will be justified in the next article). Consider a radio wave which is travelling nearly horizontally in the troposphere and its path is bent into an arc by the variation of the refractive index with height as shown in Fig. 11.34.

Let

v = Velocity ... ation

h = Height a ... rth (of the travelling ray),

R ... of the ray path,

r ...