Module 6

MODES OF PROPAGATION

The radio waves transmitting from the transmitting antenna may reach to the receiving antenna following any of the following modes of propagation.

1. **Ground Wave Propagation**

- The ground wave or surface wave propagates from transmitter to receiver by gliding over the surface of the earth in which both antennas are close to the surface of the earth. It follows the curvature of the earth. The ground wave as being produced usually by vertical antennas is vertical polarized .Any horizontal component of the electric field in contact with the earth is short circuited by the earth. Energy is lost in propagation of radio waves and attenuated as it passes over the surface. So ground waves are very useful to propagate at low frequencies below about 2 MHz. This is because they are more strongly diffracted around obstacles due to their long wavelengths, allowing them to follow the Earth's curvature. The Earth has one refractive index and the atmosphere has another, thus constituting an interface that supports the surface wave transmission. The earth is not an ideal conductor, so there will remain a tangential component of electric field resulting **wave tilt.**
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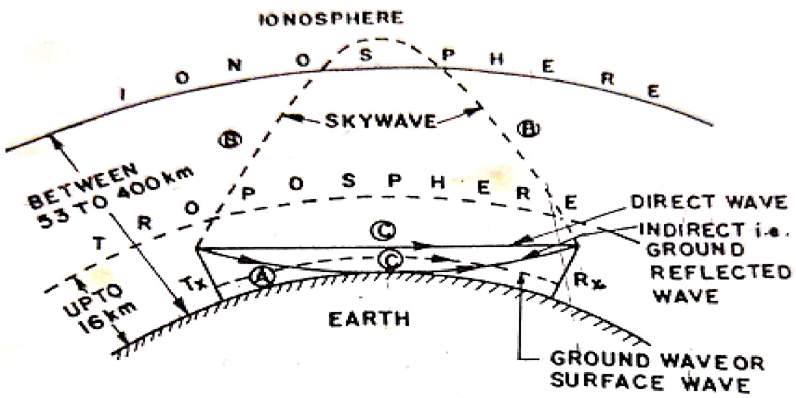

Tx = Transmitting antenna.
Rx = Receiving antenna.
Path A = Ground wave propagation.
Path B = Sky or ionospheric propagation.
Path C = Space wave propagation.
Fig. 11.5. Possible propagation paths from transmitting antenna to receiving antenna

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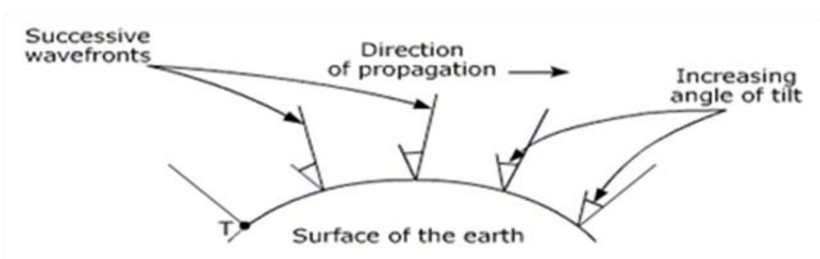

— **Sky Wave Propagation**

— Every long radio communication of medium and high frequencies are conducted using skywave propagation. In this mode reflection of EM waves from the ionized region in the upper part of the atmosphere of the earth is used for transmission of waves to longer distances.

— This part of the atmosphere is called ionosphere which is at about 70-400 km height. Ionosphere reflects back the EM waves if the frequency is between 2 to 30 MHz’s. Hence, this mode of propagation is also called as Short wave propagation.

— Using sky wave propagation point to point communication over long distances is possible. With the multiple reflections of sky waves, global communication over extremely long distances is possible.

— But a drawback is that the signal received at the receiver has faded due to a large number of waves following a large number of different paths to reach the receiving point.

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— **Space Wave Propagation**

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— When we are dealing with EM waves of frequency between 30 MHz to 300 MHz, then space wave propagation is useful. Here properties of **Troposphere** are used for transmission.

— When operating in space wave propagation mode, the wave reaches the receiving antenna directly from the transmitter or after reflection from troposphere which is present at about 16km above the earth surface. Hence space wave mode consists of two components .i.e. **direct wave** and **indirect wave**.

— Though these components are transmitted at the same time with the same phase they may reach within the phase or out of phase with each other at the receiver end depending on the different path lengths. Thus, at the receiver side signal strength is the vector sum of strengths of direct and indirect waves.

— The space wave propagation mode is used for propagation of very high frequencies.

Structure of Atmosphere

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— The various effects like reflection, refraction, diffraction, etc all come together in a real way as radio signals propagate through the atmosphere..In many instances, terrestrial radio propagation is governed to a great degree by the regions of the atmosphere through which the signals pass. Without the action of the atmosphere it would not be possible for radio communications signals to travel around the globe on the short wave bands, or travel greater than only the line of sight distance at higher frequencies. The atmosphere can be split up into a variety of different layers according to their properties.

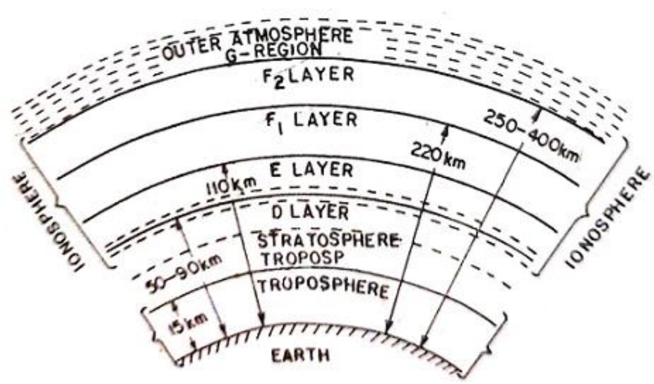


Fig. 11.12. Medium above earth surface.
(a) Troposphere upto 15 km.
(b) Ionosphere — 50—400 km.
(c) outer atmosphere above 400 km.

The lowest area in the meteorological system is referred to as the Troposphere. This extends to altitudes of around 10km above the Earth's surface. Above this is the Stratosphere that extends from altitudes around 10 to 50km. Above this at altitudes between 50 and 80 km is the Mesosphere and above this is the Themosphere: named because of the dramatic rise in temperatures here.

From the viewpoint of radio propagation, there are two main areas of interest:

- ***Troposphere:*** As a very approximate rule of thumb, this area of the atmosphere tends to affect signals more above 30 MHz or so.
- ***Ionosphere:*** The ionosphere is the area that enables signals on the short wave bands to traverse major distances. It crosses over the meteorological boundaries and extends from altitudes around 60 km to 700 km. The region gains its name because the air in this region becomes ionised by radiation primarily from the sun. Free electrons in this region have affect radio signals and may be able to refract them back to Earth dependent upon a variety of factors.

Troposphere

The lowest of the layers of the atmosphere is called the troposphere. The troposphere extends from ground level to an altitude of 10 km.

It is within the tropospheric region that what we term the weather, occurs. Low clouds occur at altitudes of up to 2 km and medium level clouds extend to about 4 km. The highest clouds are found at altitudes up to 10 km whereas modern jet airliners fly above this at altitudes of up to 12 km.

Within this region of the atmosphere there is generally a steady fall in temperature with height. This affects radio propagation because it affects the refractive index of the air. This plays a dominant role in radio signal propagation and the radio communications applications that use tropospheric radio-wave propagation. This depends on the temperature, pressure and humidity. When radio communications signals are affected this often occurs at altitudes up to 2 km.

The ionosphere

The ionosphere is the area that is traditionally thought of as providing the means by which long distance communications can be made. It has a major effect on what are normally thought of as the short wave bands, providing a means by which signals appear to be reflected back to earth from layers high above the ground.

- The ionosphere has a high level of free electrons and ions - hence the name ionosphere. It is found that the level of electrons sharply increases at altitudes of around 30 km, but it is not until altitudes of around 60km are reached that the free electrons are sufficiently dense to significantly affect radio signals.

- The ionisation occurs as a result of radiation, mainly from the sun, striking molecules of air with sufficient energy to release electrons and leave positive ions.
- Obviously when ions and free electrons meet, then they are likely to recombine, so a state of dynamic equilibrium is set up, but the higher the level of radiation, the more electrons will be freed.
- Much of the ionisation is caused by ultraviolet light. As it reaches the higher reaches of the atmosphere it will be at its strongest, but as it hits molecules in there upper reaches where the air is very thin, it will ionise much of the gas. In doing this, the intensity of the radiation is reduced
- At the lower levels of the ionosphere, the intensity of the ultraviolet light his much reduced and more penetrating radiation including x-rays and cosmic rays gives rise to much of the ionisation.
- As a result of many factors it is found that the level of free electrons varies over the ionosphere and there are areas that affect radio signals more than others. These are often referred to as layers, but are possibly more correctly thought of a regions as they are quite indistinct in many respects. These layers are given designations D, E, and F1 and F2.

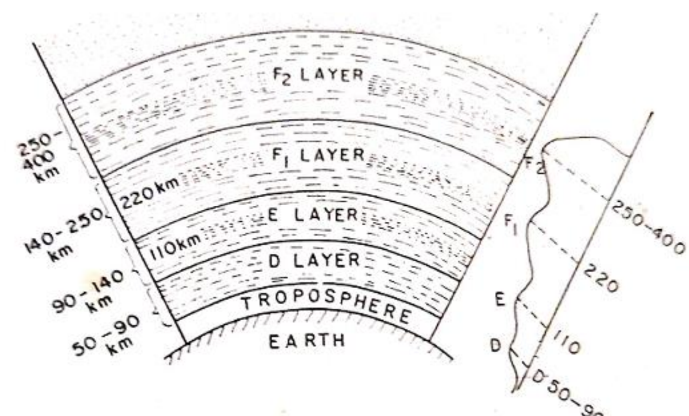


Fig. 11.13. Typical height of ionospheric layers above earth.

Ionospheric Regions

- ***D region:*** The D layer or D region is the lowest of the regions that affects radio signals. It exists at altitudes between about 60 and 90 km. It is present during the day when radiation is being received from the sun, but because of the density of molecules at this altitude, free electrons and ions quickly recombine after sunset when there is no radiation to retain the ionisation levels. The main effect of the D region is to attenuate signals that pass through it, although the level of attenuation decreases with increasing frequency. Accordingly its effects are very obvious on the medium wave broadcast band - during the day when the D region is present, few signals are heard beyond that provided by ground wave coverage. At night when the region is not present, signals are reflected from higher layers and signals are heard from much further afield.

- ***E region:*** Above the D region, the next region is the E region or E layer. This exists at an altitude of between 100 and 125 km. The main effect of this region is to reflect radio signals although they still undergo some attenuation.

  In view of its altitude and the density of the air, electrons and positive ions recombine relatively quickly. This means that after sunset when the source of radiation is removed, the layer reduces in strength very considerably although some residual ionization does remain.

- ***F region:*** The F region or F layer is higher than both the D and E regions and it the most important region for long distance HF communications. During the day it often splits into two regions known as the F_1 and F_2 regions, the F_1 layer being the lower of the two.
- At night these two regions merge as a result of the reduction in level of radiation to give one region called the F region. The altitudes of the F regions vary considerably. Time of day, season and the state of the sun all have **major** effects on the F region. As a result any figures for altitude are very variable and the following figures should only be used as a very rough guide. Typical summer altitudes for the F_1 region may be approximately 300 km with the F_2 layer at about 400 km or even higher. Winter figures may see the altitudes reduced to about 200 km and 300 km. Night time altitudes may be around 250 to 300 km.

  Like the D and E regions, the level of ionisation fort he F region falls at night, but in view of the much lower air density, the ions and electrons combine much more slowly and the F layer decays much more slowly. As a result it is able to support radio communications at night, although changes are experienced because of the lessening of the ionisation levels.

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.

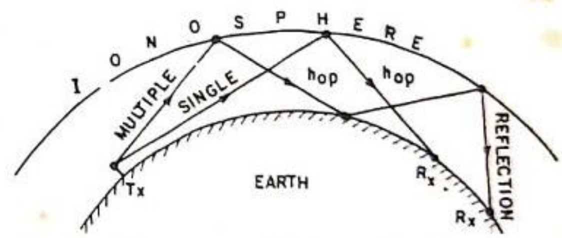


Fig. 11.16. Single and multiple-hops reflections for long distance communications.

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

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

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.

$$\text{Force} = \text{Mass} \times \text{Acceleration}$$

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

or

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

Integrating both sides

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

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

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

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

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

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

Since $\boldsymbol{D} = \varepsilon_0 \boldsymbol{E} = k_0 \boldsymbol{E}$; k_0 = constant

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

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

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

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

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)

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

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

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

where N = Number of electrons per cubic metre or ionic density and f = frequency in Hz.

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.*

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

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

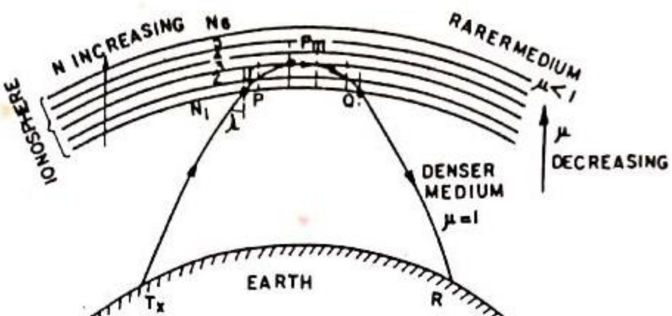


Fig. 11.17. Refraction of radio waves in the ionosphere.

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

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

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.

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

or

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

or

$$\boxed{f_c = 9\sqrt{N_m}}$$

where f_c is expressed in MHz and N_m in per cubic metre.

11.8. EFFECT 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 field. 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 superimposed 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 motion (when magnetic field was neglected) is now modified to an *elliptical or spiral motion* by the earth's magnetic field as illustrated in Fig. 11.18. The average strength of the terrestrial magnetic field is 40 A/m substantially effects the radio wave propagation and makes the ionosphere to behave like an isotropic medium *i.e.* offering different dielectric constant in different directions. The earth's magnetic field causes the electrons and ions in ionosphere to trace the complicated trajectory, the frequency of which (*i.e.* moving charged particles) depends on the magnetic field and the ratio e/m (charge to mass ratio) of the particle. For electrons earth's magnetic flux density

$$B \simeq 0.5 \times 10^{-4} \text{ webers/metre}$$

This frequency is about 1.4 MHz and is called as gyro-frequency (f_g). **It is defined as the frequency whose period is equal to the period of revolution of an electron in its circular orbit under the influence of the earth's magnetic field of the flux *B*.**

Thus
$$\omega_g = B\left(\frac{e}{m}\right) \text{ or } 2\pi f_g = B\left(\frac{e}{m}\right)$$

or
$$f_g = \frac{1}{2\pi} B\left(\frac{e}{m}\right) = \frac{Be}{2\pi m}$$

Putting the values of m, e, B we get

$$f_g = \frac{0.5 \times 10^{-4} \times 1.602 \times 10^{-19}}{2 \times 3.14 \times 9.107 \times 10^{-31}} \text{ Hz}$$

$$f_g = \frac{0.5 \times 1.602}{6.28 \times 9.107} \times 10^8 \text{ Hz} = 1.417 \text{ MHz} \equiv \mathbf{1.4\ MHz} \qquad \text{...(11.47)}$$

$$\because \quad \log f_g = (\bar{1}.6990 + 0.2095 - 0.7980 - 0.9593) \times 10^8$$

$$= (\bar{1}.9085 - 1.7573) \times 10^8 = (\bar{2}.1512) \times 10^8$$

$$\therefore \quad f_g = \text{A}' \log \bar{2}.1512 \times 10^8 = 0.01417 \times 10^8 \text{ Hz} = \mathbf{1.417\ MHz}$$

If the frequency (f) of the incident radio wave is equal or nearly equal to f_g (gyro-frequency) then there is resonance phenomenon and the oscillating electrons receive more and more energy from the incident wave. As a consequence, their velocity increases and they describe larger and larger orbits [Fig. 11.18 (b)] and hence they have more chances of having inelastic collisions, thereby dissipate a large amount of energy from the incident radio waves. Hence attenuation is maximum near gyro-frequency (when $f = f_g$) and so avoided in propagation work. During day hours in *D*-region where collision frequency is high and thus no sky wave possible between 1 to 2 MHz. Beyond the frequency about 2 MHz, the attenuation is small and hence used for communication.

At high frequencies, when $f > f_g$ the electron motions follows an elliptical path Fig. 11.18 (b) and the

(a) *High frequency* $f > f_g$

(b) *Critical frequency* $f = f_g$.

(c) *low frequency* $f < f_g$

where f_g = *Gyro–frequency* $= \dfrac{Be}{2\pi m}$

Fig. 11.18. Path followed by an electron while vibrating under earth's magnetic field.

ellipse gets narrower if frequency increases. *Consequently a high frequency plane polarized wave gets elliptically polarized after reflection from the ionosphere.*

At lower frequencies, when $f < f_g$ the electrons vibrate in small loops, usually making several loops just like a stretched spiral and the polarization is not effected much.

Virtual Height

Virtual height of an ionosphéric 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.

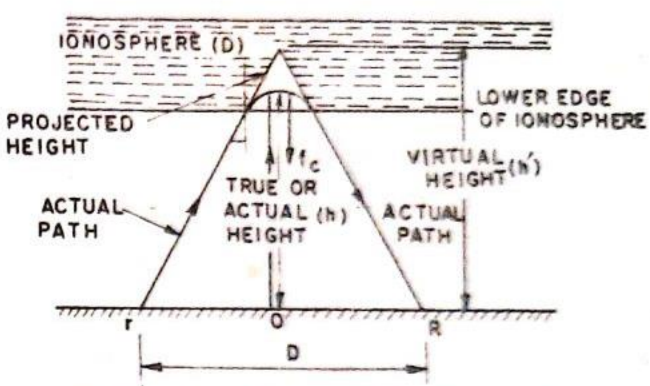


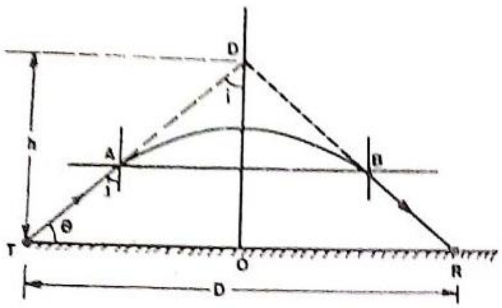
Fig. 11.20. Virtual and actual heights of an ionized layer.

Virtual height is

always greater than the actual height.

Calculation of virtual height

case1:flat earth



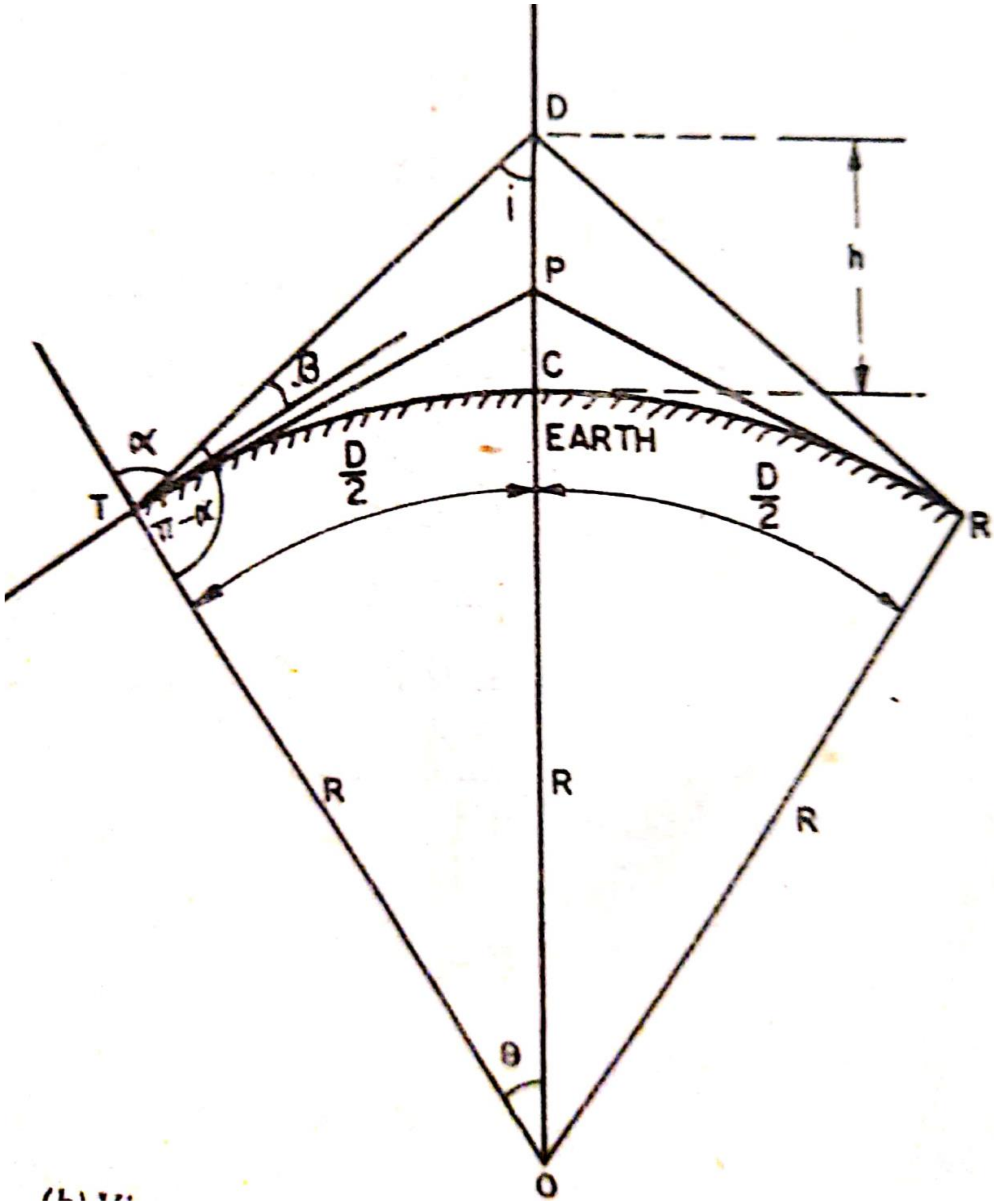
(a) Virtual height determination for flat earth.

Fig. 1......

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

$$\tan\beta = \frac{D_O}{T_O} = \frac{h}{TR/2} \text{ or } \frac{T_R}{2} = \frac{h}{\tan\beta} \qquad \because T_O = \frac{T_R}{2}$$

Case 2: curved earth



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O

From Δ TOD

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

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

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

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

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

Further, from Fig. 11.21 (b)

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

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

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

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

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

Now we know that

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

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

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

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

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

Maximum Usable Frequency

MUF is defined as the highest frequency at which a radio wave is reflected by the ionospheric layer at an angle of incidence other than normal incidence

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

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

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

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

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

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

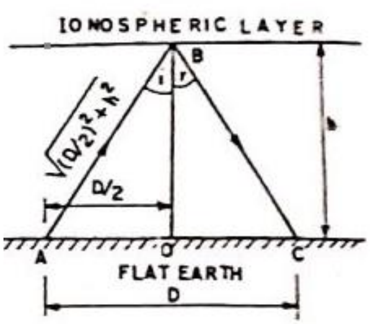
$$\boxed{f_{muf} = \sec i \cdot f_c} \qquad \text{... 11.87 (b)}$$

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

This is known as SECANT LAW

Calculation of MUF

case1: flat earth



. Reflection from a thin layer on flat earth

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

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 $\cos^2 i$ from eqn. 11.87 (a) and eqn. 11.89

$\therefore$ $$\cos^2 i = \frac{f_c^2}{f_{muf}^2} = \frac{4h^2}{4h^2 + D^2} \qquad \text{... 11.90 (a)}$$

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

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

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

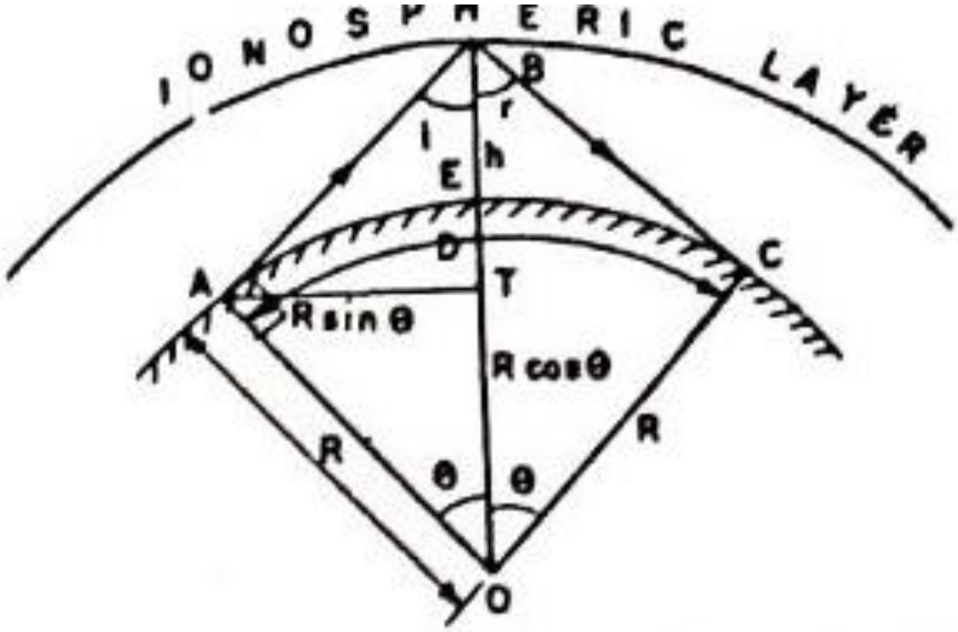


Fig. 11.25. Reflection from a thin ionospheric layer but on curved earth accouting its curvature.

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.

Then

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

or

$$\boxed{D = 2R\theta} \qquad \text{...(11.91)}$$

Now

$$AT = R\sin\theta; \quad OT = R\cos\theta$$

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

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)

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

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

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

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

r

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

Hence from eqn. 11.91

$$D^2 = 4R^2\theta^2 = 4R^2\cdot\frac{2h}{R} = 8hR$$

from eqn. 11.95

binomial expansion : $(1+x)^{-1} = 1 - x + x^2 - x^3 + \ldots\ldots\infty$

$$\boxed{h = \frac{D^2}{8R}} \qquad \ldots(11.96)$$

Hence from eqn. 11.94

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

and

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

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

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

or

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

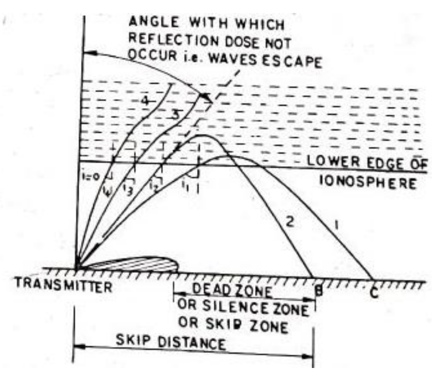
$$\boxed{(f_{muf})_{max} = f_c\frac{\sqrt{\frac{D^2}{4}+\left(h+\frac{D^2}{8R}\right)^2}}{\sqrt{\left(h+\frac{D^2}{8R}\right)^2}}} \qquad \ldots(11.9$$

Skip distance

The minimum distance from the transmitter to the point on ground at which of a given frequency will return to the earth by the ionosphere is called skip 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.

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.

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

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,

or

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

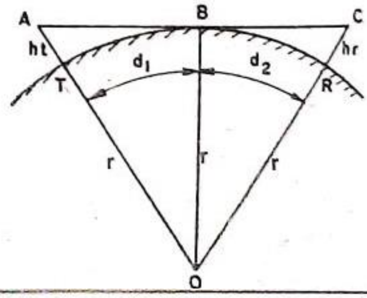
$$\boxed{D_{skip} = 2h\sqrt{\left(\frac{f_{muf}}{f_c}\right)^2 - 1}} \qquad \text{... (11.102)}$$

SPACE WAVE PROPAGATION

. 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. .

Range of space wave propagation or Line of sight distance



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

$$d = d_1 + d_2 \qquad \text{... (11.104)}$$

If r be the radius of earth (equal to 6370 km) then from ΔABO and ΔCBO,

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

$$\text{Similarly, } d_2 = \sqrt{(h_r + r)^2 - r^2} = \sqrt{h_r^2 + r^2 + 2\,h_r \cdot r - r^2} = \sqrt{2\,r \cdot h_r} \text{ metres} \qquad \because hr^2 \leq 2\,r\,h_r$$

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

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

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

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

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

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

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.

Field strength of tropospheric wave

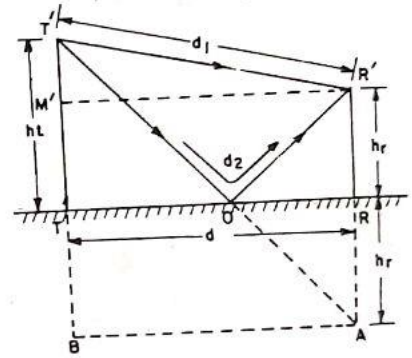


Fig. 11.36. Space wave propagation and field strength determination at Receiving Point R.

If the curvature of earth is neglected the space wave propagation takes place as illustrated in Fig.11.36 in which the energy received at the receiving point is by two ways *i.e.* one by direct rays (path $OT'\ R'$) and the other by the indirect rays after reflection from the ground (path $T'\ OR'$). The field strength received at the receiving point is vector sum of the fields of the two rays. The direct ray suffers almost negligible attenuation (except due to spreading etc.) but the indirect ray under-going reflection at the ground too will be assumed to be of almost same magnitude but of different phase, as the heights of transmitting and receiving antennas are small compared to the distance between them and so the angle of incidence at ground is also small.

Let h_t = height of transmitting antenna, above ground

h_r = height of receiving antenna, above ground

d = distance between them

d_1 = direct ray's path

d_2 = Indirect ray's path

E_0 = Field strength at R' due to direct rays.

Assuming the earth to be perfect, the magnitude of field strength at R' would be equal to E_0 as the distance travelled by both rays are approximately equal. However, if the reflection coefficient at the ground is k, then the magnitude of ground reflected wave is $k\,E_0$. The two rays combine at the receiving point vectorially. Now from Fig. 11.36 $\Delta\ T'R'M'$

$$(h_t - h_r)^2 + d^2 = d_1^2 \qquad \text{...(11.122)}$$

and similarly from the right angle triangle $T'AB$,

$$(h_t + h_r) + d^2 = d_2^2 \qquad \text{...(11.123)}$$

Now from eqn. 11.122 $\quad | \because RR' = RA$

$$d_1 = [d^2 + (h_t - h_r)^2]^{1/2}$$

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

or

$$d_1 = d + \frac{(h_t + h_r)^2}{2d} \qquad \text{... 11.124 (a)}$$

and similarly

$$d_2 = d + \frac{(h_t + h_r)^2}{2d} \qquad \text{... 11.124 (b)}$$

But the path difference between direct and indirect rays is

$$P \cdot d = d_2 - d_1$$

$$= d + \frac{(h_t + h_r)^2}{2d} - d - \frac{(h_t - h_r)^2}{2d} = \frac{2h_t h_r}{2d} + \frac{2h_t h_r}{2d} = \frac{4h_t h_r}{2d}$$

$$P \cdot d = \frac{2h_t h_r}{d} \quad \text{... (11.125)}$$

It is known from the optics that

$$\text{Phase difference } (\alpha) = \frac{2\pi}{\lambda} \text{ (Path difference)} = \frac{2\pi}{\lambda}\left(\frac{2h_t h_r}{d}\right)$$

or

$$\boxed{\alpha = \frac{4\pi h_t h_r}{d\lambda} \text{ radians}} \quad \text{... (11.126)}$$

This is the phase difference caused due to the path difference. But besides this, there is another phase difference of 180° due to reflection from the ground (*i.e.* $\beta = 180°$). Hence the total phase difference (θ) is given by

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

where α = Phase difference due to path difference and is given by eqn. 11.126

and β = Phase difference due to reflection at the ground and is equal to 180^0

Now the resultant field strength at receiving point R is given by

$$\boxed{E_R = E_0 (1 + k e^{-j\theta})}$$

$$E_R = E_0 [1 + k(\cos\theta - j\sin\theta)]$$

$$\therefore \quad |E_R| = E_0 \sqrt{(1 + k\cos\theta)^2 - (jk\sin\theta)^2} \quad | \because j^2 = -1$$

$$= E_0 \sqrt{1 + k^2\cos^2\theta + 2k\cos\theta + k^2\sin^2\theta} = E_0\sqrt{1 + k^2 + 2k\cos\theta}$$

If earth is assumed to be perfect $k = 1$ and $\beta = 180°$ or π radians

$$|E_R| = E_0 \sqrt{1 + 1^2 + 2.1\left(2\cos^2\frac{\theta}{2} - 1\right)} \quad [\because \cos\theta = 2\cos^2\theta/2 - 1]$$

$$= E_0\sqrt{2 + 4\cos^2\frac{\theta}{2} - 2} = E_0 2\cos\frac{\theta}{2}$$

$$|E_R| = 2E_0\cos\left(\frac{\alpha + \pi}{2}\right) = 2E_0\sin\frac{\alpha}{2} \quad \left| \begin{array}{l} \because \theta = \alpha + \beta = \alpha + \pi \\ \because \cos\left(\frac{\pi}{2} + \frac{\alpha}{2}\right) = \sin\frac{\alpha}{2} \end{array}\right.$$

$$|E_R| = 2E_0\sin\left(\frac{4\pi h_t \cdot h_r}{2d\lambda}\right) \quad | \text{ from eqn. 11.126} \quad \text{... (11.127)}$$

$$d >> h_t \text{ or } h_r$$

$$\sin\frac{4\pi h_t h_r}{2d\lambda} \cong \frac{4\pi h_t h_r}{2d\lambda}$$

$$\boxed{|E_R| = 2E_0 \cdot \frac{4\pi \cdot h_t h_r}{2d\lambda} = \frac{E_0\, 4\pi h_t h_r}{d\lambda}} \quad \text{... (11.128)}$$

If E_f = Field strength of the direct ray *i.e.* free space field strength at a unit distance, then

$$E_0 = \frac{E_f}{d} \qquad \text{... (11.129)}$$

But $$E_f = 7\sqrt{P} \text{ volt/metre} \qquad \text{... (11.130)}$$

where P = Effective power radiated, in Watts

$\therefore$ $$\boxed{E_0 = \frac{7\sqrt{P}}{d}} \qquad \text{... (11.131)}$$

Putting this value in eqn. 11.128, we get

$$|E_R| = \frac{7\sqrt{P}}{d} \cdot \frac{4\pi h_t \cdot h_r}{d \cdot \lambda} = \frac{7 \times 4 \times 3.14 \sqrt{P}\, h_t \cdot h_r}{d^2 \lambda} = \frac{87.92 \sqrt{P}\, hsubt \cdot h_r}{d^2 \lambda}$$

or $$\boxed{|E_R| \cong \frac{88\sqrt{P}\, h_t h_r}{\lambda d^2} \text{ volt/metre}} \qquad \text{... (11.131)}$$

where h_t, h_r, λ and d are in metres and P in Watts.

Hence for a propagation of space wave, we see that

$$E_R \propto \sqrt{P} \text{ (Effective power radiation)}$$
$$\propto h_t \text{ (height of transmitting antenna)}$$
$$\propto h_t \text{ (height of receiving antenna)}$$
$$\propto \frac{1}{\lambda} \text{ (inversely with } \lambda \text{)}$$
$$\propto \frac{1}{d^2} \text{ (inversely with square of the distance from the transmitting antenna).}$$

Eqn. 11.131 is used to calculate the field strength at the receiving point, if all above quantities are given.

Duct Propagation (Super Refraction)

At VHF, UHF and microwaves, the waves are neither reflected by ionosphere nor propagated along earth's surface, but the transmission does occur much beyond the line of sight distance due to the refraction of such high frequency waves (specially microwaves) in the troposphere. As already mentioned, troposphere is the region 16 km above the earth's surface and in troposphere temperature falls at the rate of 6.5° per kilometre till it reaches at about 50° C at the upper boundary. Region next higher to troposphere is the **stratopause** where the temperature almost remains constant to – 50° C. 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 and the presence of water vapour increases the dielectric constant still further and hence the dielectric constant depends on air conditions *i.e.* on the weather.

A normal or standard atmosphere is one where the dielectric constant is assumed to decrease uniformly with height to a value of unity at a height where air density is essentially zero. However, in actuality the condition of so called standard atmosphere hardly exists. The air is frequently turbulent and at other times there are often layers of air one above the other having different temperatures and water vapour contents. These conditions besides giving phenomena of *scattering, refraction and reflection*, give a new phenomenon called *super refraction or duct propagation*. In this two boundary surfaces between layers of air *form a duct or a sort of "leaky wave guide" which guides the electromagnetic wave between its wall.* When the frequency is sufficiently high, the region where *the variation of dielectric const. or refractive index is usually high (or refreactive index decreases rapidly with height), actually traps the energy and causes it to travel along the earth surface as happens in a waveguide. This happens near the ground often within the 50 metres of the troposphere as illustrated in Fig. 11.37. The higher frequencies or microwaves are thus continuously refracted in the duct and reflected by the ground so that they propagate around the curvature for beyond the line of sight, even upto a distance of 1000 km. This special refraction of electromagnetic waves is called super-refraction and the process is called duct propagation.* The main requirement for the formation of the duct is a *temperature inversion, i.e.* in the inversion layer the temperature increases with height rather usual decrease of temperature at the rate of 6.5°C km in the *standard atmosphere.*

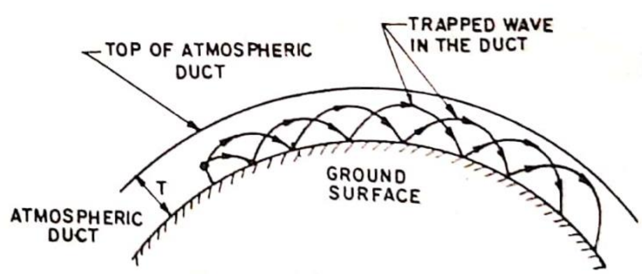


Fig. 11.37. Super-refraction in the atmospheric duct.

Where the refracting conditions are sufficiently different from the *standard* to cause trapping of the wave, *the concept of an effective earth radius does not hold good*. In order to give the necessary curvature the actual refractive index μ at a height h must be replaced by a *modified refractive index* given by

$$N = \mu + \frac{h}{r} \qquad | \text{ Appendix 11.1}$$

Although N is always close to unity, yet its actual value is important and hence when dealing with numerical values, it is convenient to introduce the excess *modified index of refractive modulus M*, related to N as

$$N - 1 = \left(\mu - 1 + \frac{h}{r}\right)$$

or

$$(N - 1) \times 10^6 = \left(\mu - 1 + \frac{h}{r}\right) \times 10^6$$

or

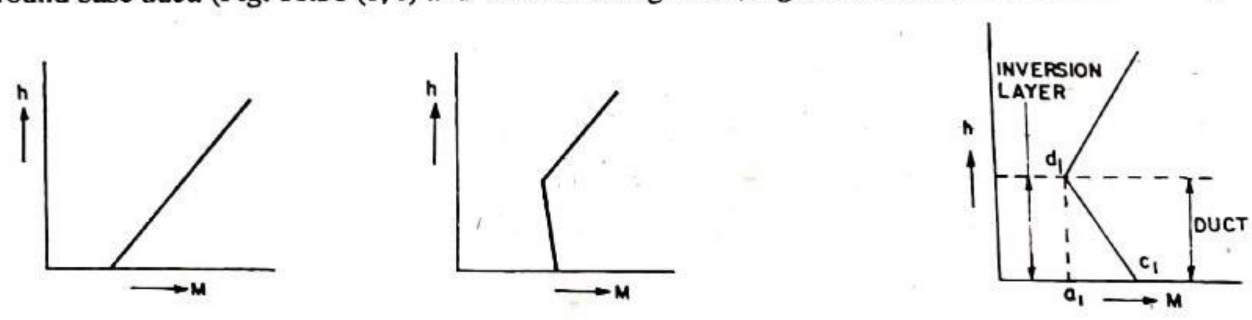
$$\boxed{M = (N - 1) \times 10^6 = \left(\mu - 1 + \frac{h}{r}\right) \times 10^6} \qquad \text{... (11.132)}$$

Where μ = Refractive index ; h = height above ground

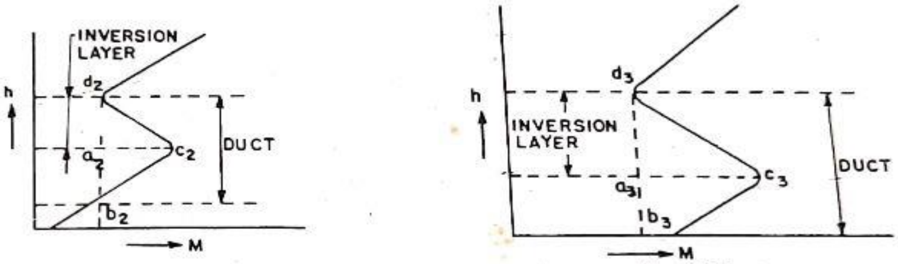
r = True radius of earth = 6370 km.

The value of gradient *i.e.* $\frac{dM}{dh}$ and its sign both depends on the tropospheric conditions. From the measurement, if M is plotted against height h, the following different curves are obtained.

As is clear from the Fig. 11.38, that duct (tube or channel) is formed only when the value of gradient $\frac{dM}{dh}$ is negative *i.e.* M decreases with increase in height h. The height for which this process of decreasing *M continues forms the inversion layer*. In Fig. 11.38, d_1c_1 , d_2c_2 and d_3c_3 are the inversion layers whose heights are respectively d_1a_1 , d_2a_2 and d_3a_3. The widths of the duct, however, are determined by the dropping the projections vertically downwards which cut at a_1 , b_2 and b_3. The horizontals drawn at these points a_1 , b_2 and b_3 give lower end of the duct and horizontals at d_1 , d_2 , d_3 give the top end of the duct. Thus, the duct widths are respectively $d_1 a_1$, $d_2 b_2$, $d_3 b_3$. If inversion layer is just above ground, it gives ground base duct. (Fig. 11.38 (c, e) and if it is above ground, it gives rise to elevated duct as in Fig. 11.38 (d).



(a) Standard atmosphere. *(b) Refraction at lower heights equal earth's curvature.* *(c) Ground based duct or surface duct.*



(d) Elevated duct. (e) ground based duct.

Fig. 11.38. Variation of M with h and formation of duct and inversion layers.

When the $h - M$ curve has a negative slope, the ray enters the duct with sufficiently small angles are bent until they become horizontal. *These rays are trapped between the upper and lower walls of the duct and are oscillating between ground and upper wall of the duct in case of ground based duct and between two walls in the atmosphere in case of an elevated duct. This phenomenon is called super refraction or duct propagation.* It may be noted that only those waves are trapped which are entering with small angles w.r.t. horizontal but if this angle exceeds a critical angle

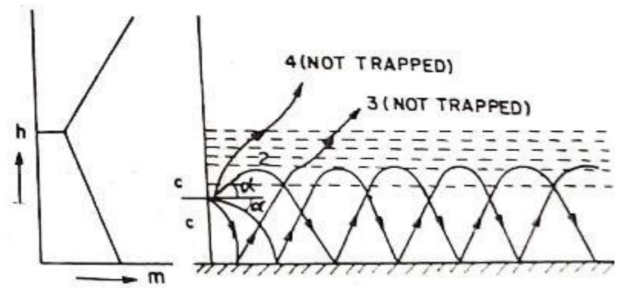


Fig. 11.39. Ground based duct propagation.

(α_c say) it is penerating the duct as in case of ray no.3 and while ray no.1 and 2 have been trapped as their angle of entrance was less than critical angle α_c

Tropospheric scatter propagation

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.

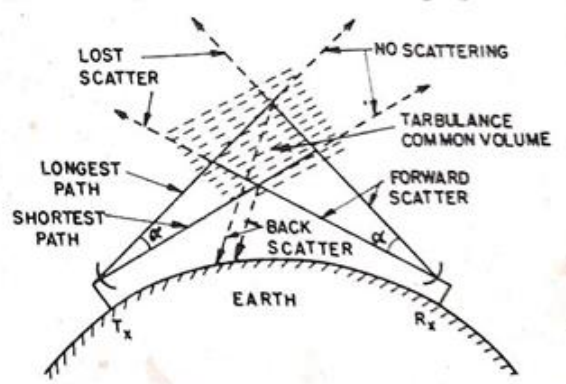


Fig. 11.11. Tropospheric scatter propagation.

A tropospheric Scatter communication link over the horizon is shown in Fig. 11.11. Here two antennas beams overlap in a common volume situated above the surface of one earth at a considerable height nearly 3 km to 8 km. The scattering of radio waves is, in many respect, analogous to the scattering of lights by dust parficles in a smoke-filled cinema. This is caused by the reflection or scattering of light or radio waves by a very large number of small particles in the scattering medium and the observation is the resultant addition of all such contributions in magnitude and phase as well.

The scattering comes from the small irregularities or the fluctuations in the refractive index of the atmosphere. However, these fluctuations are very weak but by use of sufficiently high power transmitter, a useful signal is scattered in the direction of receiving antenna due to scattering from a large volume Tropospheric—Scatter-propagation links operate in frequency range of 200 MHz to 10,000 MHz. Tropospheric—Scatter-propagation at lower frequencies are not desirable because of the cost effectiveness of the high gain antenna. Further, considerable amount of fading does occur with troposcatteric—Scatter-propagation link, as such some form of diversity reception is needed for high reliability of the link. Typically the distance covered in tropospheric scatter link is a few hundred kilometers, and at heights less than eight kilometers. At heights greater than ten kilometers the troposphere is too rarefied to produce sufficient scattering.

Although there are several theories for tropospheric scattering, but two theories are prominent as already mentioned *viz. ionospheric scatter propagation which arises because the turbulent atmosphere within the scattering volume produces blobs with different refractive indices of the surrounding atmosphere and these blobs scatter the incident energy in all directions. The other theory consider troposphere to be stratified into many homogenous layers with different heights and refractive indices and suggests that propagation through*

such a medium is affected by refraction and partial reflection in each layer. This is called tropospheric Scatter propagation. Whatever may be the case for tropospheric —Scatteric radio link, a simplified model assumes that resultant signal variation is the addition of two principal components of a slow or long term variation and a fast or short term variation.

simplified model of a tropospheric –scatter link

A simple model of a tropospheric –scatter link may be represented by an expression for the annual median value as

$$\overline{P(r)} = P(t) - L(t) \quad \ldots (11.197)$$

where $\overline{P(r)}$ = Received power levels, in dbW

$P(t)$ = Transmitted power levels, in dbW

and $L(t)$ = Transmission path loss.

The transmission loss is resultant sum of the various losses and gains along the radio link between transmitter and receiver. For example, if the transmitting and receiving antennas have gains $G(t)\, db$ and $G(r)\, db$ in the direction of the link and the combined feeder losses total $L(f)\, db$, then

$$\boxed{L(t) = \overline{L(p)} + L(f) - G(t) - G(r)} \quad \ldots (11.198)$$

where $L(p)$ = annual median path loss between the two antennas.

Further, in this expression, the gains are considered as negative losses. One of the several componens of the path loss is known as the spatial path loss $L(s)$ already given 11.10. The other loss is due to the scattering process which is known as scattering loss $L(sc)$. It is dependent on the magnitude of the scatter angle θ as shown in the Fig. 11.62. Further scattered signals reading at the large receiving antenna do not come from a point source but from an extended volume of infinite numbers of scatters. The phase in-coherence between the many components of the wavefront is responsible for an apparent loss in gain when large-aperture antennas are involved. This is called as antenna to midium coupling loss $L(s)$. The annual median path loss is therefore can be obtained by combining all these contributions and hence

$$\boxed{\overline{L(p)} = L(s) + \overline{L(\mathrm{sc})} + L(\mathrm{misc})} \quad \ldots (11.199)$$

where $L(\mathrm{misc})$ = is the miscellaneous losses in the radio link.

The above simple model of the tropospheric—Scatter—radio link is associated only for the long terms or slow variation in the received signal.

The output power level generated by the transmitter is normally 1 kW (30 dbW) or 10 kW (40 dbW) though smaller or larger power levels are also used. Since all the power does not reach the transmitting antenna and as such.

$$\boxed{P(t) = P(g) - L(ft)} \quad \ldots (11.200)$$

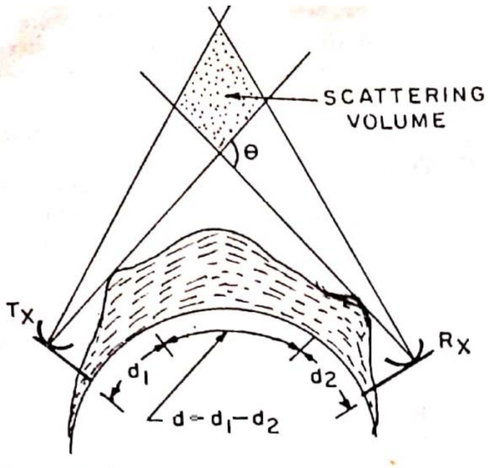


Fig. 11.62. A tropospheric-scatter-radio-link across mountainous terrain and scatter angle θ.

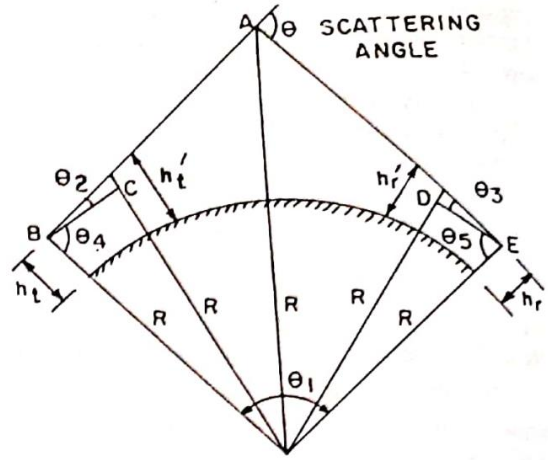


Fig. 11.63. Scattering angle θ and its trigonometry.

where $L(ft)$ = Portion of the feeder loss $L(f)$ associated with transmitting antenna (of the order of 1 or 2 db)

The antennas are normally paraboloidal reflector type with gains given by

$$\boxed{G(t) = G(r) = 20 \log_{10} f(MHz) + 20 \log D(m) - 42.3} \quad \ldots (11.201)$$

for paraboloids having illumination efficiency $\eta = 0.54$ and diameter D. In such links billboard antennas are also used.

The Scatter angle θ is calculated from the path profile shown in figures 11.63 By the definition of heights and distances it can be shown that scatter angle θ is

$$\boxed{\theta = \theta_1 + \theta_2 + \theta_3 + \theta_4 + \theta_5 - \pi} \quad \ldots (11.202)$$

where $\theta_2 = \frac{h_t' - h_t}{d_1}$, $\theta_3 = \frac{h_r' - h_r}{d_2}$

both in milliradain, heights in meters and distance in kilometers.

$$\theta_4 = \frac{\pi}{2} - \frac{d_1}{2R} \text{ rad. and } \theta_5 = \frac{\pi}{2} - \frac{d_2}{2R} \qquad \text{and } \theta_1 = \frac{d}{R} \text{ radians}$$

Combining all these, we get

$$\boxed{\theta = \frac{1000}{2ka}[2d - d_1 - d_2] + \frac{h_t' - h_t}{d_1} + \frac{h_r' - h_r}{d_2} \text{ milliradians}} \quad \ldots (11.203)$$

where k = Refractive factor = 4/3 for standard refraction.