UNIT-5
WAVE PROPAGATION

Definition: If a physical phenomenon that occurs at one place at a given time is reproduced at other places at later times, the time delay being proportional to the space separation from the first location, the group of phenomena constitutes a wave.

Depending on the nature and location of space, the characteristics of a propagating wave may get modified while propagating. The modifications may include reflection, refraction, diffraction, absorption and the rotation of plane of polarization.

The wave characteristics are modified during the propagation due to variation of media parameters (σ, ε and μ), the shape and characteristics of obstructing objects, and The paths in which the electromagnetic waves travels. These may also depend on the heights of transmitting and receiving antennas, the angle of launch of electromagnetic energy into the space, the frequency of operation, the polarization and other factors.

The electromagnetic waves can be broadly categorized into two types as 1. Guided waves, 2. Unguided waves

1. Guided waves: The waves guided by manmade structures such as parallel wire pairs, coaxial cables, waveguides, strip lines, optical fibers, etc.

Guided waves have lot of applications for signal and data communication, long telephone trunk lines , local area networks (LAN), closed circuit TV, interconnections used for providing Internet services, cable networks used by cable TV operators and networking of computers.

2. Unguided waves: Waves propagating in the terrestrial atmosphere, over and along the earth and in outer space is called unguided waves. The applications are telegraphy, telephony, radio broadcast, television, mobile communication, satellites, radars, tele control, radio location, radio navigation, remote sensing and distance measurements by radio means.

Unguided propagation is also used in geophysics, in the study of upper atmosphere, radio astronomy, study of activities of sun, stars and nebulae inside and outside our galaxy.

General Classification:

Plane wave: In phasor form, a plane wave is defined as one for which the equiphase surface is a plane.

Uniform plane wave: In a plane wave if the equiphase surface is also an equiamplitude surface, the wave is called a uniform plane wave. A uniform plane wave progressing in the z-direction will have no E_z component. In a uniform plane wave E and $H$are entirely transverse, and E and H are orthogonal to each other.

Non-uniform plane wave: In a non-uniform plane wave, the equiphase and equiamplitude surfaces are neither same nor they are parallel and the E and H are not necessarily be orthogonal.

Slow wave: When the phase velocity normal to the equiphase surfaces is less than the velocity of light 'c', the wave is referred to as a slow wave. The travelling tubes are used to slow down the speed of the wave.

Forward wave: A wave traveling in an assigned direction from the point of origin is called forward wave.

Backward wave: When a forward wave strikes a reflecting surface, the back ward wave or reflected wave exists. these waves exists

Traveling wave: When a wave is progressing only in one direction and there is no reflected wave present, it is called a traveling wave.

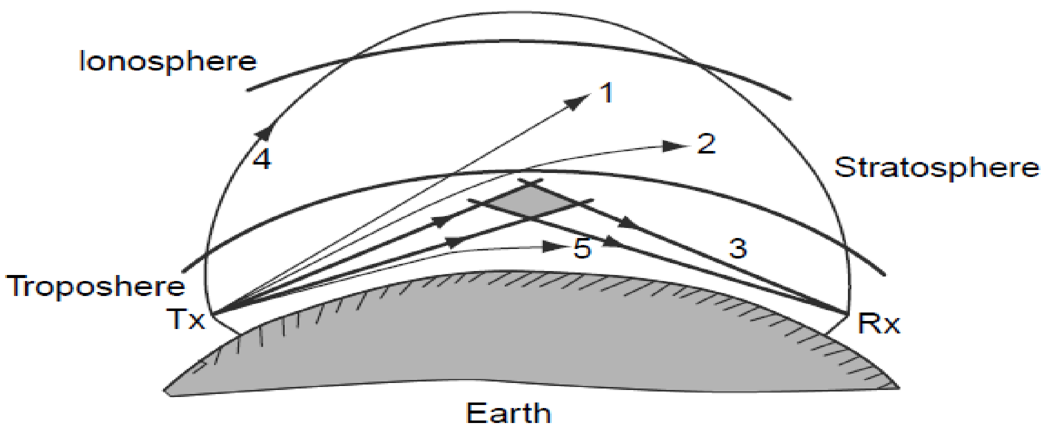
Standing wave: In a wave both forward and reflected waves are simultaneously present, they combine and result a wave called standing wave. Such a wave does not progress and maxima's or minima's (of *E* and *H)* for different time instants will appear at the same space location but with varying magnitudes.

Surface wave: The wave which is supported by some kind of surface between two media is called a surface wave. In strip lines, the wave travels as a surface wave.

Trapped wave: A surface wave is also called a trapped wave because it carries its energy within a small distance from the interface. This wave does not radiate except at discontinuities.

Leaky wave: When discontinuities are densely placed along the line, another type of traveling wave results and is a called a leaky wave.

Different Modes of Wave Propagation: The energy radiated from a transmitting antenna may travel through space with (or without) alteration in its characteristics. The path to be adopted by the electromagnetic waves to arrive at the receiver will not only depend on the characteristics of the space between the two antennas and the angle of launch of the energy into the space.



Different modes of wave propagation

The wave propagating over paths near the earth's surface is often referred as ground wave. The Ground (surface) waves are vertically polarized and exist if antennas are close to earth. All broadcast signals in daytime and the waves used in ground wave radars are the ground waves. The ground wave is sub divided surface wave and the space wave.

The surface waves are guided waves which are guided by the earth surface, the space waves are the direct waves between the transmitter and receiver. The wave reaching the receiver after getting refracted and reflected from the ionosphere, is called ionospheric or sky wave. These waves also referred as ionospherically reflected or ionosphericayll scattered wave. The ionospheric propagation occurs at above 80 Km from the earth surface.

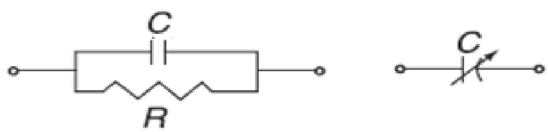
The wave reflected or scattered in the troposphere is termed as tropospheric wave. This mode of propagation is the result of irregularities of troposphere, which extends to nearly 10 to15 km from the earth surface.

Ray and Mode Concepts: Ray is defined as the perpendicular drawn to an equiphase plane and the mode is a group of rays which have same propagation characteristics. There are mainly two methods of analyzing the wave phenomena. These are referred as 'ray theory' and 'mode theory'.

Ray theory is applicable only if the distance between two reflecting layers is several wavelengths long, mode theory is normally employed for shorter distances from the reflecting surface. The ray theory is applicable for low frequency waves.

The mode theory is applicable when the transmitter receiver is separated by a large distance. To understand mode theory, the problem can be simplified by assuming the earth to be flat and the ionosphere to begin abruptly at a height h above the earth. The effective reflection coefficients for both parallel and perpendicular polarization at ground and at lower edge of ionosphere can be calculated.

Ground Wave Propagation: The waves, which glide over the earth's surface while traveling, are called ground waves. Ground waves are always vertically polarized and induce charges in the earth. The horizontal polarized waves will not propagate in this mode because they are completely absorbed by the earth surface. As the wave travels over the surface, it gets weakened due to absorption of some of its energy. This absorption is due to the effect that the earth behaves like a leaky capacitor.

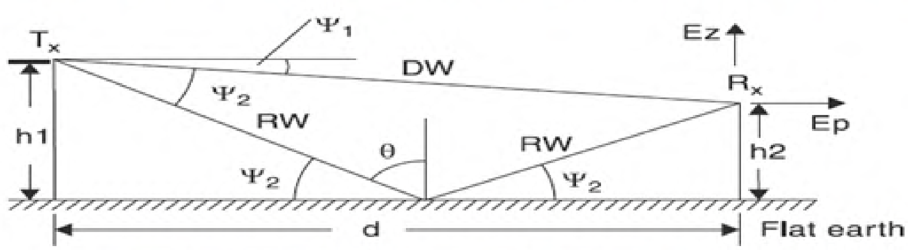


Earth Represented by a leaky capacitor

The ground wave propagation is effective over the frequency 535KHz -1605 KHz which are called medium frequencies, all waves that are propagates during day time are ground waves. The study of this wave propagation can be done by assuming earth as plane as well as spherical. The earth's surface is considered to be a plane, when the distance between the transmitter and the receiver is within the distance'd'. Beyond the distance'd' the earth is considered as spherical.

$$\boxed{d = \frac{50}{(f\ in\ MHz)^{1/3}}\ miles}$$

Plane Earth Reflection: The transmitting and receiving antennas are above the earth surface, and the two antennas are at the line of sight of each other. the received signal consists both direct and reflected waves as shown below.



Direct wave (DW) and reflected wave (RW)

When the earth is smooth and finitely conducting the magnitude and phase of the reflected wave is slightly differ from that of the incident wave. When the earth is rough, the reflected wave tends to be scattered and may be much reduced in amplitude compared with smooth earth reflection. The roughness is generally estimated by the Raleigh criterion given by the relation:

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$$R = 4\pi\sigma sin\theta/\lambda$$

Where

$\boldsymbol{\sigma}$ is the standard deviation of the surface irregularities relative to the mean surface height,

$\boldsymbol{\theta}$ is the angle of incidence measured from the normal angle, and

$\boldsymbol{\lambda}$ is the wavelength.

If R <0.1, the reflecting surface is considered as being smooth.

If R >10, the reflecting surface is considered to be rough.

` The surface may be considered rough for wave incident at large angles. It may be smooth as the angle of incidence approaches the grazing angle ($\theta \rightarrow 0$). The reflection coefficient approaches minus one for both polarizations when the incident angle approaches the grazing angle. The earth is not a good conductor like copper or silver, and also not a perfect dielectric. Therefore the reflection coefficient of the earth can be calculated by considering the earth with finite dielectric constant (ε) and conductivity (σ).

The expression for reflection coefficients (E_r/E_i) for horizontal polarization (R_H) is given as

$$\boxed{R_H = \frac{\sin\psi - \sqrt{(\varepsilon_r - jX) - cos^2\psi}}{\sin\psi + \sqrt{(\varepsilon_r - jX) - cos^2\psi}}}$$

The expression for reflection coefficients (E_r/E_i) for vertical polarization (R_V) is given as

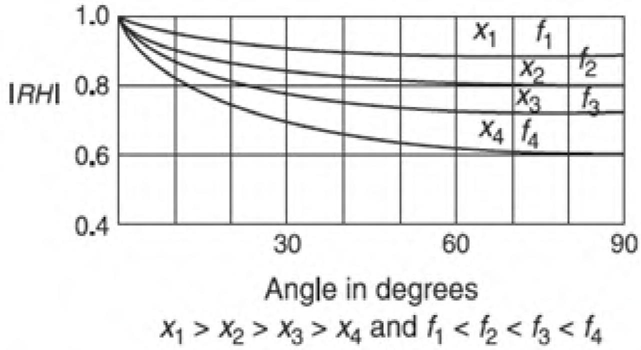
$$\boxed{R_V == \frac{(\varepsilon_r - jX)\sin\psi - \sqrt{(\varepsilon_r - jX) - cos^2\psi}}{(\varepsilon_r - jX)\sin\psi + \sqrt{(\varepsilon_r - jX) - cos^2\psi}}}$$

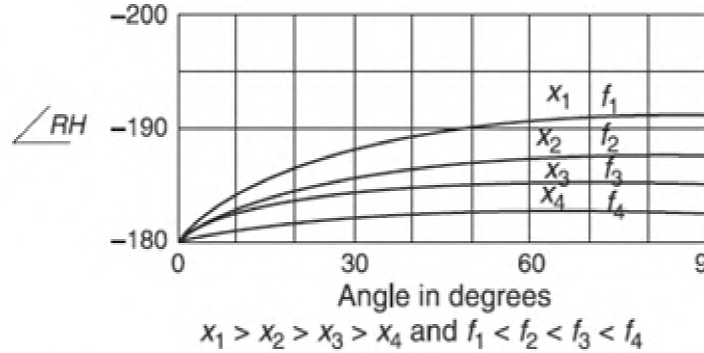
Where $\frac{\varepsilon}{\varepsilon_0} = \varepsilon_r$ and let $\frac{\sigma}{j\omega\varepsilon_0} = -jX$

NOTE: The $R_{H,}$ R_V are complex quantities then they can be written as.

$$R_H = R_H/\underline{R_H} \quad ; \; R_V = R_V/\underline{R_V}$$

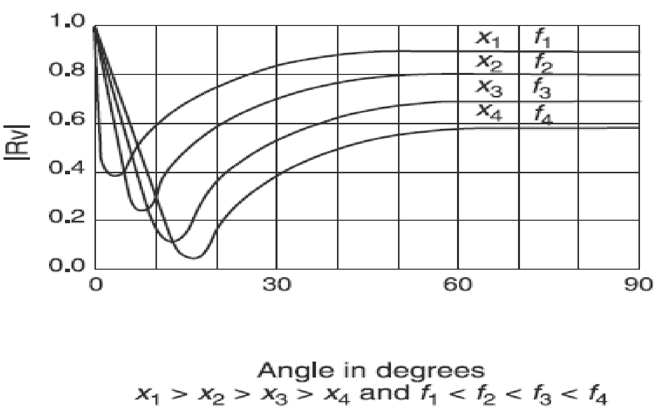
Where | R_H| and $|R_V|$ are the amplitudes and $/\underline{R_H}$ and $/\underline{R_V}$ are the phase angles of R_H and R_V respectively. The reflection coefficients are functions of $\boldsymbol{X}$ and angle $\boldsymbol{\psi}$ .The reflection coefficients are complex in nature, the reflected wave will differ from the incident wave, both in magnitude and phase. The variation of these factors with angles of incidence, with the values of $\boldsymbol{X}$ and frequencies f are as shown below.

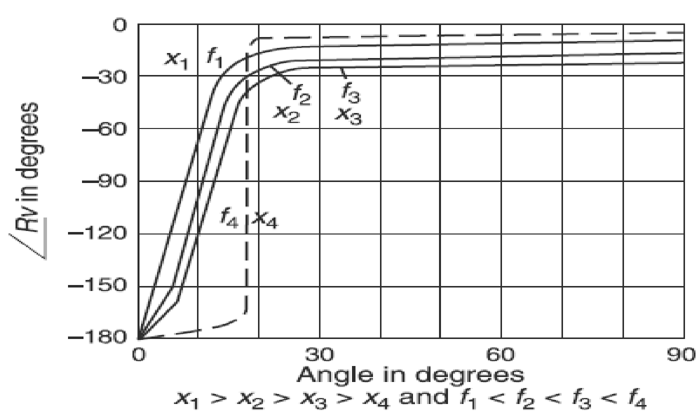




The above graph gives the relation between R_H and incident angle, $/\underline{R_H}$ and incident angle. From the graph we can observe the following.

- The phase of the reflected wave differs from that of the incident wave by nearly 180◦ for all angles of incidences.
- For angles of incidence near grazing (θ= 0), the reflected wave is equal in magnitude but 180◦ out of phase with the incident wave for all frequencies and for all ground conductivities.
- As the angle of incidence is increased, both the magnitude and phase of the reflection factor change, but not to a large extent. The change is greater for the higher frequencies and lower ground conductivities.



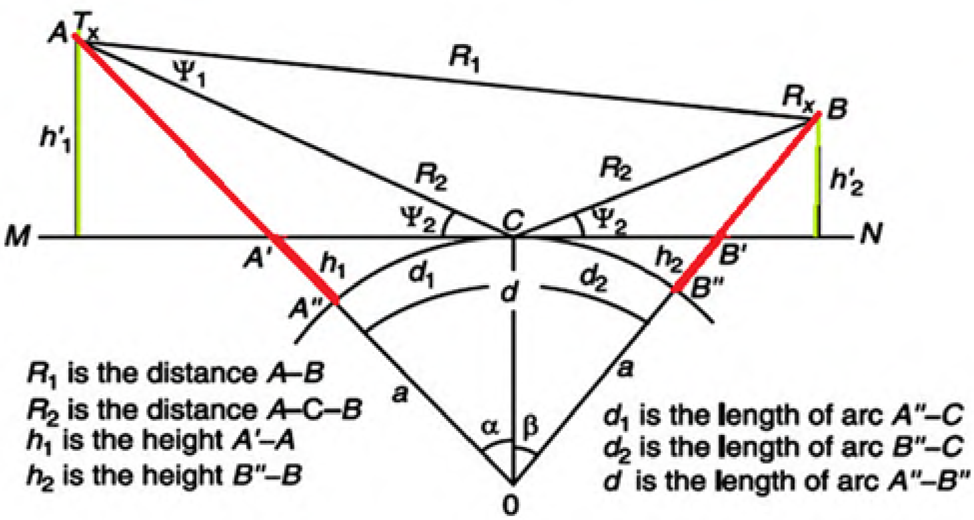


The above graph gives the relation between R_V and incident angle, $/\underline{R_V}$ and incident angle. From the graph we can observe the following.

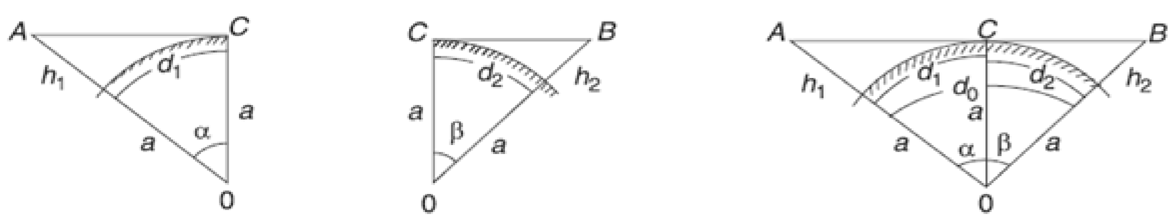
- At grazing incidence E, the reflected wave is equal to that of the incident wave and has an 180◦ phase reversal for all finite conductivities.
- As the angle increases from zero, the magnitude and phase of the reflected wave decrease rapidly. The magnitude reaches a minimum and the phase change goes through −90◦ at an angle known as pseudo-Brewster angle (or just Brewster angle) by the analogy of a perfect dielectric case. At angles of incidence above this critical angle, the magnitude increases again and the phase approaches zero.
- For very high frequencies and low conductivities, the Brewster angle has very nearly the same value as it has for a perfect dielectric. For εr= 15, the Brewster angle occurs at 14.5◦ for the perfect dielectric case.
- For lower frequencies and higher conductivities, the Brewster angle is less, approaching zero as x becomes much larger than εr.

- When the incident wave is normal to the reflecting surface (ψ = 90∘), it is evident that there is no difference between horizontal and vertical polarization. The reflection coefficients R_V and R_H should have the same value, as E will be parallel to the reflecting surface in both cases. Comparison of these figures illustrate that RV and RH have the same magnitude but differ by 180∘in phase. This is due to the different positive directions assigned for the reflected waves in two cases.
- For angles of incidence near grazing, a more accurate plot of reflection coefficient is often required. Such curves plotted on logarithmic scales are available.

Curved Earth Reflection: When the distance between the transmitter and receiver is more than $\left(d = \frac{50}{(f\ in\ MHz)^{1/3}}\right)$miles.Then the earth is considered as curved surface. When the wave hits the curved surface the reflected wave may be diverge and will become weaker while reaching the receiver. In this case effective antenna heights $\boldsymbol{h'_1}$ and $\boldsymbol{h'_2}$ are less than the actual antenna heights $\boldsymbol{h_1}$and $\boldsymbol{h_2}$, and thus all equations obtained for flat earth are to be modified.



Line of sight distance: Let the antenna heights are h_1, h_2 and the earth radius is $\boldsymbol{a}$



From the OAC triangle:

$$\cos\alpha = \frac{a}{a+h_1} = \left[\frac{a+h_1}{a}\right]^{-1} = \left[1+\frac{h_1}{a}\right]^{-1}$$

$$\cos\alpha = 1-\frac{h_1}{a}+\left[\frac{h_1}{a}\right]^2-\left[\frac{h_1}{a}\right]^3+\left[\frac{h_1}{a}\right]^4 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

Expand above equation and neglect higher order terms

$$\cos\alpha = 1-\frac{h_1}{a} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

For small value of α,

$$Cos\,\alpha = 1 - \frac{\alpha^2}{2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

From (1) and (2), we can write,

$$1 - \frac{\alpha^2}{2} = 1 - \frac{h_1}{a}$$

$$\alpha^2 = \frac{2h_1}{a}$$

$$\alpha = \sqrt{\frac{2h_1}{a}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots .. (3)$$

From diagram we can write $d_1 = \alpha a$

$$\alpha = \frac{d_1}{a} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

From (3) and (4)

$$\alpha = \sqrt{\frac{2h_1}{a}} = \alpha = \frac{d_1}{a}$$

$$\sqrt{\frac{2h_1}{a}} = \frac{d_1}{a}$$

$d_1 = \sqrt{2ah_1}$ Similarly $d_2 = \sqrt{2ah_2}$

The total distance can be written as,

$$d_0 = d_1 + d_2 = \sqrt{2ah_1} + \sqrt{2ah_2}$$

$$d_0 = \sqrt{2a}\left[\sqrt{h_1} + \sqrt{h_2}\right]$$

$$d_0 = \sqrt{2X6.37X10^6}\left[\sqrt{h_1} + \sqrt{h_2}\right] = 3.57\left[\sqrt{h_1} + \sqrt{h_2}\right]10^3$$

$$\boxed{\boldsymbol{d_0 = 3.57\left[\sqrt{h_1}(m) + \sqrt{h_2}(m)\right] Km}}$$

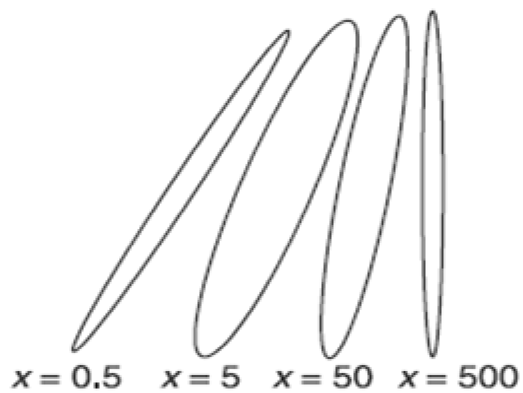
The distance d_0 can be termed as line-of-sight (LOS) distance. Let the antennas are *A* and *B* and the distance$d < d_0$. As in case of flat earth, the total field at *Rx* should be the sum of *DR* (*AB*) and *RR* (*ACB*).

The curvature of the earth has the following effect on the wave propagation within the LOS range:

1. For fixed antenna heights, the path length difference between *DR* and *RR* will be different from that of flat earth case.
2. The reflection at the convex surface will result in divergence of the *RR* path and hence will reduce the power received via *RR*.

Tilt of Wave Front due to Ground Losses: The electromagnetic waves originating from a vertical antenna can be considered to be entirely perpendicular to the earth. During the passage of travel the wave front weakened due to the energy absorption by the earth due to the earth resistance. The wave front starts tilting in the forward direction as it progresses. The magnitude of tilt will depend upon the conductivity and permittivity of the earth.

In general, the components of E parallel and perpendicular to earth will neither be in phase nor will have equal magnitude and thus E above the earth will be elliptically polarized.



$$x = \frac{\sigma}{j\omega\varepsilon_0}$$

The surface wave impedance Z_S of earth is given by

$$Z_S = \sqrt{\frac{\omega\mu}{\sqrt{\sigma^2 + \omega\varepsilon}}}\ \angle\ \frac{1}{2}\tan^{-1}\left(\frac{r}{\omega\varepsilon}\right)$$

The horizontal and vertical components of E are

$$E_H = J_s Z_s$$

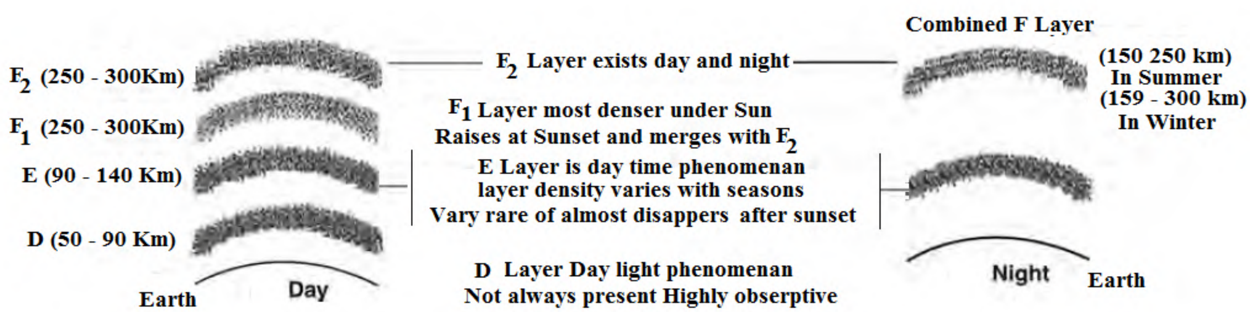
$$E_v = \eta H$$

The we can write

$$\frac{E_H}{E_v} = \frac{Z_s}{\eta}$$

Sky wave propagation: The propagation of sky waves or ionospheric waves is based on the refraction mechanism in the ionosphere. The electromagnetic waves are launched towards the ionosphere, and they return to the earth due to the refraction mechanism. Their satisfactory return depends on a number of factors including frequency of operation, angle of takeoff and ionospheric conditions.

Structural Details of the Ionosphere: The ionosphere is a region above the earth and these regions are composed into four layers, namely D, E, F1 and F2, these layers are composed based on the concentration of maximum ionized electrons. All the layers of the ionosphere will not exist in all the times some layers appears day time and disappears at night. Some of the layers will change with the seasons.



D layer: The D layer exists from 50 to 90 km above the earth's surface. It is a daytime phenomenon and is largely absent in the night. Ionization in the D layer is low because less ultraviolet light penetrates to this level. At VLF, the space between the D layer and the ground acts as a huge waveguide, the communication with this layer is possible only with large antennas and high power transmitters.

At LF and MF ranges, this layer is highly absorptive and limits daytime communication to about 300 km. It is responsible for much of the daytime attenuation of HF waves. This layer starts losing its absorptive nature in the MHz range and at 30 MHz, waves cross the D layer without any attenuation. Its structural details are not yet known with certainty.

E layer: The E layer exists from 90 to 140 km above the earth's surface, with maximum density at about 110 km. It is almost constant with little seasonal variations. It depends on the amount of ultraviolet light from the sun and uniformly decays with time at night. At night, the D layer slightly rises and the E layer slightly lowers to form one layer, which is again called the E layer. This layer permits medium distance communication in LF and HF bands.

F1 layer: The F1 layer exists from 150 to 250 km above the earth's surface in summer and 150 to 300 km in winter. This layer is also almost constant with little diurnal or seasonal variations.

F2 layer: The F2 layer exists from 250 to 400 km. At night, the F1 layer slightly rises and the F2 layer slightly lowers to form one layer, which is again called the F2 or F layer. The F2 layer is responsible for most of the HF long-distance communication.

Dielectric constant and conductivity of ionosphere: The ionospheric or sky wave propagation is based on the refraction of EM waves. The refraction phenomenon of sky wave is depends on the dielectric constant and conductivity of the ionosphere.

$$\varepsilon = \varepsilon_0 \varepsilon_r$$

$$\varepsilon_r = \left[1 - \frac{Ne^2}{\varepsilon_0 m\omega}\right]$$

$$\sigma = \left[1 - \frac{Ne^2 \omega_0}{m(\omega_0^2 + \omega^2)}\right]$$

Where

σ = Conductivity.

ε_r = Relative permittivity.

N = Charge density.

m = Mass of the electron.(9×10^{-31})

e = 1.6×10^{-19}

$\omega = 2\pi f$

$\varepsilon_0 = 8.85 \times 10^{-12}$

Refraction and Reflection of Sky Waves by Ionosphere: When the wave incident on the lower edge of the ionosphere the wave penetrates the ionosphere and follows a curved path and moves away from the region of greater electron density. The curved path that is followed by the wave in the region can be obtained by Snell's law.

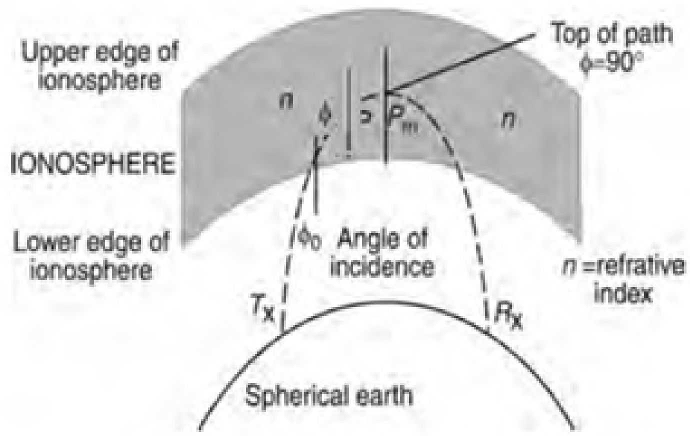
$$n = \frac{\sin \varphi_0}{\sin \varphi}$$

Where

n = Refractive index.

φ_0 = Incident angle.

φ = Refracted angle.



The refractive index of the ionosphere media can be defined as below,

$$n = \frac{\textit{Velocity of light in free space}}{\textit{Velocity of light in media}} = \frac{C}{V_p}$$

We know the velocity of propagation as,

$$\varepsilon_r = \left[1 - \frac{Ne^2}{\varepsilon_0 m\omega}\right]$$

Therefore

$$V_P = \frac{C}{\sqrt{\left[1 - \frac{Ne^2}{\varepsilon_0 m\omega}\right]}} \approx \frac{C}{\sqrt{\left[1 - \frac{81N}{f^2}\right]}}$$

We know that

$$V_P V_g = C^2$$

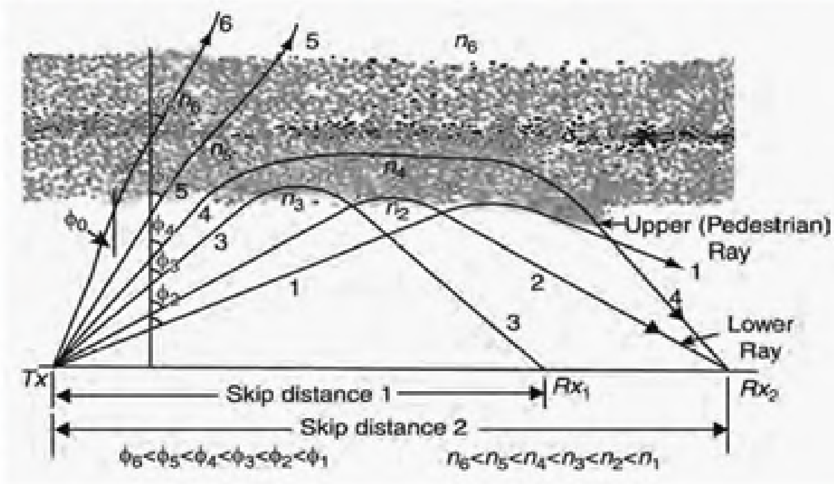
$$V_g = \frac{C^2}{V_p} = \frac{C^2}{\frac{C}{\sqrt{\varepsilon_r}}} = C\sqrt{\varepsilon_r} = C\sqrt{\left[1 - \frac{81N}{f^2}\right]}$$

$$\boxed{V_g = C\sqrt{\left[1 - \frac{81N}{f^2}\right]}}$$

The refractive index can be written as, $n = \frac{C}{V_P} = \frac{C}{\frac{C}{\sqrt{\varepsilon_r}}} = \sqrt{\varepsilon_r} = \sqrt{\left[1 - \frac{81N}{f^2}\right]}$

$$\boxed{\boldsymbol{n = \sqrt{\left[1 - \frac{81N}{f^2}\right]}}}$$

Ray Path, Critical Frequency, MUF, LUF, OF, Virtual Height and Skip Distance: Ray Path: The path followed by a wave is termed ray path. Six different paths followed by a wave under different conditions are as shown below. When $f > f_c$, the effect of the ionosphere depends on the angle of incidence φ_0.



1. When φ_0 is relatively large, the wave satisfies the relation $n = sin\ \varphi_0$. When drops to less than 1, the wave returns after slight penetration.
2. When φ_0 decreases, and penetration of the wave increases
3. When φ_0 further decreases, cannot be satisfied even with the maximum electron density of the layer, the wave penetrates and crosses the layer.

Critical Frequency: The highest frequency that returns from an ionosphere layer at a vertical incidence is called the critical frequency for that particular layer. At critical frequency the angle of incidence is zero, when the angle of incidence is zero the refractive index is also zero.

$$\boxed{f_c = \sqrt{81N_{max}}}$$

Maximum Usable Frequency: The maximum possible value of frequency for which refraction takes place for a given distance of propagation is termed as maximum usable frequency *(MUF),* beyond MUF the wave will not return.

If φ_0 is the incident angle and φ_r is the reflection angle, the refractive index n can be written as

$$\boxed{f_{MUF} = f_c \sec \varphi_i}$$

Lowest Usable Frequency: The frequency below which the entire power gets absorbed is referred to as lowest usable frequency (LUF).

Optimum Frequency: The frequency at which there is optimum return of wave energy is called the optimum frequency (OF).

Virtual Height: It is defined as the height to which a short pulse of energy sent vertically upward and traveling with the speed of light would reach taking the same two-way travel time as does the actual pulse reflected from the ionospheric layer.'

Skip Distance: The minimum distance at which the wave returns to the ground at a critical angle φ_c is termed the skip distance. Two different skip distances which correspond to rays 2, 3 and 4 are as shown below. As mentioned earlier, the skip distance and the maximum usable frequency correspond to each other.

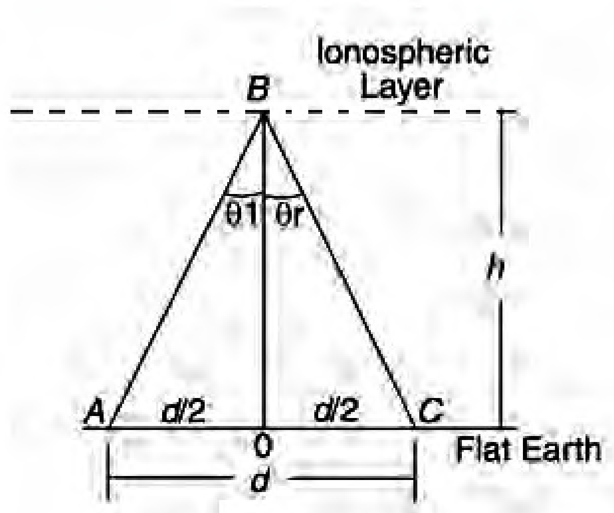
Relation between the MUF and skip distance:

Flat earth case: The distance between the Tx and Rx is short then the earth is considered as flat. Let the height of the ionospheric layer is'**h**', skip distance'**d**', angle of incidence φ_i , and angle of incidence φ_r.

From diagram:

$$\cos\varphi_i = \frac{OB}{AB} = \frac{h}{\sqrt{h^2 + d^2/4}}$$

$$\cos\varphi_i = \frac{2h}{\sqrt{4h^2 + d^2}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$



We know $\quad f_{MUF} = f_c \sec\varphi_i$

$$\frac{f_{MUF}}{f_c} = \sec\varphi_i$$

Substitute in above equation in (1)

From (1) and (2)

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

$$\frac{f^2{}_{MUF}}{f^2{}_c} = \frac{4h^2}{4h^2 + d^2}$$

$$4h^2 + d^2 = \frac{4h^2 f^2{}_c}{f^2{}_{MUF}}$$

$$d^2 = \frac{4h^2 f^2{}_c}{f^2{}_{MUF}} - 4h^2$$

$$\boxed{d = 2h\sqrt{\frac{f^2{}_c}{f^2{}_{MUF}} - 1}}$$

$$d^2 = \frac{4h^2 {f^2}_c}{{f^2}_{MUF}} - 4h^2$$

$$\boxed{d = 2h\sqrt{\frac{{f^2}_c}{{f^2}_{MUF}} - 1}}$$

Curved earth case:

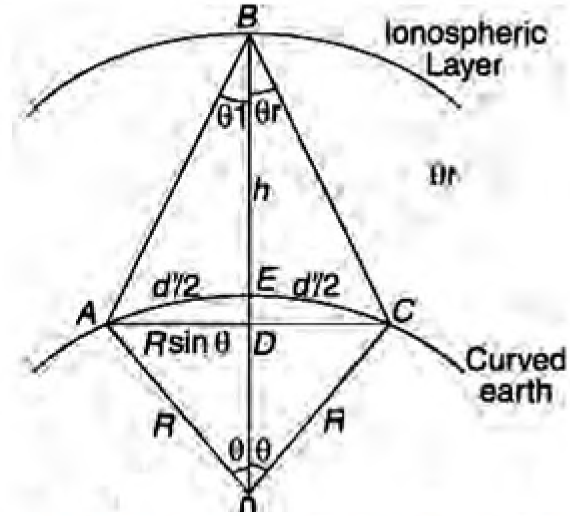
$$\boldsymbol{d' = \frac{2R}{X} \pm 2\sqrt{\left(\frac{R}{X}\right)^2 - 2hR}}$$

Where

$$X = \sqrt{\frac{{f^2}_c}{{f^2}_{MUF}} - 1}$$

$d' = Skip\ distance$

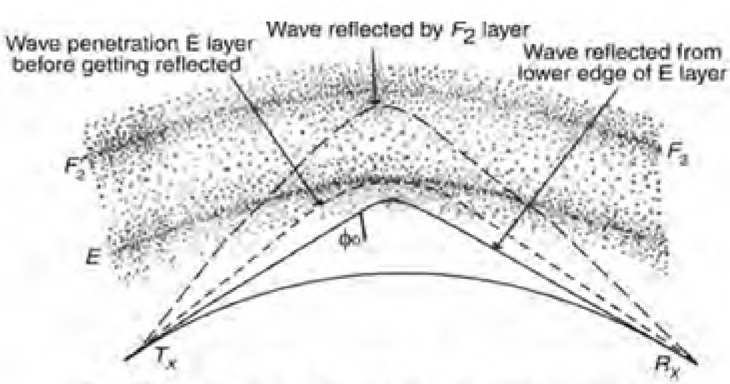
$R = Radious\ of\ the\ earth$



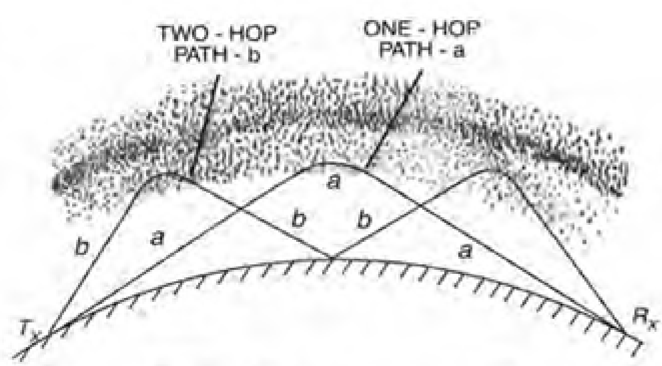
Multi-Hop Propagation: The wave originating from *Tx* arrives without touching the ground anywhere in between. This distance is termed as one hop distance. When the distance between the transmitter and receiver is greater than the skip distance multi hop system is an alternative for establishing the communication.

If the frequency of the wave is between critical frequencies of *E* and *F*1 layers and the receiver is beyond the skip distance for *E* layer, two or even three separate layers may contribute the propagation. Based on the distance between the transmitter and receiver these propagation modes are,

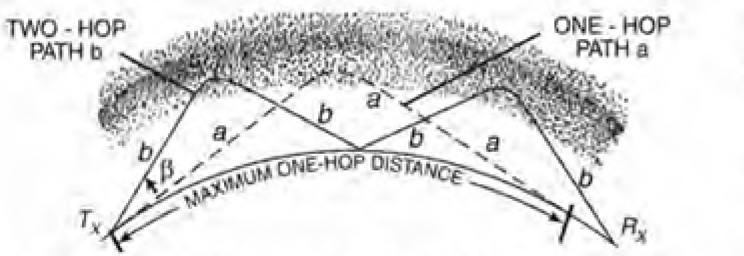
i) Single hop single layer,
ii) Single hop multi layer,
iii) Multi hop single layer,
(iv) Multi hop multi layer systems.



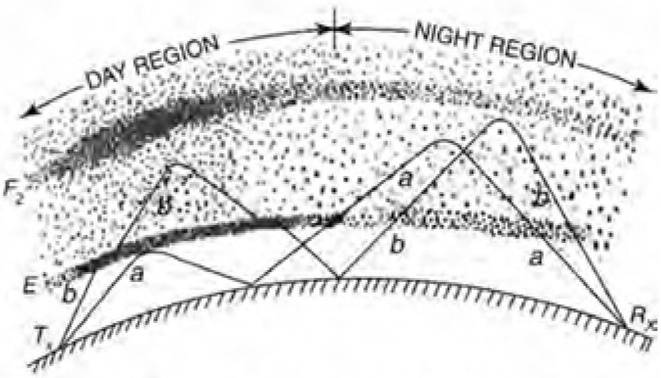
(a) One-hop multilayer propagation



(b) Skip distance less than half of the distance to the receiver



(c) Distance to the R_x is greater than maximum possible one-hop distance for LR



(d) Multilayer propagation

Energy loss in ionosphere and sky wave signal strength: Even though gas pressure in the ionosphere is very low, the vibrating electrons collide with gas molecules and acquired kinetic energy from the wave energy. The amount of this loss depends on the gas pressure, velocity of vibration, likelihood of collision and frequency of collisions. Most of the absorption loss takes place at a lower edge of the ionized region, where the atmospheric pressure is greater (i.e., in the *D* layer and lower part of *E* layer).

The absorption is less at higher frequencies and maximum at gyro and lower frequencies. At high frequency, the energy loss due to collision occurs mainly just below the *E* layer (in the *D* layer) where product of collisional frequency and electron density is maximum. This type of loss is called nondeviative absorption loss.

The attenuation constant for non-deviative absorption in *E* layer in dB/unit length of path is given by

$$\alpha = k\left(\frac{f_E}{f^2}\right)$$

Where $f_E = f_c$ for the *E* layer,
f = The wave frequency
k = constant

Wave Characteristics: Some of the characteristics exhibited by the waves in different modes of propagation and different frequency ranges are summarized below.

VLF Wave Propagation:

- Range of VLF spreads over 3 kHz – 30 kHz.
- Low carrier frequency limits the bandwidth and hence the information contents and thus cannot be used for conventional communication.
- These waves can penetrate deeper into sea as well as the earth, and therefore can be used for submarine and mine communication.
- Waves can travel thousands of kilometers along the earth's surface and have a very steady phase. Therefore, a VLF wave can be used for navigation and for time and frequency standards.
- These waves find extensive applications in magnetospheric probing. These waves travel from one hemisphere to the other in the earths' magnetic field lines in whistler mode. A study of these whistlers reveals information on magnetospheric electron and ion densities.

- In general, VLF has attenuation of about 3 dB/1000 km for propagation over seawater and about 6 dB/1000 km over land. Frequencies around 20 kHz show the least attenuation.
- An antenna has to be comparable to wavelength for meaningful radiation. Thus, VLF antennas have to be very large in length (i.e., several kilometers long). Horizontal antennas can be made quite long but their efficiency is less than 1%. Vertical antennas have efficiencies greater than 70% but need expensive ground plane and top hat structures.
- In VLF range, lightning discharges are the main source of noise. The level of noise at this range is considerably higher than that at higher frequencies.
- VLF waves are almost completely reflected both by the lower ionosphere and the earth. Thus they are guided in the region between ground and ionosphere much like waves in the waveguides. The height of the waveguide may be around 70–80 kilometers.

20 kHz – 100 kHz

- This range encompasses part of the VLF band and a part of LF band.
- In this range, ground waves have relatively low attenuation.
- Received ground wave signals show little diurnal, seasonal and yearly variation.
- Ground-wave mode is mostly used up to 1000 km.
- Sky waves are reflected back to the earth only after little absorption and slight penetration in the ionosphere.
- Received signal shows diurnal and seasonal variations.
- Signals are stronger at night than in day.
- Signals are stronger in winter than in summer.
- Although signals even after traveling great distances behave in a fairly regular manner, neither daily nor yearly cycles repeat exactly vis-à-vis signal strength.
- For distances greater than 1000 km, mostly the sky wave mode is used.
- Average yearly intensity correlates fairly well with 11-year sunspot cycle.

100 kHz – 535 kHz

- This range encompasses part of the LF band and a part of MF band.
- Ground waves attenuate more rapidly as the frequencies are raised above 100 kHz.
- Range of ground waves reduces as the frequency increases.
- Sky waves become the obvious choice for moderate distances.
- Ionospheric losses tend to be high in daytime but remain low at night.
- Due to relatively high ionospheric absorption in day time, long-distance communication in day time is dependable.
- Night-time communications for long distances by sky wave are reliable.

535 kHz – 1600 kHz

- This range is a segment of MF band.
- This range encompasses frequencies primarily used for broadcast purposes.
- Daytime broadcast depends entirely on ground wave propagation.
- Daytime signal strength decreases more rapidly with distance for ground waves.
- Lower the earth's conductivity, the higher is the frequency of the signal.
- Sky waves in this range are completely absorbed in day.

1600 kHz – 30 MHz

- This range encompasses part of the MF band along with the entire HF band.
- Ground waves attenuate very rapidly. Thus, this mode of propagation is of no use except for very short distances.
- Almost all long-distance communications use ionospheric reflections.
- The range of frequencies to be used depends on the given set of conditions.
- The lower-frequency limit depends on the ionospheric absorption over the path, the radiated power and the noise level at the receiver.
- The maximum usable frequency (MUF) depends on the distance, height and electron density at the location of reflection in the ionosphere.
- The frequency which gives the best signal is the optimum frequency (OF), normally taken 15% below the maximum usable frequency. It allows short-term fluctuations in MUF.
- OF tends to be high (10 to 20 MHz) in the day for long paths and is low (5 to 10 MHz) at night for short paths and is normally greater in summer than winter.
- Optimum frequencies are susceptible to sunspot activity and tend to be higher for paths with lower altitude. For similar conditions, signals over north–south paths are stronger than over east–west paths. This is mainly because of large variation in the quantum of sunlight and hence the ionization on east – west paths.
- For long-distance communication (beyond 1000 km), OF is determined mainly by the F2 layer. OF may also be determined by E or F1 layers under certain circumstances at noon.
- For medium distances (200 to1000 km) at lower heights, the *E* layer causes $\varphi 0$ to be glancing than for F2 layer; *E* layer alone determines MUF.
- Sporadic *E* may cause increase in OF (maximum 80 to 100 MHz is reported and 20 to 40 MHz is common)
- Sporadic *E* is more prevalent in summer and may control ranges up to 2000 km at 15 MHz.
- OF increases with path distance for one hop transmission. On an average, it is 4000 km for F2layer and 2000 km for *E* layer.
- For short distances, OF = fc and for long distance MUF = $3fc$ for F2 layer.
- For $\beta < 3.5°$, energy leaving the transmitter tends to be absorbed by the earth near the transmitter.

Frequencies above 30 MHz, i.e., all bands above HF

- Rarely reflected back to earth by ionosphere except occasionally from sporadic *E* in the 30 to 60 MHz range.
- Usefulness above 30 MHz depends mainly upon space-wave propagation.
- Communication even with reasonable transmitted power is normally not appreciably possible beyond line-of-sight distance.
- Heights of transmitting and receiving antennas determine the distance.

VHF (metric) Waves

- All modes of propagation possible, i.e., as ground and tropospheric waves along the earth surface and also between 4 m to 10 m wavelength as ionospheric wave.
- Capable of passing through ionosphere as direct wave.

UHF (decimetric) and SHF (centimetric) Waves

- Can propagate as ground wave over short (LOS) distance.
- Communication for long distances through tropospheric waves (mainly due to scattering from Irregularities and lees due to ducting).
- Diffraction in this range is negligible.
- Practically, no molecular absorption or absorption in precipitation particles.
- Absorption due to rain, hail, snow at 3–5 cm and due to water vapours at 1.35 cm are significant.

EHF (millimetric) Waves

- No effect of ionosphere, troposphere causes bending due to atmospheric refraction.
- Rain, fog, hail, snow and other forms of precipitation particles responsible for marked absorption.
- Heavy rain and dense fog will completely stop propagation.
- Strong molecular absorption by tropospheric gases, especially water vapor and oxygen.

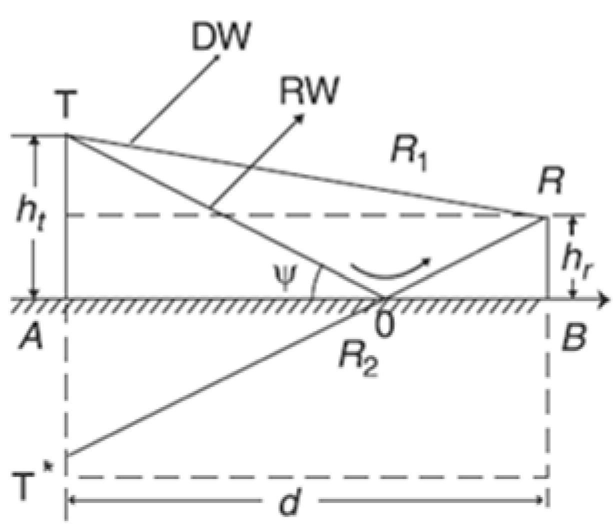
Sub-millimetric and Optical Waves

- Can propagate only as ground and direct wave.
- Atmospheric refraction causes bending of path.
- Heavy rain and dense fog will completely stop propagation.
- Well suited for space com

The space-wave propagation: In ground wave propagation the rate of attenuation increases with the frequency. The signal strength at 30 MHz will reduce to almost zero for short distance travel. Except the sporadic E layer, the ionosphere also not reflects energy towards earth at these frequencies. In such a situation, the space wave propagation is the only useful means for any effective and meaningful communication.

The space-wave travel from transmitter to receiver as direct wave (*DW*) and reflected wave (*RW*). The net field strength at the receiving antenna will be the vector sum of DW and RW fields. Up to a certain range of frequencies, the wave traveling through the space shall have negligible attenuation other than that caused by spreading phenomena. Also, DR and RR are almost 180◦ out of phase for both vertically and horizontally polarized waves. Beyond these frequencies, waves will be subjected to attenuation by rain, fog, snow, and clouds and due to absorption by gases present in the atmosphere. The field strength of a wave, in general, follows the inverse relation with the distance.

The transmitting antenna T located at A, with height h_t, receiving antennas R located at B with height h_r , R_1 the distance traveled by DW, R_2 the distance traveled by RW both between T and R and the angle-ψ. The R_2 shown is the distance between T and R via 0. Alternatively, it is the distance traveled by RR from T^* to R where T^* is the image of the transmitting antenna. The resultant field E can be written as,



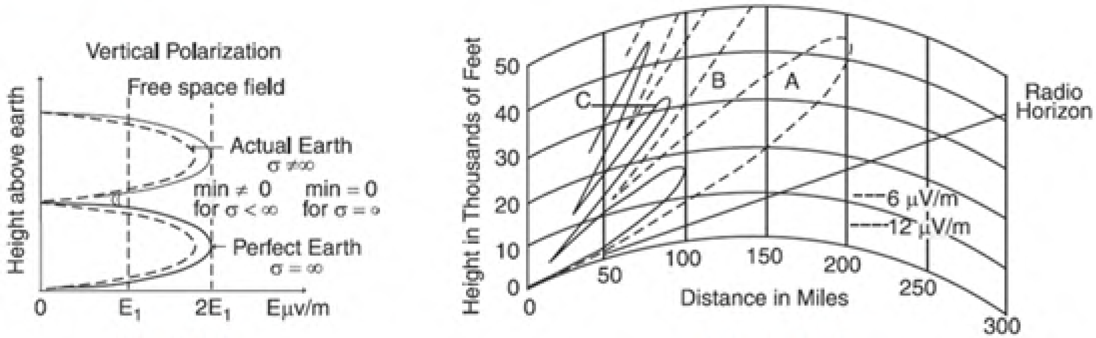
$$R_1^2 = d^2\left[1 + \frac{(h_t - h_r)^2}{d^2}\right]; \ R_1 = d\left[1 + \frac{(h_t - h_r)^2}{d^2}\right]^{1/2}$$

$$R_2^2 = d^2\left[1 + \frac{(h_t + h_r)^2}{d^2}\right]; \ R_2 = d\left[1 + \frac{(h_t + h_r)^2}{d^2}\right]^{1/2}$$

$$\boxed{R_2 - R_1 = \frac{2h_t h_r}{d}}$$

$$\boxed{E = E_0 \frac{4\pi h_t h_r}{\lambda d^2}}$$

Variation of Field Strength with Height: The impact of height on the distribution of field is shown below. The locations of minima's and maxim's depend on h_t, h_r, frequency and the distance between the transmitter and receiver. The field strength contours are produced by a transmitter located on ground radiating a vertically polarized wave.



Flat Earth **Curved earth**

Variation of field strength with height

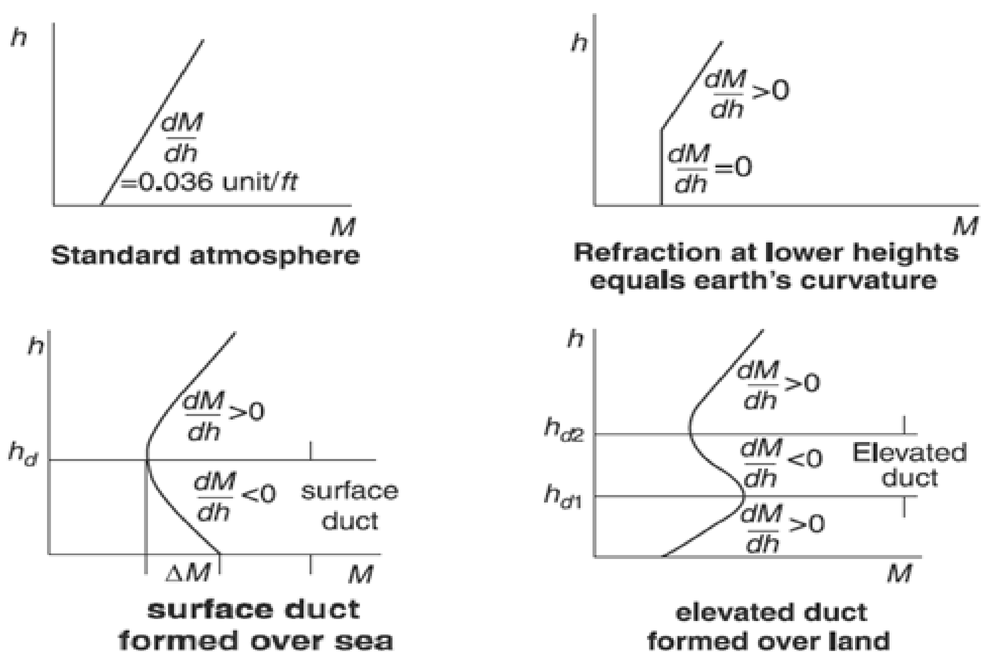
Super Refraction: The refractive index for free space is given by the relation,

$$n = 1 + \frac{80}{T} 10^{-6} \left(P + \frac{4600w}{T} \right)$$

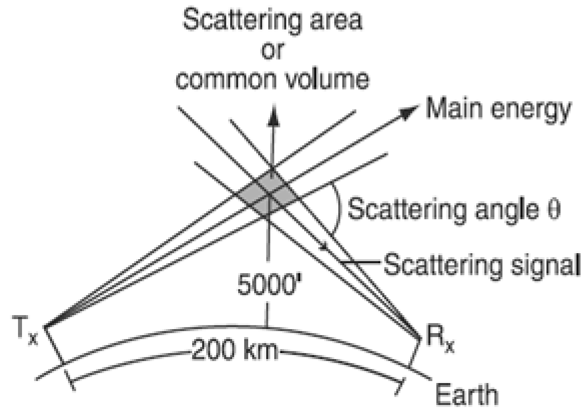
Where, T is the absolute temperature of air, P is the air pressure in millibars and w is the partial pressure of water (humidity) in millibars.

In connection with n, the following points need to be noted:

Different type of refractive index profiles observed are as shown below.



Scattering phenomenon: Reception far beyond the optical horizon in VHF and UHF range is possible due to scatter propagation. Both troposphere and ionosphere are in continual state of turbulence. This gives rise to local variation in ***n*** of the atmosphere. Waves passing through such turbulent regions get scattered. When λ is small compared to these irregularities then most of the scattering takes place within a narrow cone surrounding the forward direction of propagation of the incident radiation. To receive scattered signal at a point well beyond the horizon, the transmitting and receiving antennas must be of high gain and must be so oriented that their beams overlap in a region where forward scattering is taking place. The scattering angle should also be as small as possible. This process is shown in Figure Since the scattering process is of random nature, the scattered signals continuously fluctuate in amplitude and phase over a wide range.



The scattering is of significant practical utility in the following regions:

500MHzonwards with troposphere as the scattering medium: It is called tropospheric scattering. Depending upon the bandwidth of transmitter, its maximum range lies between 300 to 600 km.

30 to 50 MHz with ionosphere as medium: It is called ionospheric scattering and mainly occurs in the *E* region with maximum range of about 2000 km. The level of scattered signals in this case is much small, some 10 to 20 dB below the free space signal for the same distance.

Tropospheric propagation: The scattering phenomena discussed above can be utilized for the communication purpose. A general mathematical relation governing the received power at a distance can be derived as below:

Consider an omnidirectional antenna which radiates uniformly in all directions. Let the transmitted power be denoted by P_t and the power density (i.e., the power per unit area) in free space at a distance R from the transmitter is denoted by P_{rf}. It will be equal to the transmitted power divided by the surface area $4\pi R^2$ of an imaginary sphere of radius R. Thus

$$P_{rf} = \frac{P_t}{4\pi R^2} \ watts$$

If the transmitting antenna is directional with gain G_t, the increased power reaching the point of observation as compared to the power that would have been reaching in case of an omni-directional antenna is given by

$$P_{rf} = \frac{P_t G_t}{4\pi R^2} \text{ watts}$$

At the point of observation, the receiving antenna will capture a portion of this radiated power. If the effective capture area of the receiving antenna is Ar, the received power will be

$$P_{rf} = \frac{P_t G_t A_r}{4\pi R^2} \text{ watts}$$

The antenna gains G_r and the effective area A_r for receiving antenna bear the following relations:

$$G_r = \frac{4\pi A_r}{\lambda^2} \quad \text{or} \quad A_r = \frac{\lambda^2 G_r}{4\pi}$$

Substitution of A_r in the expression of P_{rf} results in

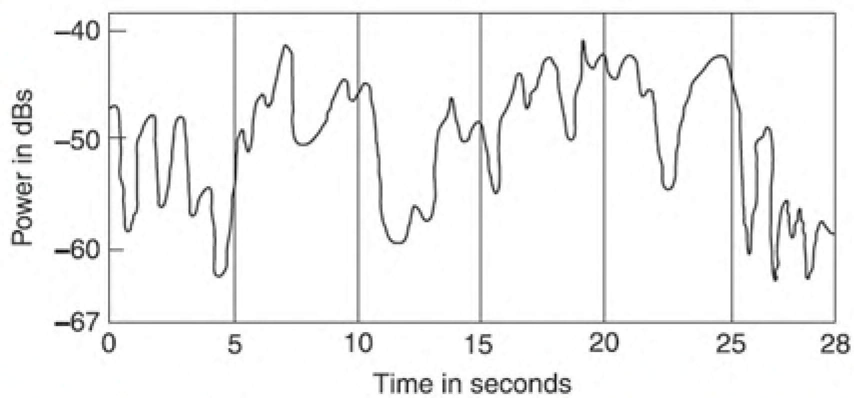
$$P_{rf} = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2} \text{ watts}$$

In all above relations, λ is the wavelength. In case of involvement of scattering process, P_{rf} will be obtained by multiplying RHS of above equation by an attenuation factor F given by

$$F = \frac{2}{R\sqrt{\pi}}\sqrt{\sigma(\theta)v}$$

Where $\sigma(\theta)$ is the effective scattering cross-section, v is the scattering (common) volume and θ is the scattering angle.

Fading: The tropospheric signals often suffer from fading which is a phenomenon of reduction of signals due to variation in refractive index. This variation is attributed to sudden changes in temperature, pressure and humidity. The variation of signal in view of the fading phenomena is as shown below. Fading normally is of Rayleigh nature. It can be classified in many ways.



It can be fast or slow, single path or multi-path and short term or long term. For fast or multi-path fading, the duration is of the order of 0.01 second. For long-term fading, on an average, the variation of the signal is of the order of 10 dB. The fading phenomena may occasionally result in sudden disruption of communication. To avoid the fading, the techniques employed are called *diversity techniques*.

Path Loss Calculations: The basic path loss for general communication is given by the relation,

$$Path\ loss = 32.45 + 20\ log10 fMHz + 20\ log10\ dkm$$

The total path loss in dBs,

$$L_{total} = L_{fs} + L_s + L_{ref} + L_{fad} + L_{cpl} + G_t - G_r$$

Where Lfs is the free space path loss and is given by,

$$L_{fs} = 10\ log_{10}\,(4\pi d/R)^2$$

L_s is the medium scattering loss and is given by,

$$Ls = 57 + 10(\theta - 1)10\, log_{10}(fMHz/400)\ (for\ \theta_0 > 1^0)$$

$$\theta = (\theta_0 - \theta_1 - \theta_2) = [(d - d_1 - d_2)/R]\ (180/\pi)\ degrees$$

$$L_{ref} = -0.2(N_s - 310),\ \ N_s = (n_s - 1) \times 10^{-6}$$

$\boldsymbol{n_s}$ = The surface refractive index,
$\boldsymbol{L_{fad}}$ = The fading margin in dBs, and
$\boldsymbol{L_{cpl}}$ = The aperture to medium coupling loss and is given by

$$L_{cpl} = 0.07\, exp\, [0.055\, (G_t + G_r)]\, dB$$

G_t and G_r are gains of transmitting and receiving antennas. The parameters θ_0, θ_1, θ_2, d, d_1 and d_2 are shown in Figure,