15EC304- ANTENNA AND WAVE PROPAGATION

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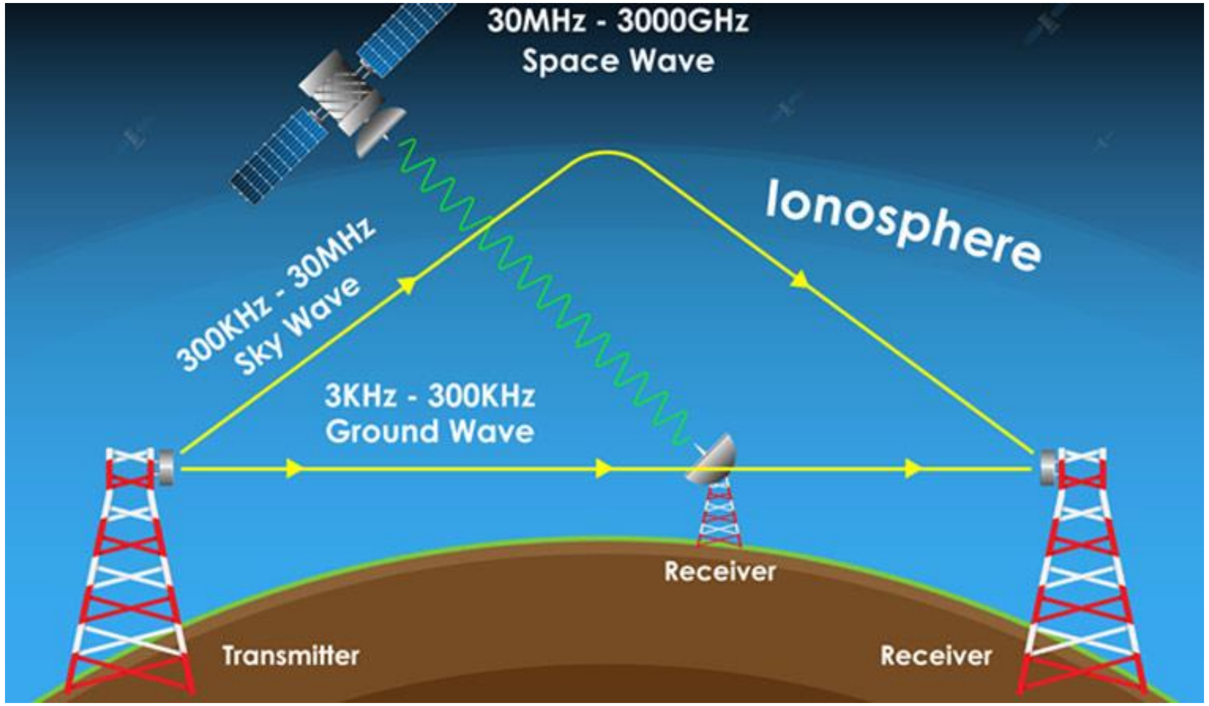
UNIT V- RADIO WAVE PROPAGATION (Topics)

- Basics of propagation: Definition and General Classification
- Different Modes of propagation
- Structure of ionosphere
- Refraction and Reflection of sky wave by ionosphere
- Ray path, Critical frequency, MUF, LUF , OF, Virtual Height and skip distance
- Relation between MUF & Skip distance for flat Earth & Curved Earth
- Ionospheric abnormalities, Impact of solar activity
- Multi-Hop propagation and
- Radio wave characteristics

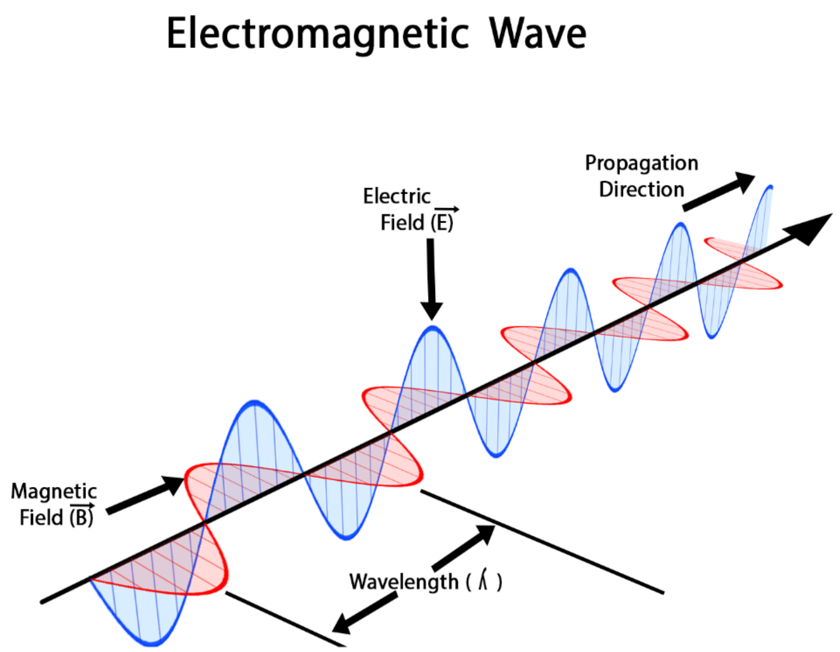
RADIO WAVE PROPAGATION

INTRODUCTION : RADIO WAVE PROPAGATION



What is Electromagnetic Wave?

- Electromagnetic Waves also called Electro-magnetic Radiations are basically defined as superimposed oscillations of an Electric and a Magnetic Field in space with their direction of propagation perpendicular to both of them.
- In simple words, electromagnetic waves are oscillations produced due to crossing over of an electric and a magnetic field.



The direction of the propagation of such waves is perpendicular to the direction of the force of either of these fields as seen in the above figure.

Properties of Electromagnetic(EM) Wave Propagation

- EM waves travel at the speed of light.
- EM waves do not require any medium for propagation.
- EM waves travel in a transverse form.
- EM waves are not deflected by electric or magnetic field.
- EM waves can be polarized.
- EM waves undergo interference and diffraction.

Wavelength & Frequency of the EM waves

- The wavelength(λ) and frequency (f) of the EM waves can be related as:

$$c = f.\lambda$$

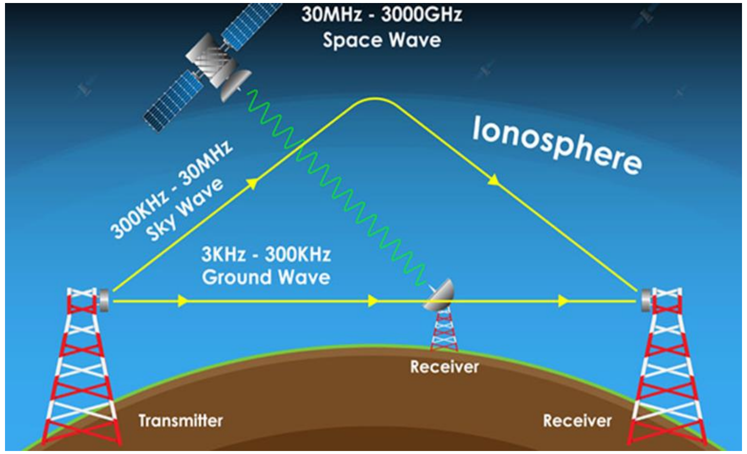
where c = velocity of the wave.

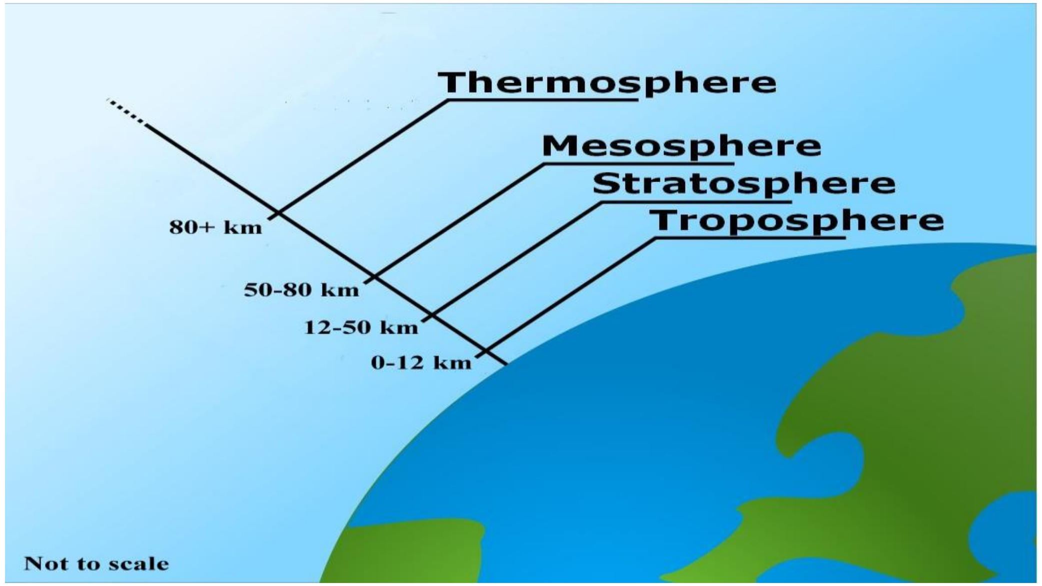
Now let us study some MODES of propagation of EM waves:

Mesosphere, Troposphere, Ionosphere are the different layers.

Classification : Radio Wave Propagation

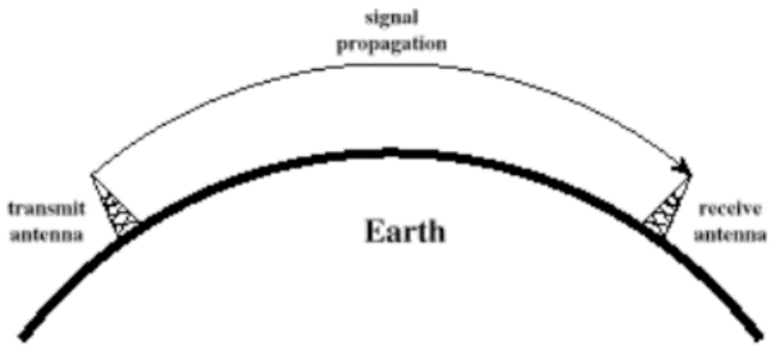
- These layers are used for propagation of EM waves and that EM waves travel basically in any one of the three methods given below:
  - Ground Wave
  - Space Wave
  - Sky Wave

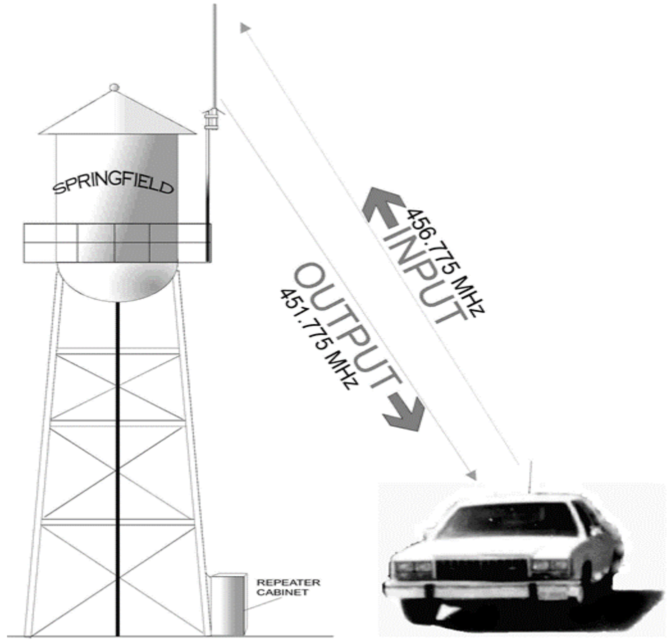




What is Ground Wave /Surface Wave Propagation ?

- To radiate signals with high efficiency, the antennas should have a size comparable to the wavelength λ of the signal (at least ~ λ/4).
- At longer wavelengths (i.e., at lower frequencies), the antennas have large physical size and they are located on or very near to the ground.
- In standard AM broadcast, ground based vertical towers are generally used as transmitting antennas. For such antennas, ground has a strong influence on the propagation of the signal.
- The mode of propagation is called surface wave propagation and the wave glides over the surface of the earth.

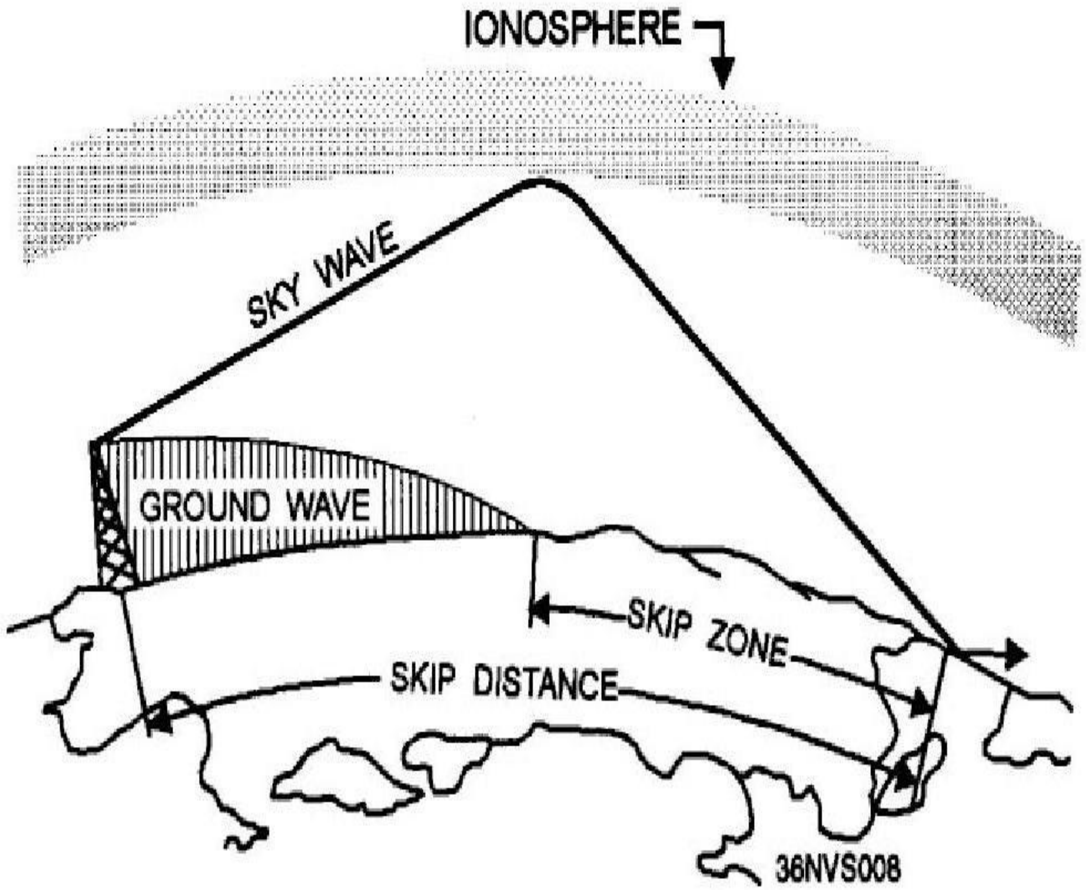


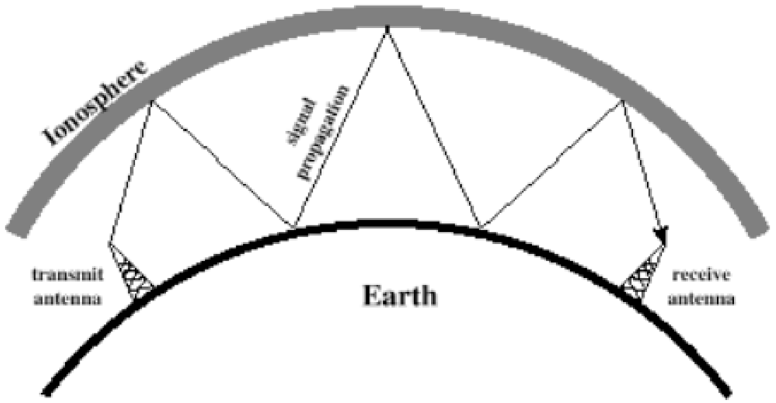


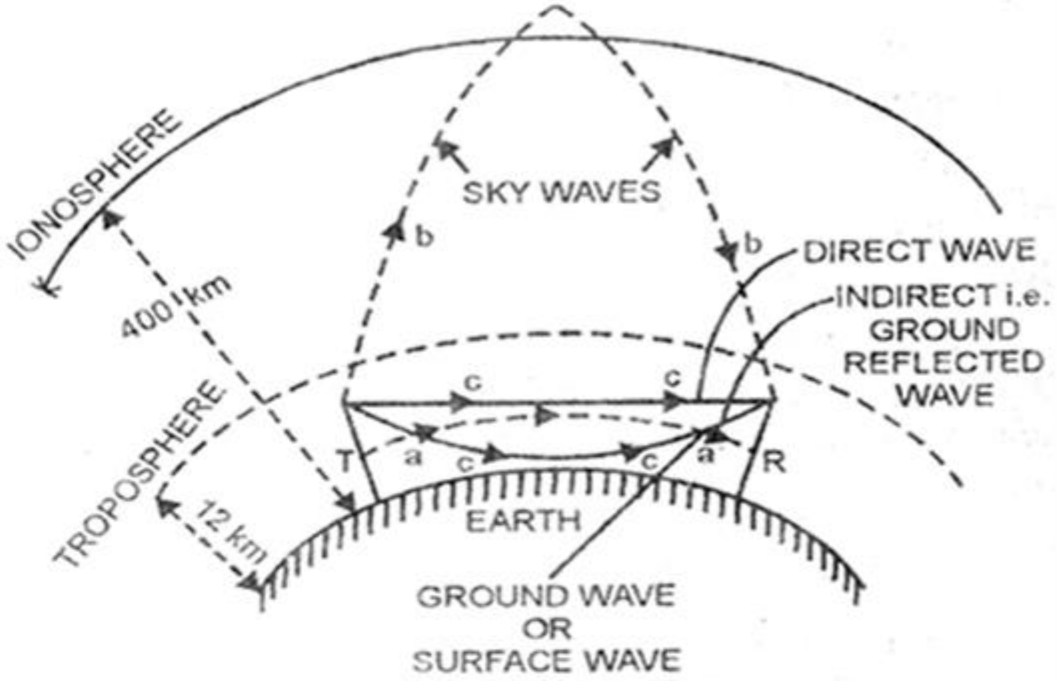
Properties of Ground Wave Propagation

- Used for a low-frequency range transmission, mostly less than 2MHz.
- Employs the use of large antennas order of which is equivalent to the wavelength of the EM waves and uses the ground or Troposphere for its propagation.
- Signals over large distances are not sent using this method.
- It causes severe attenuation which increases with increased frequency of the waves. The maximum range of coverage depends on the transmitted power and frequency (less than a few MHz).

2. Sky Wave Propagation

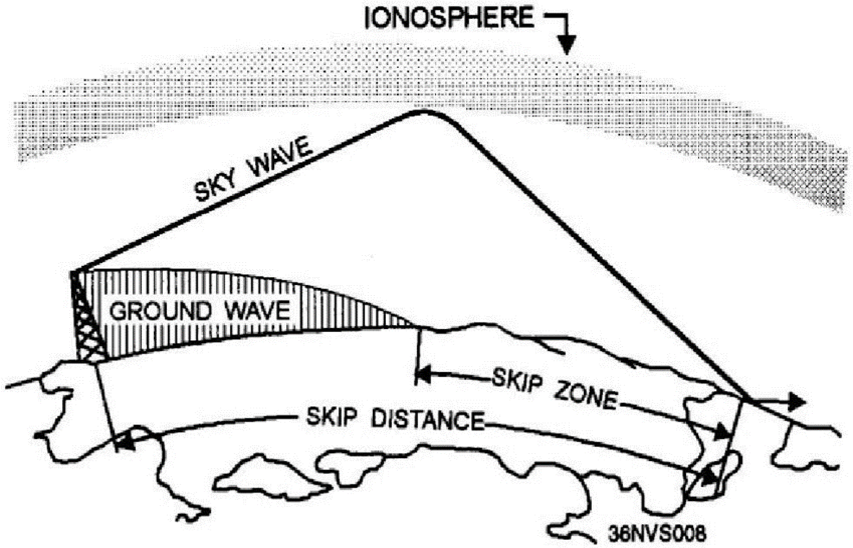






What is Sky Wave Propagation?

- In the Frequency range 300KHz–30MHz, long distance communication can be achieved by ionospheric reflection of radio waves back towards the earth.
- The sky wave, often called the ionospheric wave, is radiated in an upward direction and returned to Earth at some distant location because of refraction from the ionosphere.
- This form of propagation is relatively unaffected by the Earth's surface and can propagate signals over great distances. Usually the high frequency (HF) band is used for sky wave propagation.

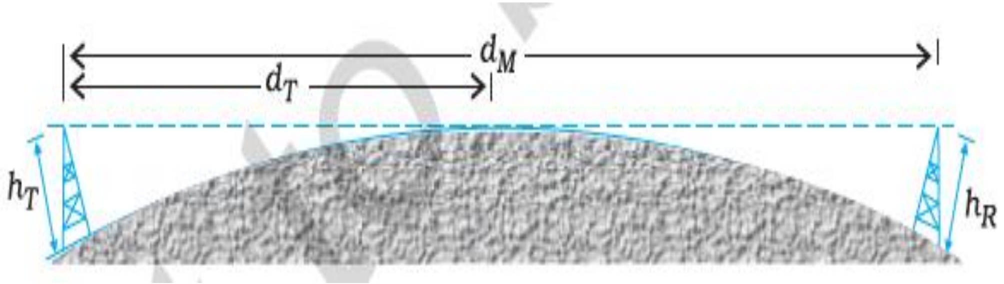


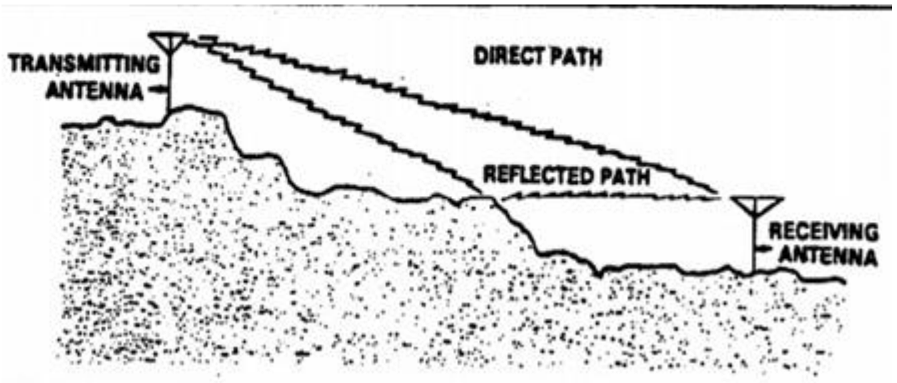
Properties of Sky Wave Propagation

- Used for the propagation of EM waves with a frequency range of 300KHz – 30MHz.
- Make use of the ionosphere so called due to the presence of charged ions in the region of about 60 to 300 km from the Earth surface. These ions provide a reflecting medium to the radio or communication waves within a particular frequency range.
- Use of the property of the ionosphere for long-distance transmission of the waves without much attenuation and loss of signal strength.
  - Examples
    - o Amateur radio , Citizens Band (CB) radio , International broadcasts

3. Space Wave Propagation

- Another mode of radio wave propagation is by *space waves*.
- The space wave follows two distinct paths from the transmitting antenna to the receiving antenna :
  - one through the air directly to the receiving antenna,
  - the other reflected from the ground to the receiving antenna.



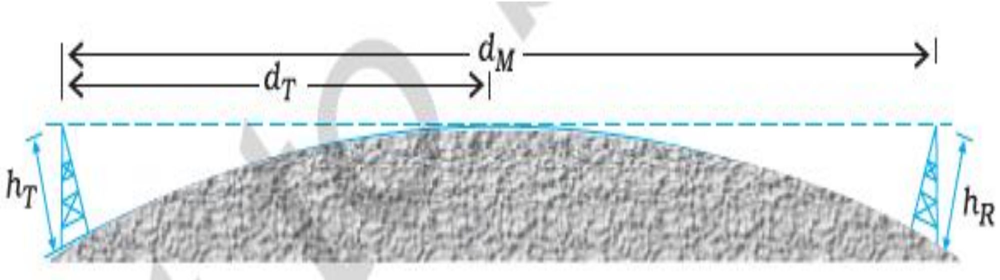


Direct Wave Propagation

- The primary path of the space wave is directly from the transmitting antenna to the receiving antenna. So, the receiving antenna must be located within the radio horizon of the transmitting antenna.
- Because space waves are refracted slightly, even when propagated through the troposphere, the radio horizon is actually about one-third farther than the LOS or natural horizon.

Direct Wave Propagation (Cont'd)

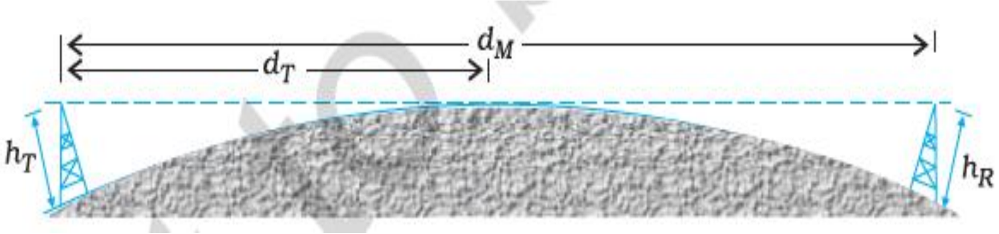
- At frequencies above 40 MHz, communication is essentially limited to LOS paths. At these frequencies, the antennas are relatively smaller and can be placed at heights of many wavelengths above the ground. Because of LOS nature of propagation, direct waves get blocked at some point by the curvature of the earth as illustrated in Fig.
- If the signal is to be received beyond the horizon then the receiving antenna must be high enough to intercept the LOS waves.



Direct Wave Propagation (Cont'd)

- If the transmitting antenna is at a height h_T, then the distance to the horizon d_T is given as

$$d_T = 2Rh_T$$



where R is the radius of the Earth (approximately 6400 km).

d_T is also called the radio horizon of the transmitting antenna.

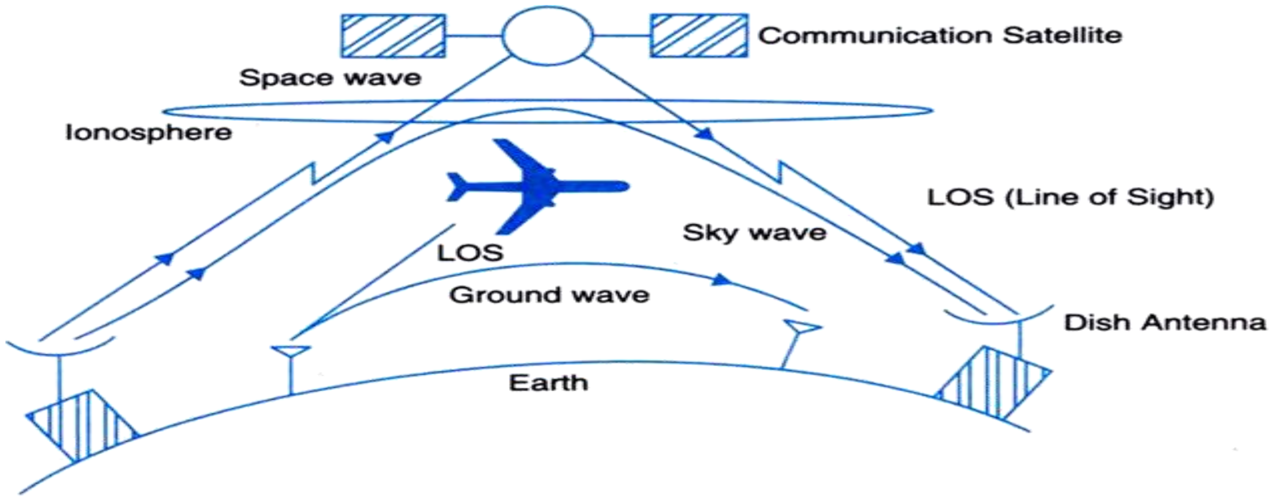
- The maximum LOS distance d_M between the two antennas having heights h_T and h_R above the earth is given by

$$d_M = \sqrt{2Rh_T} + \sqrt{2Rh_R}$$

where h_R is the height of receiving antenna.

Space wave propagation (Satellite)

- Space satellite communication and very high-frequency waves use this propagation method.
- For very large distances, the height of the tower used for transmission is high enough to prevent waves from touching the earth curvature thus preventing attenuation and loss of signal strength.

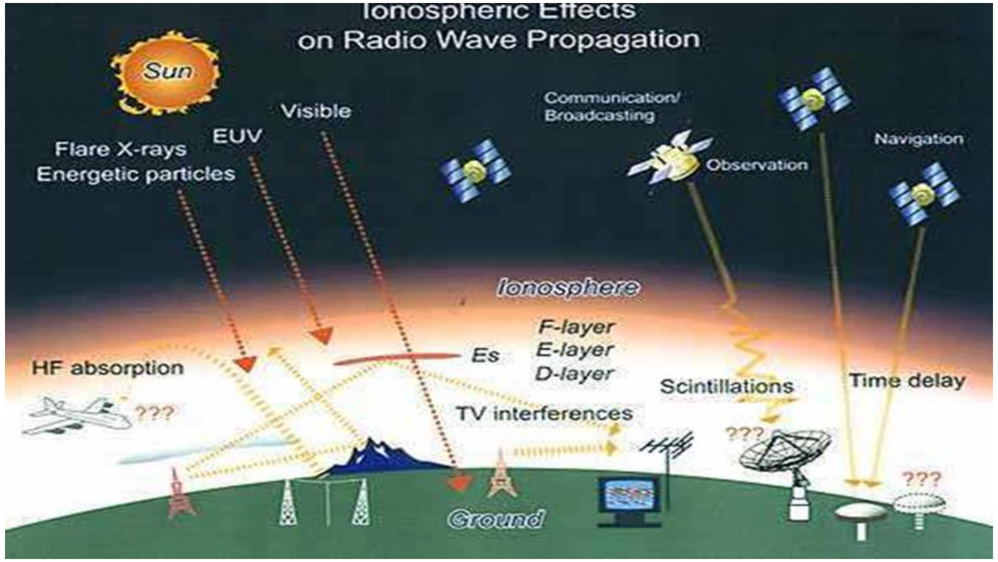


Properties of Space Wave Propagation

- Space waves are used for LOS communication as well as satellite communication.
- Space satellite communication and very high-frequency waves use this propagation method.

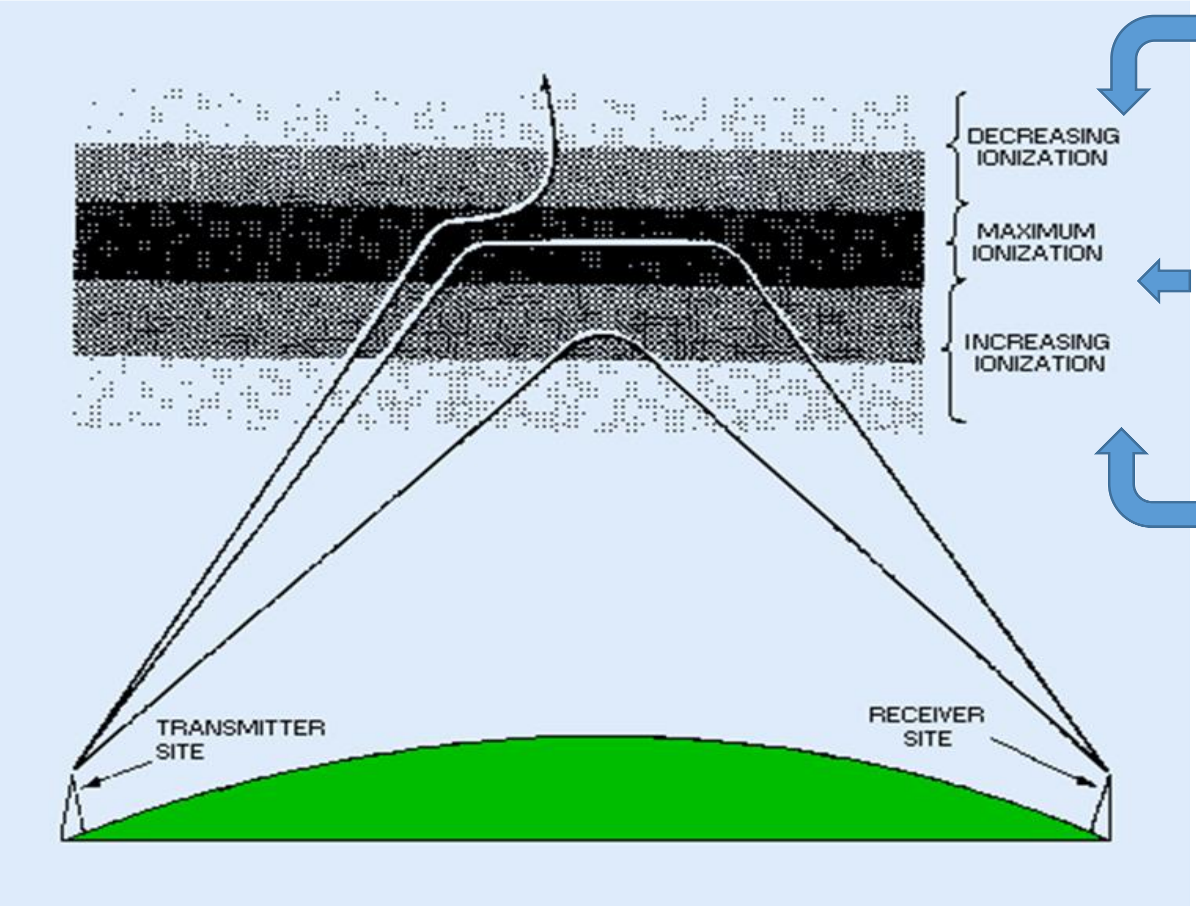
Structure of Ionosphere

- In radio communication, **skywave** or **skip** refers to the propagation of radio waves reflected or refracted back toward Earth from the ionosphere, an electrically charged layer of the upper atmosphere.
- The ionosphere is a region of the upper atmosphere, from about 80 km to 1000 km in altitude, where neutral air is ionized by solar photons and cosmic rays.
- Ionization occurs due to the absorption of the ultraviolet and other high-energy radiation coming from the sun by air molecules.



Ionospheric Effects on Radio Wave Propagation

- Each ionized layer has a central region of relatively dense ionization, which tapers off in intensity both above and below the maximum region.



The relationship between radio waves and ionization density.

As the wave enters into the upper part of the layer of **DECREASING IONIZATION**, the velocity of the radio wave decreases, and the wave is bent away from the Earth.

As the wave is in the highly dense centre portion of the layer, however, refraction occurs more slowly because the **DENSITY OF IONIZATION IS ALMOST UNIFORM.**

As a radio wave enters a region of **INCREASING IONIZATION**, the increase in velocity of the upper part of the wave causes it to be bent back towards the Earth.

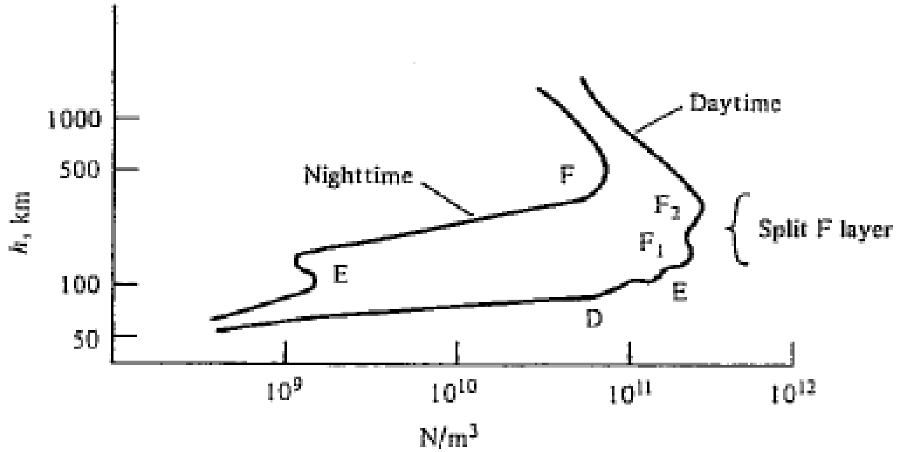
Ionisation in the Ionospheric Layers

- The ionosphere is further subdivided into several layers, the details of which are given in Table.
- **Ionospheric Layers: C, D, E, F1, F2, Regions**

RADIATION CAUSING IONISATION IN THE IONOSPHERIC LAYERS	
LAYERS	**PRIMARY IONISING RADIATION FORMS**
C	Cosmic
D	Lyman alpha, Hard X-Rays
E	Soft X-Rays and some Extreme Ultra-Violet
F1	Extreme Ultra-violet, and some Ultra-Violet
F2	Ultra-Violet

Electron density as a function of altitude

- Layers of high electrons densities : **D, E, and F layers**, as shown in Figure.
- During the day the F layer splits into two layers called the F1 and F2 layers.
- The D layer vanishes completely at night.



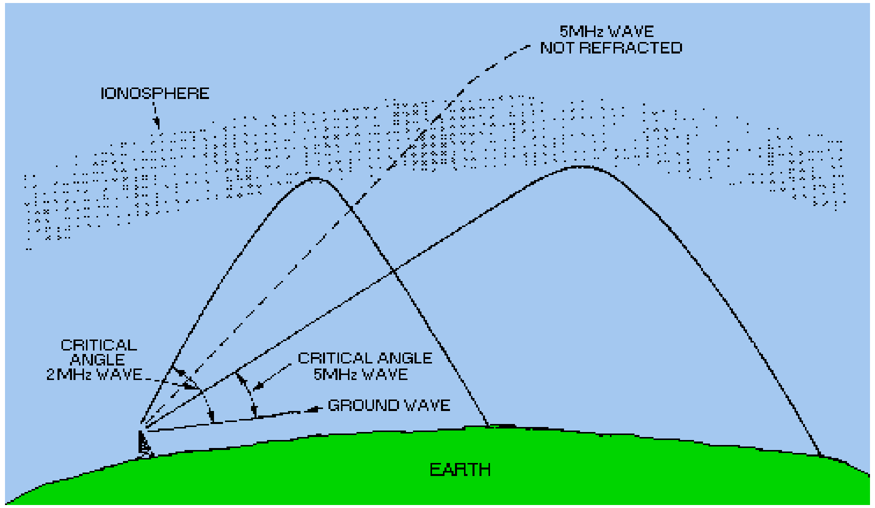
Electron density as a function of altitude, and various ionospheric layers

Refraction by the Ionosphere

- When a radio wave is transmitted into an ionized layer, refraction, or bending of the wave, occurs.
- Refraction is caused by an abrupt change in the velocity of the upper part of a radio wave as it strikes or enters a new medium.
- The amount of refraction that occurs depends on three main factors:
  - ✓ the density of ionization of the layer,
  - ✓ the frequency of the radio wave, and
  - ✓ the angle at which the wave enters the layer

Reflection by the Ionosphere

- When **high-frequency signals** enter the ionosphere at a low angle they are bent back towards the earth by the ionized layer.
- When operating at **frequencies just below the MUF**, losses can be quite small, so the radio signal may effectively "bounce" or "skip" between the earth and ionosphere two or more times.
- If the **ionization is not great enough**, the wave only curves slightly downwards, and subsequently upwards as the ionization peak is passed so that it exits the top of the layer only slightly displaced. The wave then is lost in space.
- To prevent this a lower frequency must be chosen.



Properties of Ionization

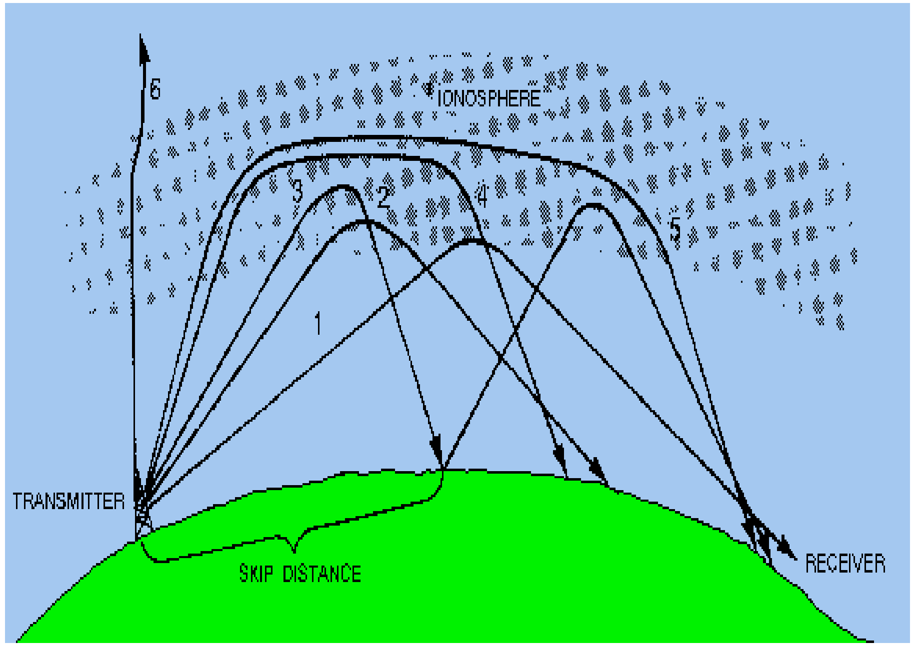
- The degree of ionization varies with the height. The density of atmosphere decreases with height.
- At great heights the solar radiation is intense but there are few molecules to be ionised.
- The ionospheric layer acts as a reflector for a certain range of frequencies (3 to 30 MHz). EM waves of frequencies higher than 30 MHz penetrate the ionosphere and escape.
- The phenomenon of bending of EM waves so that they are diverted towards the earth is similar to total internal reflection in optics.

Key factors within ionospheric High Frequency (HF) radio communication link

- Ray path
- Critical frequency
- Maximum Usable Frequency (MUF)
- Lowest Usable Frequency (LUF)
- Optimum Frequency (OF)
- Virtual Height and
- Skip distance

Ray Path/Propagation Path

- The path that a refracted wave follows to the receiver depends on the angle at which the wave strikes the ionosphere.
- It may also, reach the receiving antenna over a path involving more than one layer, by multiple **hops/skip** between the ionosphere and Earth, or by any combination of these paths.

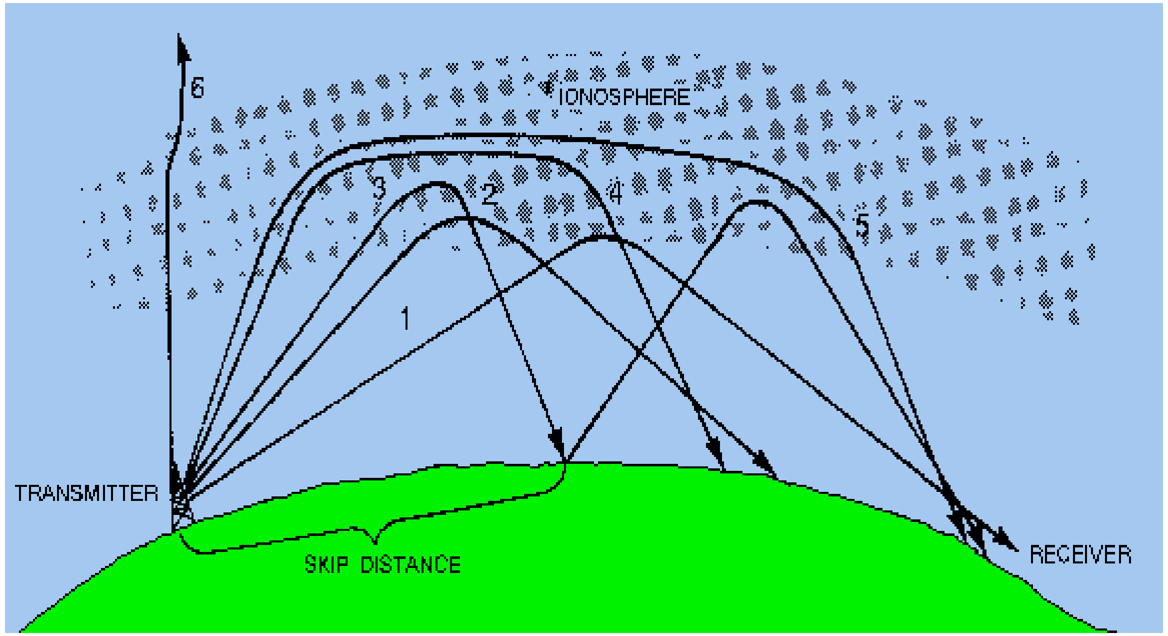


Ray paths with varying angles of incidence.

The various angles at which RF waves strikes the layer are represented by dark lines and designated as rays 1 through 6.

Ray Path/Propagation Path (Cont'd)

- **Ray 1** -- the propagation path is long.
- **Ray 2 and Ray 3**-- the rays penetrate deeper into the layer but the range of these rays decreases.
- When a certain angle is reached (**Ray 3**), the refraction of the ray is first returned to Earth , its second refraction from the ionospheric layer.
- **Ray 4 and Ray 5**--the RF energy penetrates the central area of maximum ionization of the layer. These rays are refracted rather slowly and are eventually returned to Earth at great distances.
- **Ray 6--** the ray is not returned at all, but passes on through the layer.



Frequency Selection Considerations

Selection of a suitable operating frequency (within the bounds of frequency allocations and availability) is of prime importance for successful communications between any two specified locations at any given time of the day:

- Critical frequency (CF)
- Maximum usable frequency(MUF),
- Lowest usable frequency(LUF),
- Optimum working frequency(OWF) that can be used.

Critical frequency

- The critical frequency is an important figure that gives an indication of the state of the ionosphere and the resulting HF propagation.
- It is obtained by sending a signal pulse directly upwards.
- Critical frequency is defined as the maximum frequency at which the **total internal reflection(TIR)** takes place from the ionosphere.

The mathematical representation is given as:

$$f_c = 9\sqrt{N_{\max}}$$

Where,

f_c is the critical frequency in Hz

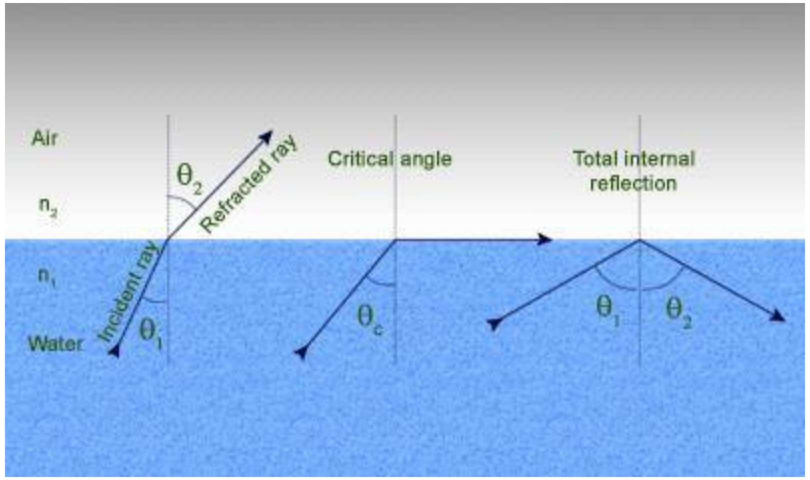
N_{max} is the maximum electron density /ionization density **(electrons per cubic meter)**

Critical frequency varies depending upon atmospheric conditions, time of the day and the angle of incidence of the radio waves by the antenna.

Total Internal Reflection

- **Example: A ray of light passes from a medium of water to that of air.**
- Obviously, the light ray will be refracted at the junction separating the two media. Since it passes from a medium of a higher refractive index to that having a lower refractive index, the refracted light ray bends away from the normal.
- At a specific angle of incidence, the incident ray of light is refracted in such a way that it passes along the surface of the water.
- This particular angle of incidence is called the critical angle. Here the angle of refraction is 90 degrees.

Definition : The radio frequency at or below the wave gets reflected from the ionosphere and above this frequency waves penetrate through the ionospheric layer . This frequency is known as **Critical Frequency**



Maximum usable frequency (MUF)

- When a signal is transmitted using HF propagation, over a given path there is a maximum frequency that can be used.
- **A maximum frequency that can be used for communications between two given locations**. This frequency is known as the **MUF**.
- Waves at frequencies above the MUF are normally refracted so slowly that they return to Earth beyond the desired location, or pass on through the ionosphere and are lost.
- However, that use of an established MUF certainly does not guarantee successful communications between a transmitting site and a receiving site. Variations in the ionosphere may occur at any time and consequently raise or lower the predetermined MUF.

Maximum usable frequency (MUF)

The mathematical representation of critical frequency as a function of MUF is:

$$f_c = f_{MUF} / \sec\theta; \qquad f_{MUF} = f_C / \cos\theta$$

Where,

f_c is the critical frequency in Hz

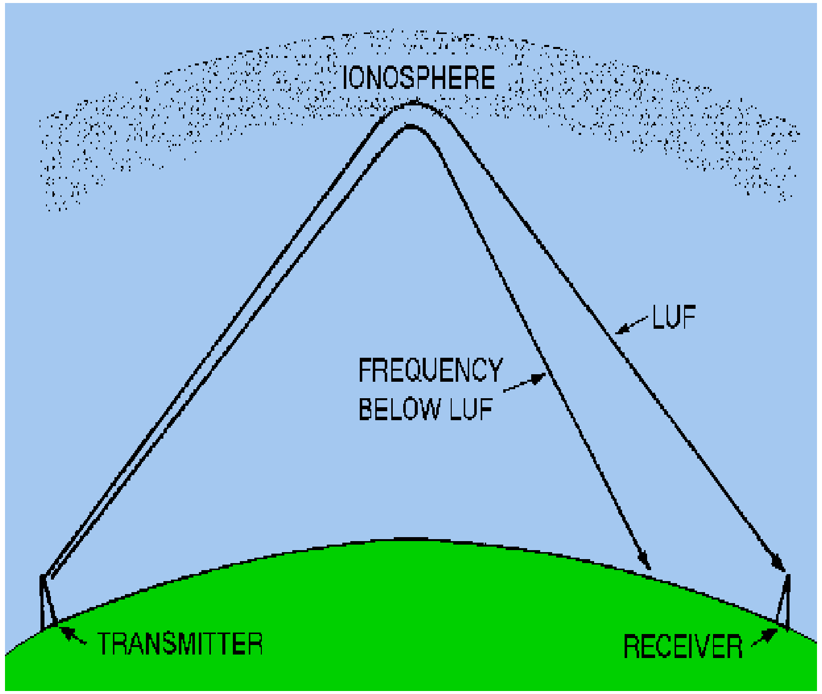
$\boldsymbol{f_{MUF}}$ is the maximum usable frequency (3 to 4 times of f_c)

θ is the angle of incidence

The factor **sec θ** is called the MUF factor and it is a function of the path length if the height layer is known.

Lowest Usable frequency (LUF)

- ✓ As there is a maximum operating frequency that can be used for communications between two points, there is also a minimum operating frequency. This is known as the LUF.
- ✓ As the frequency of a radio wave is lowered, the rate of refraction increases. So the wave whose frequency is below the established LUF is refracted back to Earth at a shorter distance than desired, as shown in Figure.
- ✓ The LUF is defined as the **frequency at below which the signal falls below the minimum strength required for satisfactory reception.**
- ✓ The LUF is the practical limit below which communication cannot be maintained between two particular radio communications stations.



Refraction of frequency below the LUF

Optimum Working Frequency (OWF)

- Neither the MUF nor the LUF is a practical operating frequency.
- When the radio waves at the LUF can be refracted back to Earth at the desired location, **the signal-to-noise ratio is still much lower than at the higher frequencies, and the probability of multipath propagation is much greater.**
- Operating at or near the MUF can result **in frequent signal fading and dropouts when ionospheric variations** alter the length of the transmission path.
- The most practical operating frequency is one that you can rely on with the least amount of problems. It should be high enough to avoid the **problems of multipath, absorption, and noise encountered at the lower frequencies**; but not so high as to result in the adverse effects of rapid changes in the ionosphere.
- A frequency that meets the above criteria has been established and is known as the OWF

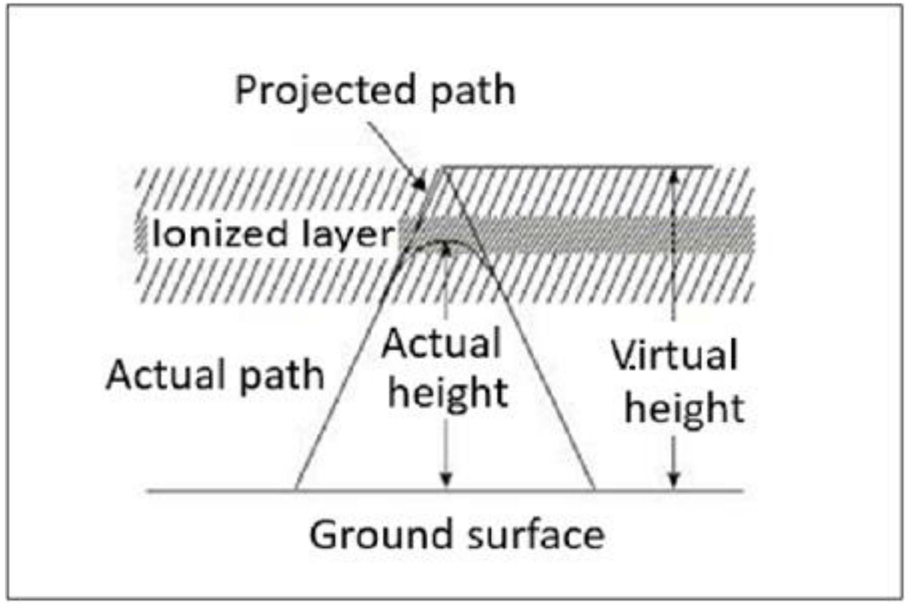
OWF (Cont'd)

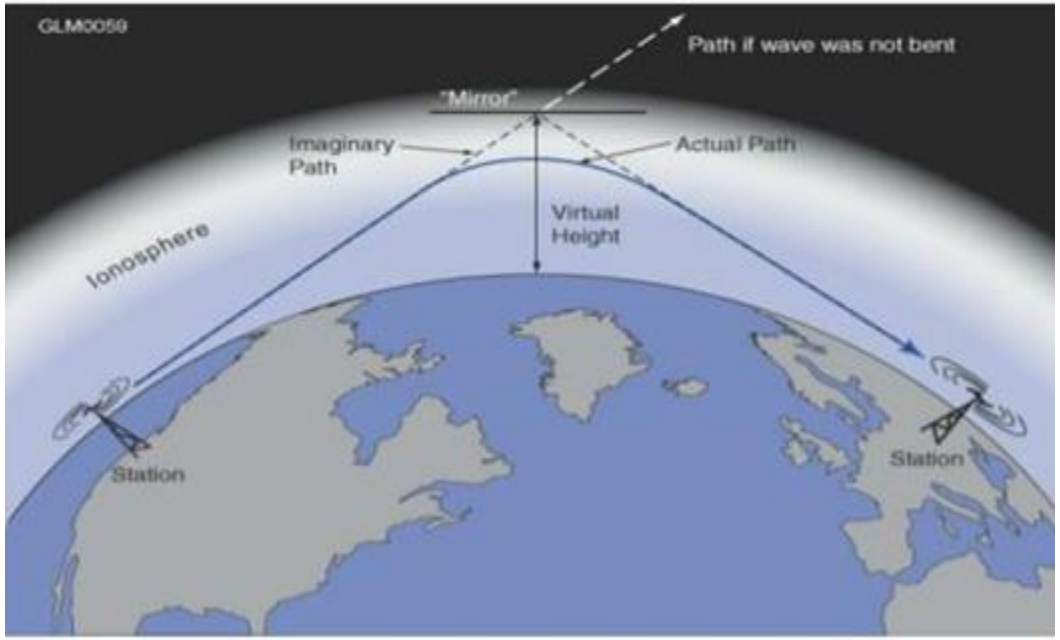
- The frequency, which is being used mostly for a particular transmission and which has been predicted to be used over a particular period of time, over a path, is termed as OWF.
- Estimates the maximum frequency that must be used for a given critical frequency and incident angle. It is the frequency chosen to avoid the irregularities of the atmosphere.

$$OWF = 0.85\, f_{MUF} = 0.85\, f_C / \cos\theta$$

Virtual Height

- When a wave is refracted, it is bent down gradually, but not sharply. However, the path of incident wave and reflected wave are same if it is reflected from a surface located at a greater height of this layer.
- Such a greater height is termed as virtual height.





Virtual Height(Cont'd)

- As shown in Figure, the curve path reaches an altitude of $\boldsymbol{h_1}$ before being returned to the Earth.
- If the incident and returned rays are extrapolated to a vertex, they meet at a height ***h'***, which is called the virtual reflection height of the ionospheric layer.

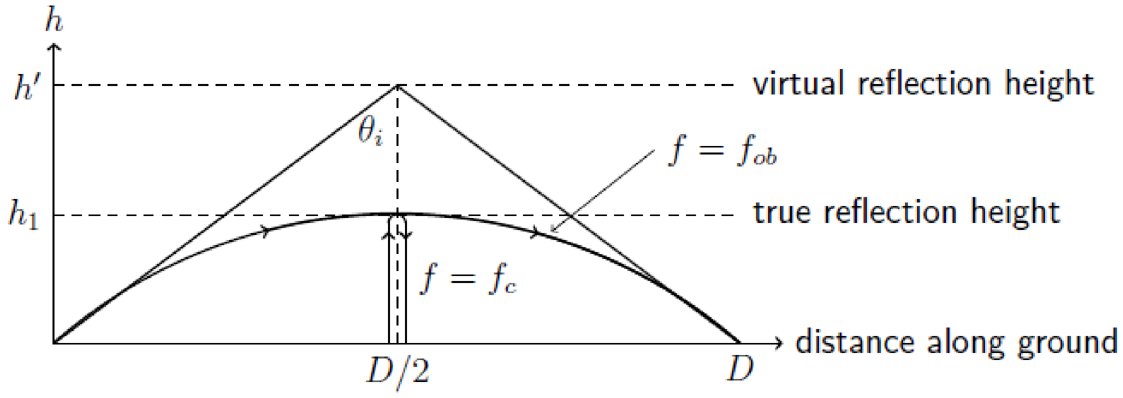


Fig. The curved path of a refracted ray associated with frequency $\boldsymbol{f_{ob}}$.

Virtual heights of various ionospheric layers

- The virtual height depends on conditions, the time of day, and the layer, as shown in Table.

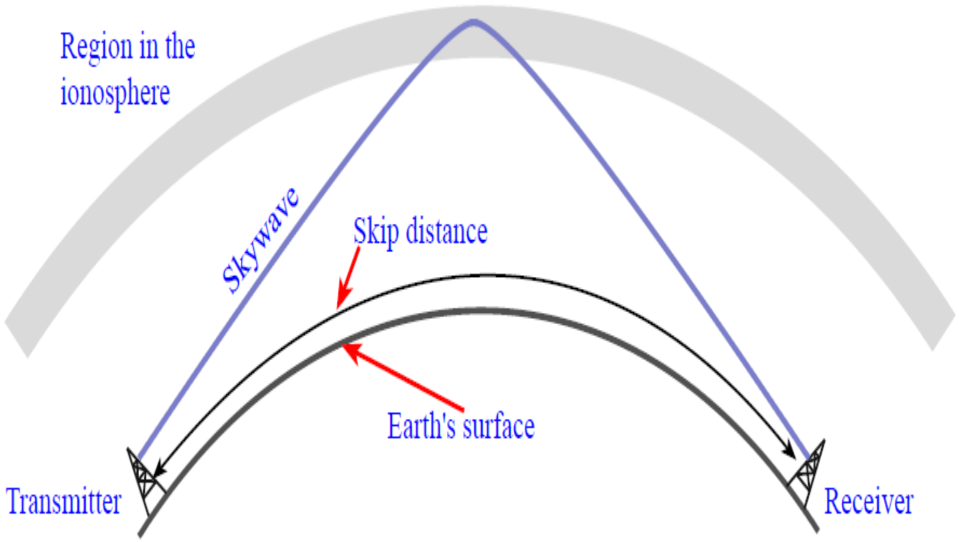
Ionospheric Layer	Daytime virtual re. height	Night time virtual ref. height
F2	250-400 km	-
F1	200-250 km	-
F	-	300 km
E	110 km	110 km

Skip distance, Sky zone

- The skip distance is the distance over the Earth's surface between the point where a radio signal is transmitted, and the point where it is received having travelled to the ionosphere, and been refracted back by the ionosphere.

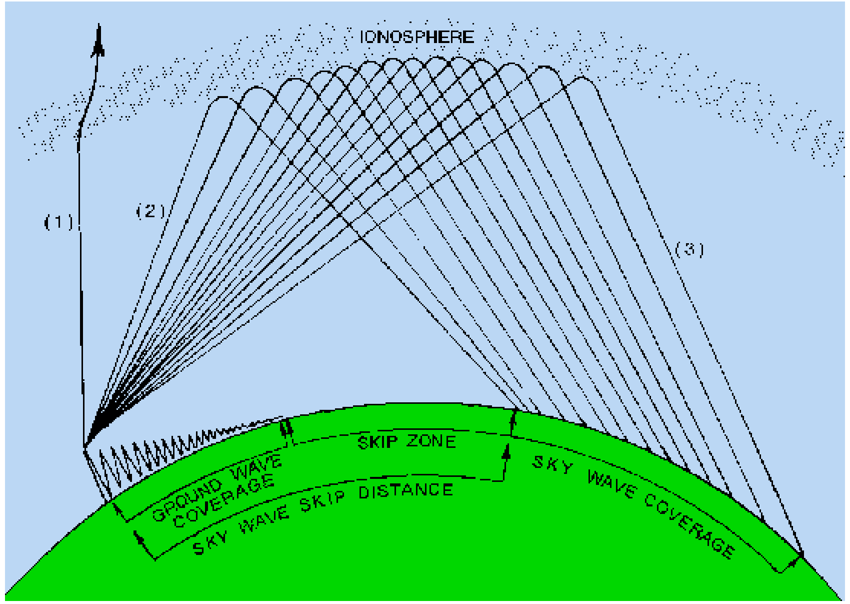
$$D_{skip} = 2h\sqrt{\left(\frac{f_{MUF}}{f_C}\right)^2 - 1}$$

Where,
D_{skip}: skip distance
h: height at which reflection happens
f_{MUF}: maximum usable frequency
f_c: critical frequency



Skip distance, Sky zone (Cont'd)

- The size of the skip distance depends on
  - the frequency of the wave,
  - the angle of incidence, and
  - the degree of ionization present.
- The **SKIP ZONE** is a zone of silence between the point where the ground wave becomes too weak for reception and the point where the sky wave is first returned to Earth.
- The size of the skip zone depends on the extent of the ground wave coverage and the skip distance.
- When the ground wave coverage is great enough or the skip distance is short enough that no zone of silence occurs, there is no skip zone.

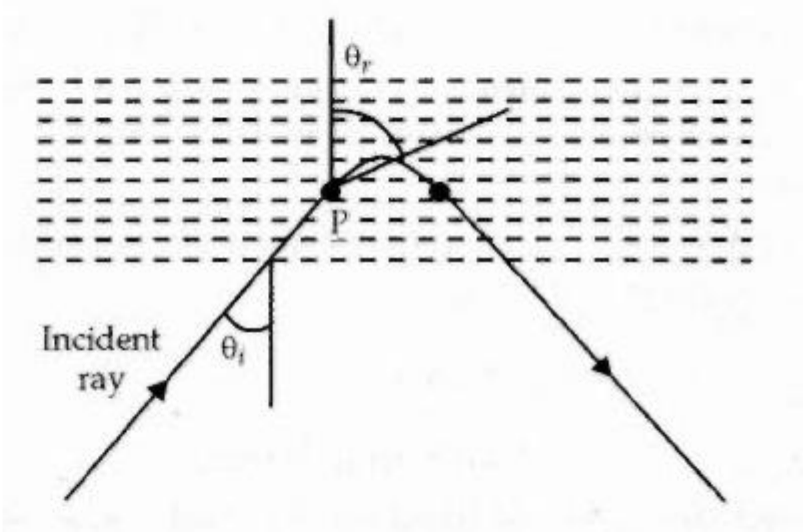


Relationship between skip zone, skip distance, and ground wave coverage

Refractive Index in the Ionosphere

- As the wave incident at angle of incidence, θ_i the wave is bent towards the Earth. The bending of the wave produced by the ionosphere follows optical laws.

- The direction of propagating the wave at a point in the ionosphere is given by **SNELL'S LAW**



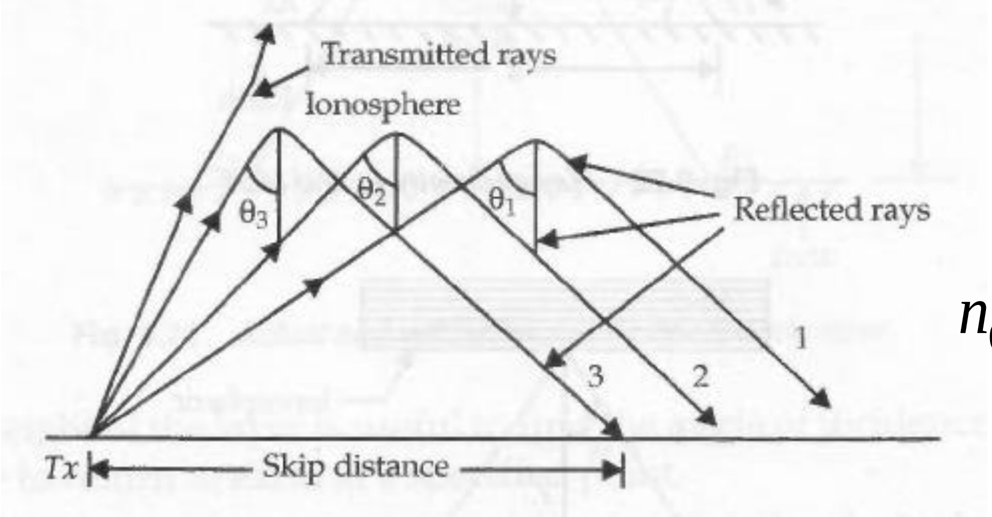
$$n = \frac{\sin \theta_i}{\sin \theta_r} \quad \text{----> (1)}$$

Where,

θ_i is the angle of incidence at lower edge of the ionosphere
θ_r is the angle of refraction at point P
n is the refractive index
ε_r is the relative permittivity of the ionosphere

Relation between MUF & Skip distance for Flat Earth

The ionosphere has many tiny layers , for atmospheric refraction



$$n_0 \sin\theta_i = n_1 \sin\theta_1 = n_2 \sin\theta_2 \cdots n_k \sin\theta_k$$ ----→ **(2)**

- The condition for the wave to return to earth is to have total internal reflection(TIR), which begins when the refracted angle ,θ_r is 90^0.
- If this happens at the ***k^th*** layer,

$$n_0 \sin\theta_i = n_k \sin 90^0 = n_k$$ ----→ **(3)**

and since $n_0 = 1$,

$$\sin\theta_i = n_k \qquad \sin^2\theta_i = n_k^2 = \varepsilon_r \qquad n_k = \sqrt{\varepsilon_r}$$ ----→ **(4)**

Relation between MUF & Skip distance (Cont'd)

Critical Frequency (CF)

- For a given angle of incidence θ_i and frequency *f*, the minimum electron density required to achieve TIR is

$$\varepsilon_r = \sin^2 \theta_i = 1 - \frac{NQ_e^2}{\varepsilon_0 m_e w^2} \quad \text{----→ (5)}$$

Where, **N** is the electron density (m-3)

m_e is the mass of electron at rest , $m_e = 9.109 \times 10^{-31} kg$

w is the angular frequency of the wave , $w = 2\pi f$

Q_e is the magnitude of electron charge $Q_e = 1.6021 \times 10^{-19} C$

ε_o is the permittivity of free space $\varepsilon_o = 8.854 \times 10^{-12} F/m$

Relation between MUF & Skip distance (Cont'd)

Critical Frequency (CF)

- If the maximium electron density present is N_{max}, refraction of the wave at normal incidence (**θ_i=0 & sinθ_i = 0**), the only possible way for the wave to be totally internally reflected is **if *ε= 0*.**
- This requires the frequency to be less than the critical frequency f_c, given by

$$\varepsilon_r = \sin^2\theta_i = 1 - \frac{NQ_e^2}{\varepsilon_0 m_e w^2} = 1 - \frac{81N}{f^2} \quad \text{----} \rightarrow (5)$$

if *ε*

if $\varepsilon_r = 0$,

$$\frac{81N_{\max}}{f_C^2} = 1$$

$$f_C = 9\sqrt{N_{\max}} \quad \text{----} \rightarrow (6)$$

Relation between MUF & Skip distance (Cont'd)

Maximum Usable Frequency (MUF)

- Refractive Index as the function of frequency

$$n^2 = 1 - \frac{w_p^2}{w^2} = 1 - \frac{(2\pi f_p)^2}{(2\pi f)^2} = 1 - \left(\frac{f_p}{f}\right)^2 \quad \text{----> (7)}$$

$$n^2 = 1 - \left(\frac{f_p}{f}\right)^2 \qquad n = \sqrt{1 - \left(\frac{f_p}{f}\right)^2} \Rightarrow n = \frac{\sin\theta_i}{\sin\theta_r} = \sqrt{1 - \left(\frac{f_p}{f}\right)^2} \quad \text{----> (8)}$$

- For MUF,

$$\theta_r = 90^o, \qquad \sin\theta_i = \sqrt{1 - \left(\frac{f_p}{f_{MUF}}\right)^2} \qquad \because \sin 90^o = 1 \quad \text{----> (9)}$$

$$\left(\frac{f_p}{f_{MUF}}\right)^2 = 1 - \sin^2\theta_i = \cos^2\theta_i \qquad f_{MUF}^2 = \frac{f_C^2}{\cos^2\theta_i} = f_C^2 \sec^2\theta_i \quad \text{----> (10)} \qquad f_p = f_c$$

$$\boxed{f_{MUF} = f_C \sec \theta_i} \quad \text{----> (11)}$$

Where, w_p is the angular plasma frequency

Relation between MUF & Skip distance (Cont'd)

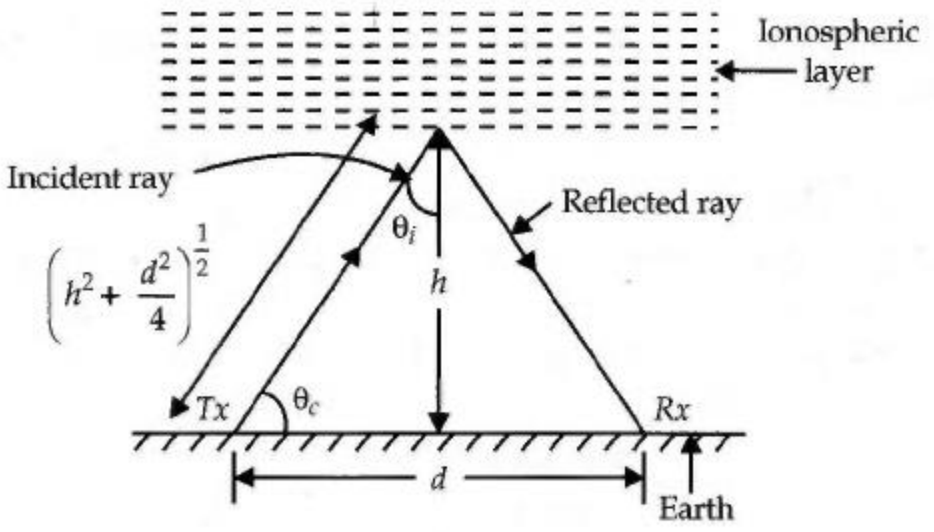
MUF,

$$f_{MUF} = f_c \sec \theta_i = 9\sqrt{N_{\max}} \sec\theta_i$$

- This value of f_{MUF} is called the maximum usable frequency, and is less than 40 MHz, and can be as low as 25-30 MHz in period of low solar activity.
- Equation (11) is called the **Secant Law.**
- **Secant law** is applicable for flat earth and ionospheric layer.

Relation between MUF & Skip distance (Cont'd)

Skip Distance



$$\cos\theta_i = \frac{h}{\sqrt{\left(h^2+\frac{d^2}{4}\right)}} \quad \text{----→ (12)}$$

$$\cos\theta_i = \frac{2h}{\sqrt{d^2+4h^2}}$$

Eqn(10) $$f_{MUF}^2 = \frac{f_C^2}{\cos^2\theta_i}$$

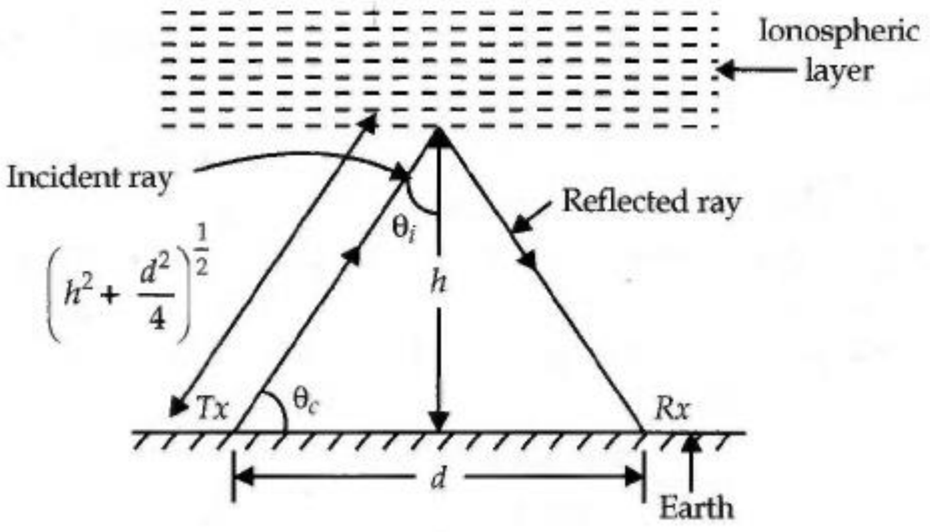
$$\frac{f_{MUF}^2}{f_C^2} = \frac{1}{\cos^2\theta_i} = \left(\frac{\sqrt{d^2+4h^2}}{2h}\right)^2 = \frac{d^2+4h^2}{4h^2}$$

$$\frac{f_{MUF}^2}{f_C^2} = \frac{d^2}{4h^2}+1 \quad \Rightarrow \quad f_{MUF} = f_C\sqrt{\frac{d^2}{4h^2}+1} \quad \text{----→ (13)}$$

h is the height of the layer
d is the skip distance on the flat Earth's surface

Relation between MUF & Skip distance (Cont'd)

Skip Distance



$$\tan\theta_C = \frac{h}{d/2}$$ ----→ **(14)**

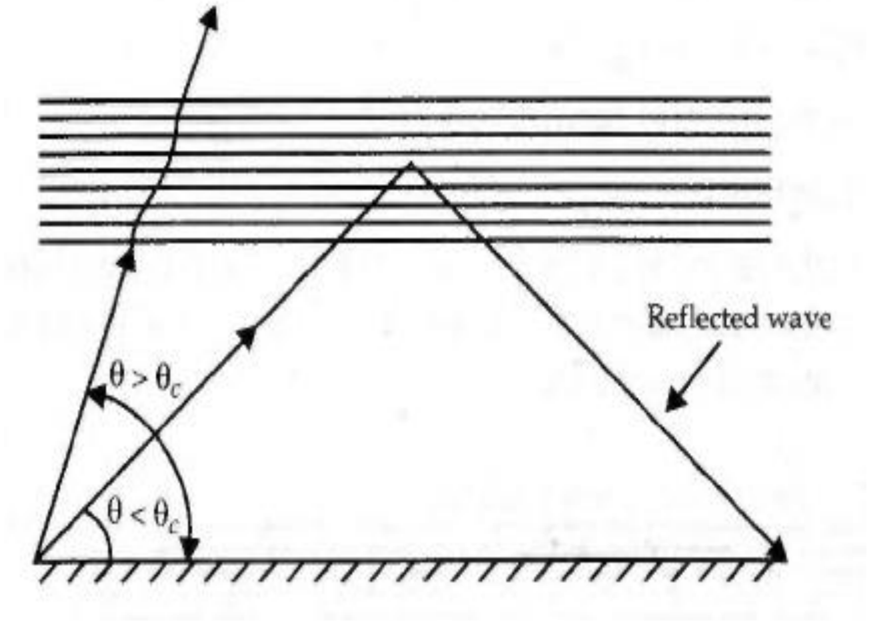
$$h = \frac{d}{2}\tan\theta_C$$

$$d = \frac{2h}{\tan\theta_C}$$

$$d_{skip} = 2h\left[\left(\frac{f_{MUF}}{f_C}\right)^2 - 1\right]^{1/2}$$ ----→ **(15)**

Critical Angle

The wave will **NOT** be reflected when $\theta > \theta_C$



The wave will be reflected when $\theta < \theta_C$

Curved Earth Case :
The Relationship between MUF and the skip Distance

Considering the ionospheric layer is thin with sharp ionization density gradient so as to obtain mirror like reflections.
In this figure, 2θ is the angle subtended by the skip distance *d'* at the center of the earth.

From the geometry of Fig., the following relations are obtained:

$$Arc\ \ d' = 2R\theta; \quad Angle\ 2\theta = \frac{d'}{R}$$

$$OE = R;\ EB = h$$

$$AD = R\sin\theta;\ OD = R\cos\theta;\ BD = OE + EB - OD$$

$$BD = R + h - R\cos\theta$$

$$AB = \sqrt{(AD)^2 + (BD)^2}$$

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

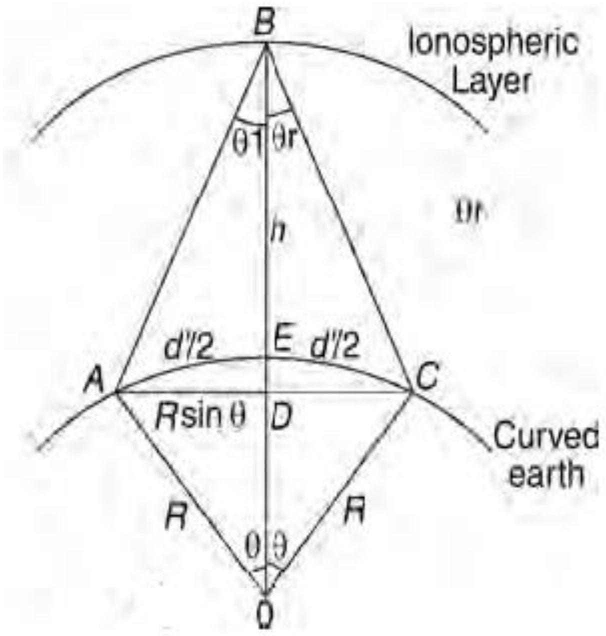
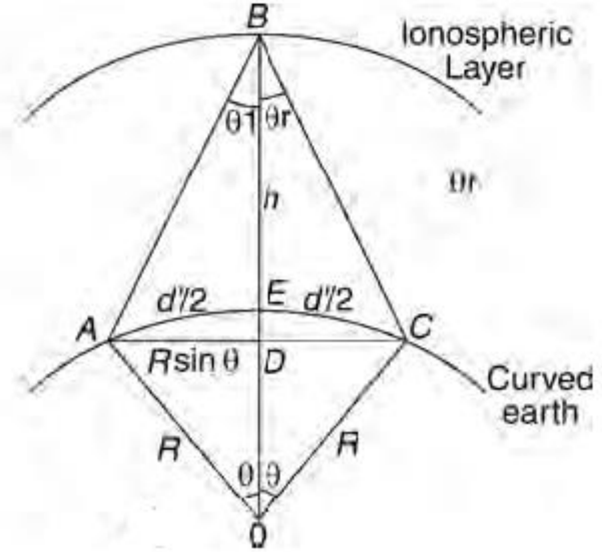


Fig. The ionized layer and the curved earth

Curved Earth Case :
The Relationship between the MUF and the skip Distance(Cont'd)

$$\cos\theta_i = \frac{BD}{AB} = \frac{R+h-R\cos\theta}{\sqrt{(R\sin\theta)^2 + (R+h-R\cos\theta)^2}} \quad \text{----→ (1)}$$



$$(\cos\theta_i)^2 = \frac{(R+h-R\cos\theta)^2}{(R\sin\theta)^2 + (R+h-R\cos\theta)^2}$$

$$\text{Since } \frac{f_C^2}{f_{MUF}^2} = (\cos\theta_i)^2$$

$$(\cos\theta_i)^2 = \frac{f_C^2}{f_{MUF}^2} = \frac{(R+h-R\cos\theta)^2}{(R\sin\theta)^2 + (R+h-R\cos\theta)^2} \quad \text{----→ (2)}$$

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

When the skip distance d' is maximum. $\angle OAB = 90^O$

The curvature of the earth limits both the MUF and the skip distance. This limit is obtained when a wave leaves the transmitter at a grazing angle *OAB* = 90°.

Under this condition,

$$\cos\theta \approx 1 - \frac{h}{R}$$

$$\because \cos\theta = 1 - \frac{h}{R} + \ldots$$

$$\sqrt{1-\sin^2\theta} = 1 - \frac{h}{R}$$

Curved Earth Case :
The Relationship between MUF and the skip Distance(Cont'd)

Since the actual value of θ is very small, this relation can be expanded as

$$\cos\theta \approx 1-\frac{h}{R}$$

$$\sqrt{1-\sin^2\theta} = 1-\frac{h}{R} \qquad \sqrt{1-\theta^2} = 1-\frac{h}{R} \qquad 1-\frac{\theta^2}{2} = 1-\frac{h}{R} \Rightarrow \theta^2 = \frac{2h}{R}$$

$$\boxed{\theta^2 = \frac{2h}{R}} \quad \text{----→ (3)}$$

$$From \quad Fig., \quad Arc\ d' = 2R\theta$$

$$d'^2 = 4R^2\theta^2 = 4R^2.\frac{2h}{R} = 8hR$$

$$d' = \sqrt{8hR} \quad (or) \quad h = \frac{d'^2}{8R}$$

$$\cos\theta \approx 1-\frac{h}{R} = 1-\frac{\left(\frac{d'^2}{8R}\right)}{R}$$

$$\boxed{\cos\theta = 1-\frac{d'^2}{8R^2}} \quad \text{----→ (4)}$$

Curved Earth Case :
The Relationship between MUF and the skip Distance(Cont'd)

Eqn (3) $$\theta^2 = \frac{2h}{R}$$ $$\sin\theta \approx \theta = \sqrt{\frac{2h}{R}}$$

$$\sin\theta \approx \theta = \sqrt{\frac{2\left(d'^2 / 8R\right)}{R}} = \sqrt{\frac{d'^2}{4R^2}} = \frac{d'}{2R}$$

$$\sin\theta = \frac{d'}{2R}$$ **----→ (5)**

By substituting the values of $\sin\theta \; and \; \cos\theta$

Eqn (2) $$(\cos\theta_i)^2 = \frac{f_C^2}{f_{MUF}^2} = \frac{(R + h - R\cos\theta)^2}{(R\sin\theta)^2 + (R + h - R\cos\theta)^2}$$

Curved Earth Case :
The Relationship between MUF and the skip Distance(Cont'd)

$$\frac{f_C^2}{f_{MUF}^2} = \frac{\left(h + d'^2/8R\right)^2}{\left(d'^2/4\right) + \left(h + d'^2/8R\right)^2} \quad \text{----→ (6)}$$

$$\frac{f_{MUF}^2}{f_C^2} = 1 + \frac{d'^2/4}{\left(h + d'^2/8R\right)^2} \qquad \frac{d'^2}{4} = \left(h + \frac{d'^2}{8R}\right)^2\left[\left(\frac{f_{MUF}}{f_C}\right)^2 - 1\right] \quad \text{----→ (7)}$$

The equations (8) and (9) give maximum usable frequency in terms of skip distance

$$f_{MUF} = f_C\left(1 + \frac{d'^2/4}{\left(h + d'^2/8R\right)^2}\right)^{1/2} \quad \text{----→ (8)}$$

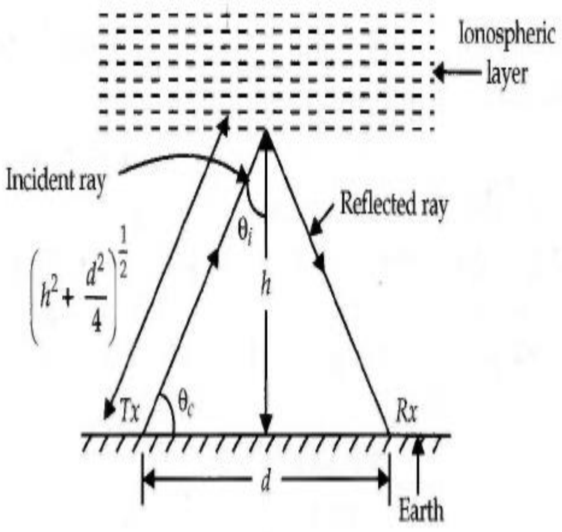
$$d' = 2\left(h + \frac{d'^2}{8R}\right)\left[\left(\frac{f_{MUF}}{f_C}\right)^2 - 1\right]^{1/2} \quad \text{----→ (9)}$$

The Relationship between MUF and skip distance

(a) Flat Earth case

$$f_{MUF} = f_C\sqrt{\frac{d^2}{4h^2}+1}$$

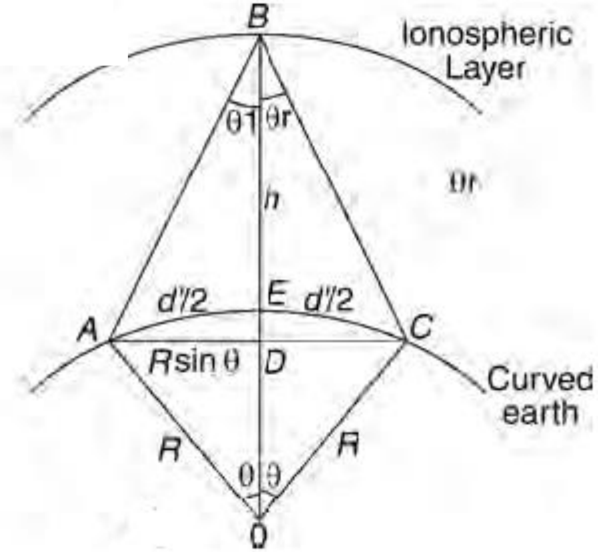
$$d_{skip} = 2h\left[\left(\frac{f_{MUF}}{f_C}\right)^2 - 1\right]^{1/2}$$



(b) Curved Earth case

$$f_{MUF} = f_C\left(1+\frac{d'^2/4}{\left(h+d'^2/8R\right)^2}\right)^{1/2}$$

$$d' = 2\left(h+\frac{d'^2}{8R}\right)\left[\left(\frac{f_{MUF}}{f_C}\right)^2 - 1\right]^{1/2}$$



Ionospheric Abnormalities (Cont'd)

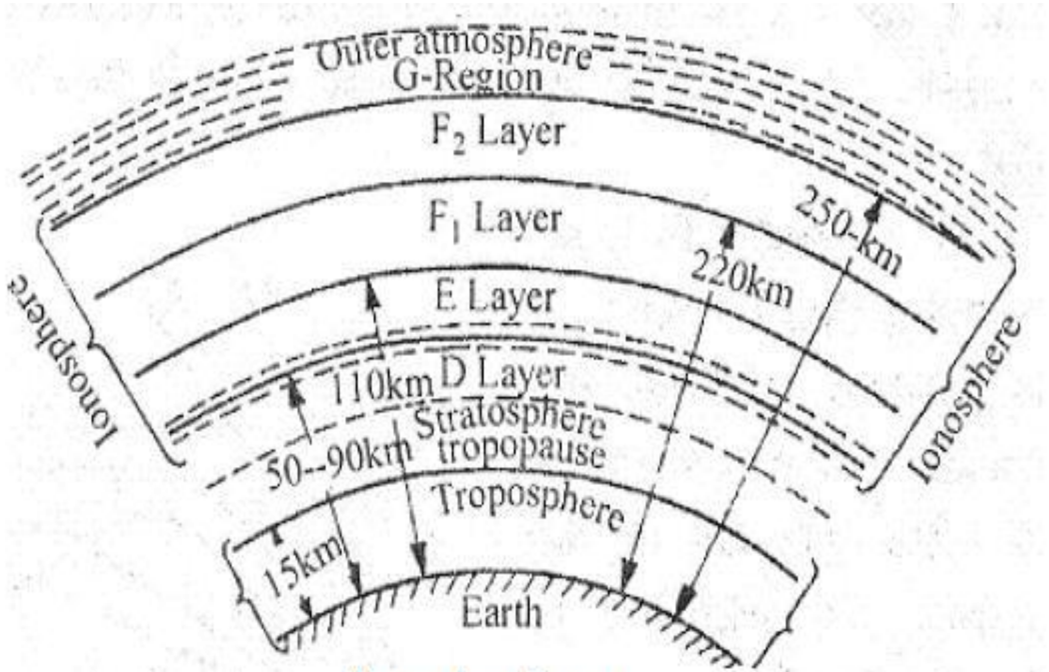
The variations of the ionosphere are classified as follows :

- **Normal**
  - Dirnual (Daily)
  - Seasonal
  - Thickness and
  - Height variations of the ionospheric layer

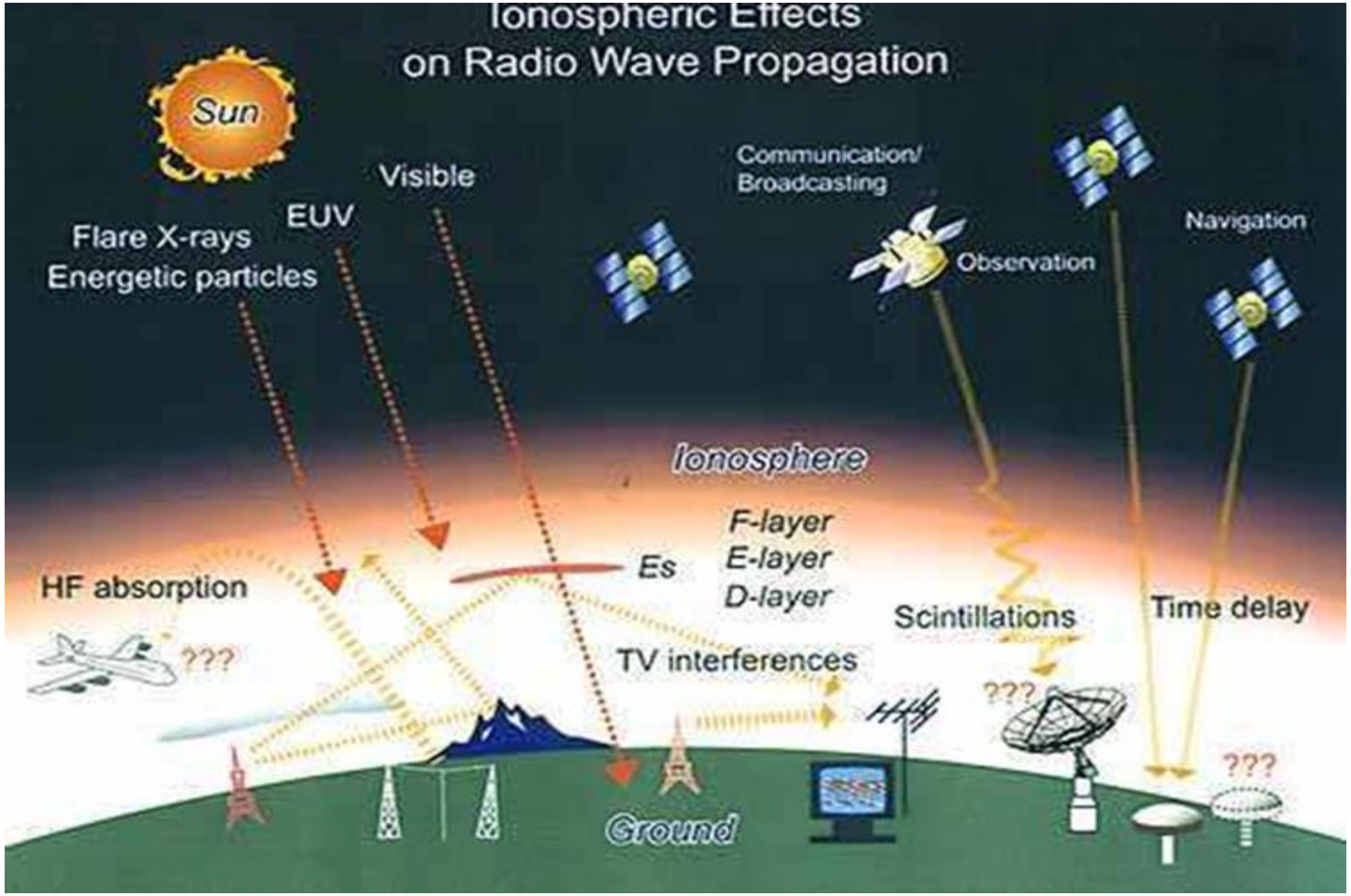
- **Abnormal**
  - Ionospheric storms
  - Sudden Ionospheric Disturbances
  - Sunspot Cycle
  - Fading
  - Whistlers
  - Tides and winds

Ionospheric Effects on Radio Wave Propagation

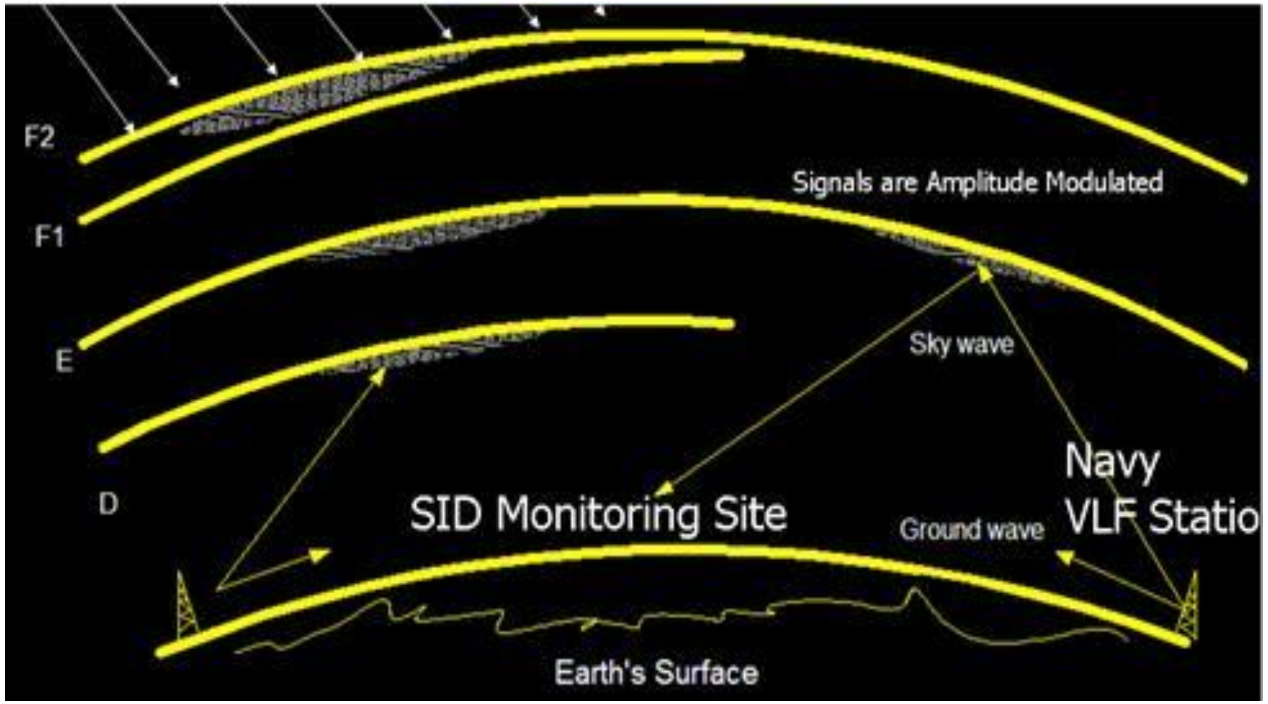
- Normal
- Abnormalities



Ionosphere Layers

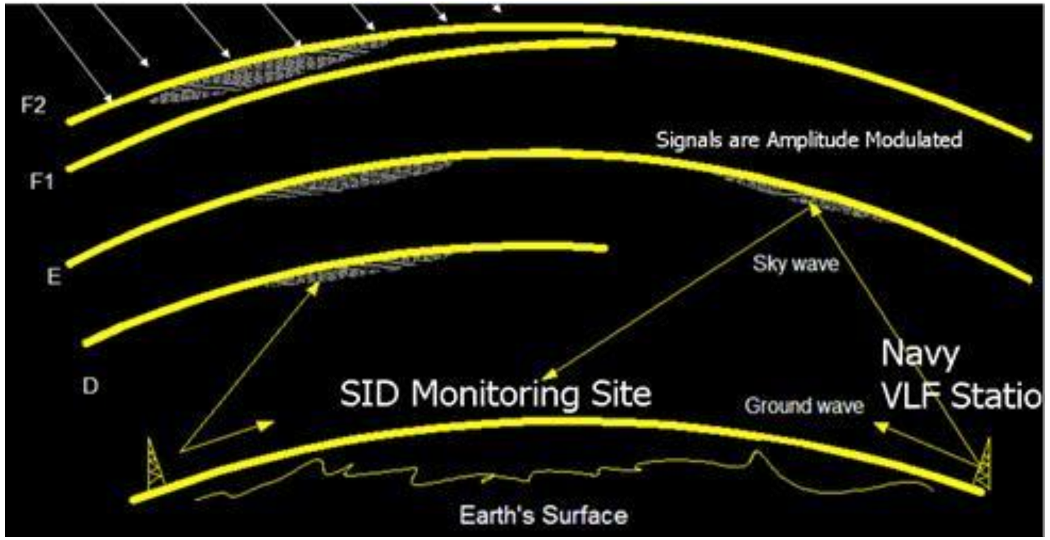


Ionospheric Effects (Cont'd)



- ❑ During the night, the ionosphere has only the F and E layers.
- ❑ A VLF wave from a transmitter reflects off the ions in the E layer and bounces back.

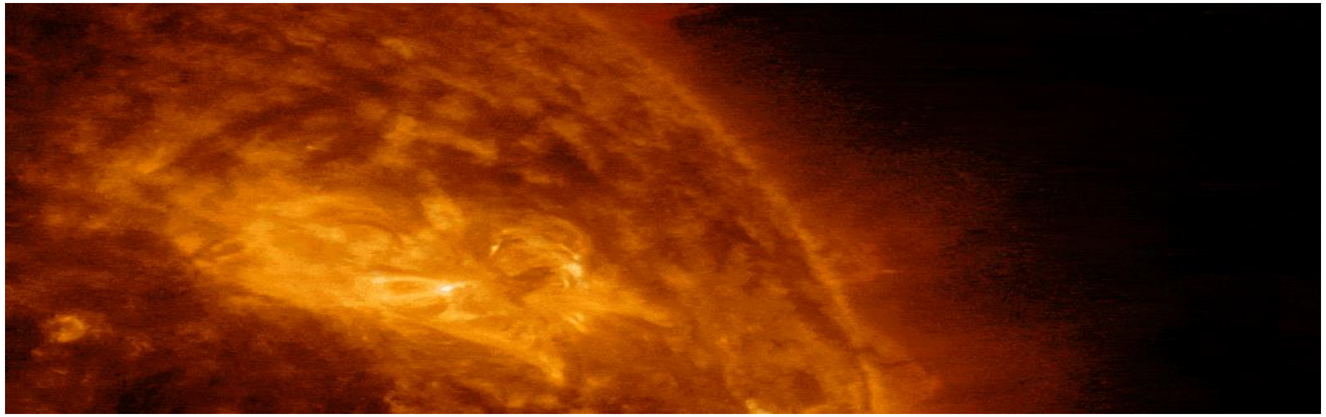
The Sun Effects on the Ionosphere



- During the daytime, Flares on the Sun's X-ray and UV light increase the ionization of the ionosphere, creating the D and enhancing the E layers, and splitting the F region into 2 layers. The D layer is normally not dense enough to reflect the radio waves.
- The signals lose energy as VLF waves penetrate through the D layer and hence radios pick up weaker signals from the transmitter during the day.
- So, **the more active the Sun, the thicker the ionosphere**

Solar Flare

- A **solar flare** is a sudden flash of increased brightness on the Sun, usually observed near its surface and in close proximity to a sunspot group.



NASA's Solar Dynamics Observatory captured this imagery of a solar flare, as seen in the bright flash. Image credit: NASA/SDO/Goddard

- Solar flares release a lot of radiation into space.
- If a solar flare is very intense, the radiation it releases can interfere with radio communications on the Earth.

Ionospheric storms

- An **Ionospheric storm** is a turbulence in the ionosphere of the Earth's atmosphere. Such storms are triggered by enhanced flux of energetic electrons that are emitted at a large level by the Sun.
- Solar activity such as flares produce large variations in the particle and electromagnetic radiation incident upon the earth. Such variations lead to disturbances of the "quiet-time" magnetosphere and ionosphere.
- These disturbances, when affecting the ionosphere are known as **ionospheric storms**, tend to generate large disturbances in ionospheric density distribution, total electron content, and the ionospheric current system.

Ionospheric storms (Cont'd)

- Ionospheric storms have important terrestrial consequences such as disrupting satellite communications and interrupting the flow of electrical energy over power grids.
- Important to monitor such storms and forecast their evolution.
- These storms mainly affect the $\boldsymbol{F_2}$ layer, reducing its ion density and causing critical frequencies, $\boldsymbol{f_C}$ to be lower than the normal.
- These storms usually persist for a few days.

Sudden Ionospheric Disturbance (SID)

- Abnormally high ionization/plasma density in the D region of the ionosphere and caused by a solar flare and/or solar particle event (SPE).
- The SID results in a sudden increase in radio-wave absorption that is most severe in the upper medium frequency (MF) and lower high frequency (HF) ranges, and as a result often interrupts or interferes with telecommunications systems.
- The ionospheric disturbance enhances VLF radio propagation. Scientists on the ground can use this enhancement to detect solar flares; by monitoring the signal strength of a distant VLF transmitter, sudden ionospheric disturbances (SIDs) are recorded and indicate when solar flares have taken place.

SID-Effects on radio waves

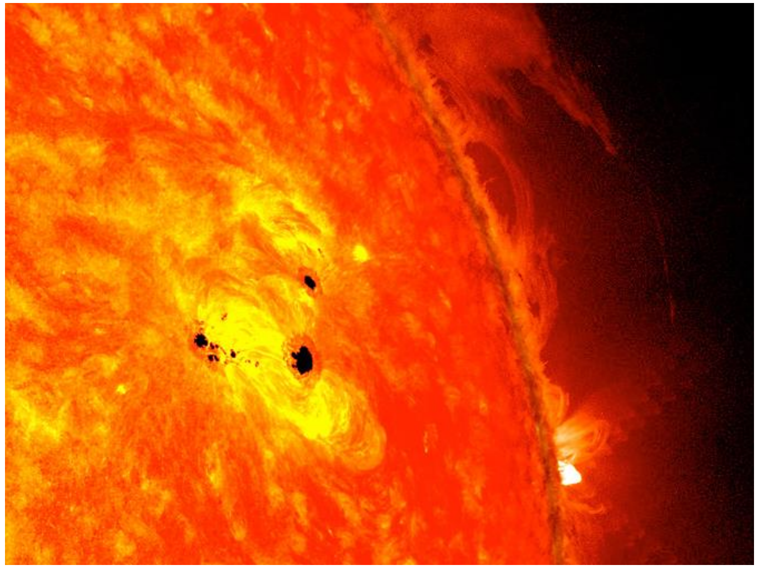
- Short wave radio waves (HF range) are absorbed by the increased particles in the low altitude ionosphere causing a complete blackout of radio communications. This is called a short wave fadeout (SWF).
- These fadeouts last for a few minutes to a few hours and are most severe in the equatorial regions where the Sun is most directly overhead.

Sunspot Cycle

- **Sunspots** are the dark, irregularly shaped areas on the surface of the sun which keep on appearing and disappearing in two cycles, every 27 days and every 11 years.
- Caused by violent eruptions on the sun and are characterized by strong magnetic fields.
- The occurrence of sunspots, their life span, shapes, size and location on the sun's surface are all variable and unpredictable.
- Sunspots cause variations in the ionization level of the ionosphere and hence affect the propagation characteristics of the waves.

Sunspot Cycle (Cont'd)

- **Sunspots** are areas that appear dark on the surface of the Sun. They appear dark because they are cooler than other parts of the Sun's surface. **Solar flares** are a sudden explosion of energy caused by tangling, crossing or reorganizing of magnetic field lines near sunspots.



An active region on the sun with dark sunspots. Source: NASA/SDO/AIA/HMI/Goddard Space Flight Center

Whistlers

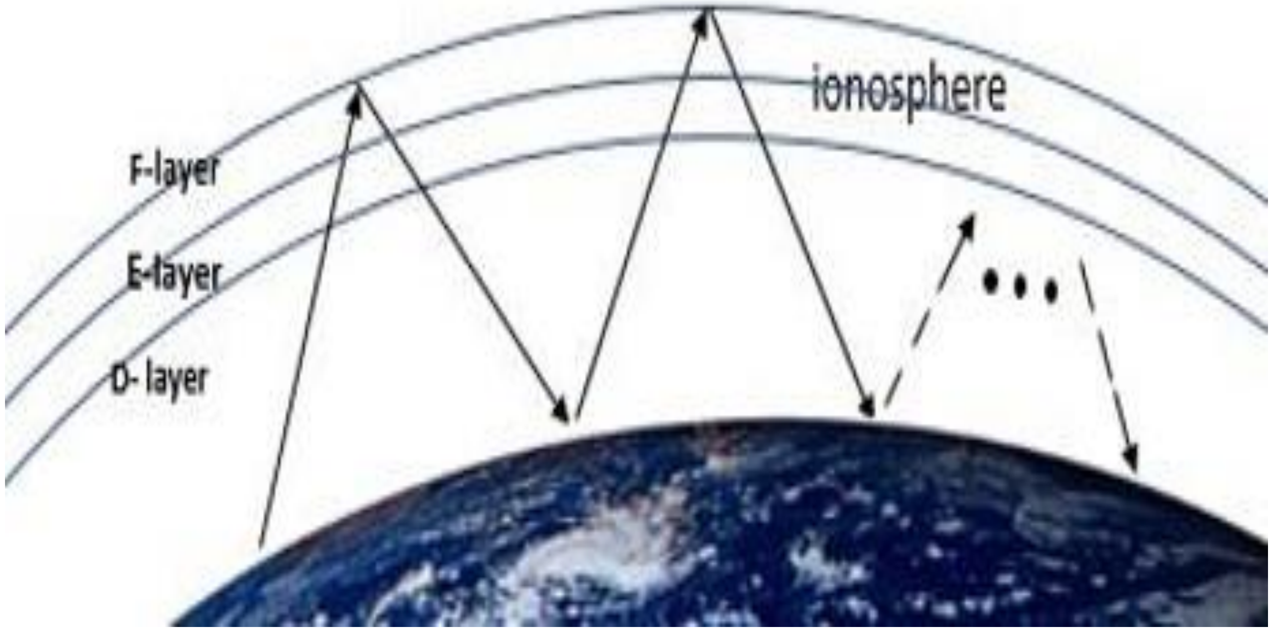
- The transient electromagnetic disturbances which occur naturally.
- EM pulses of audio frequency radiation along the direction of the magnetic field of the earth between conjugate in the northern and southern hemisphere.
- Types : Long, Short and Noise

Tides and Winds

- Occurred due to the motion of turbulence in F2 layer
- Introduces a small peak of maximum ionization density in the layer at mid-night

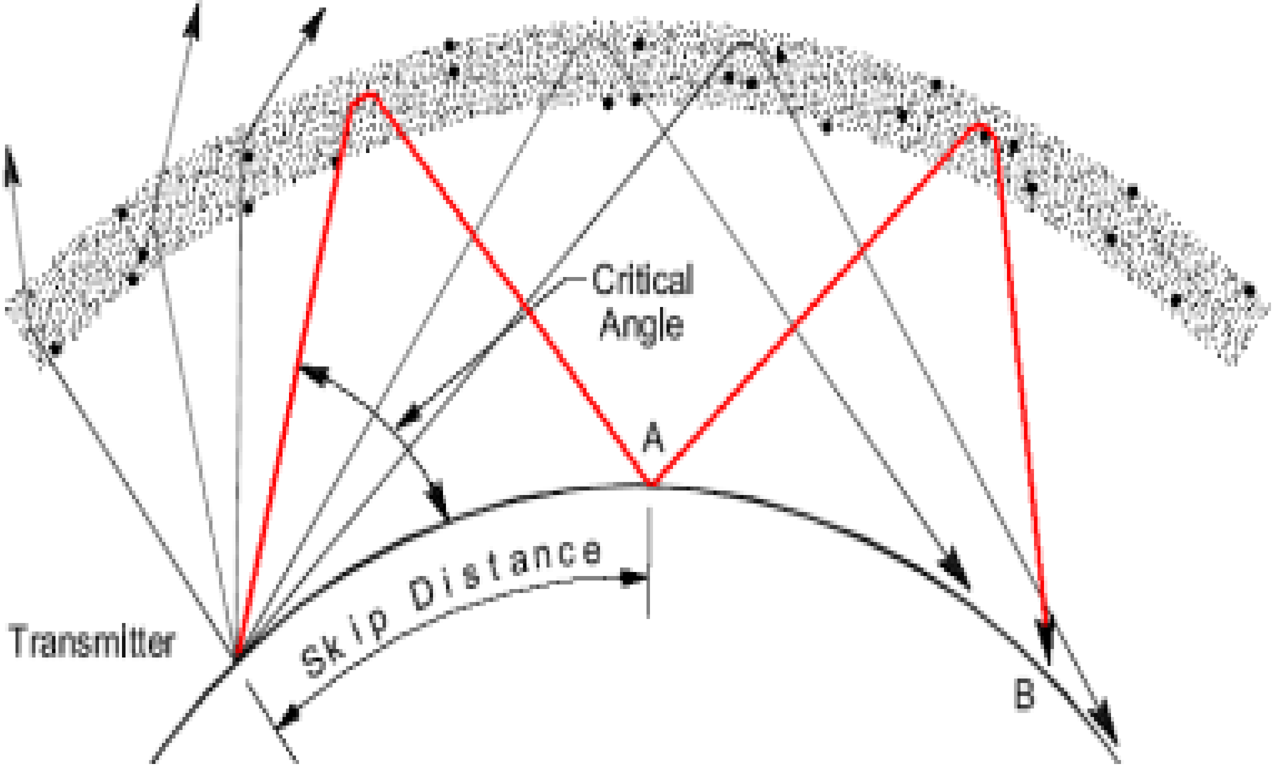
Multi-hop Propagation

- Multiple reflections from the ionosphere and returned to the earth like **Multi-Hops**
- Ionosphere- Reflector
- Earth- Reflector



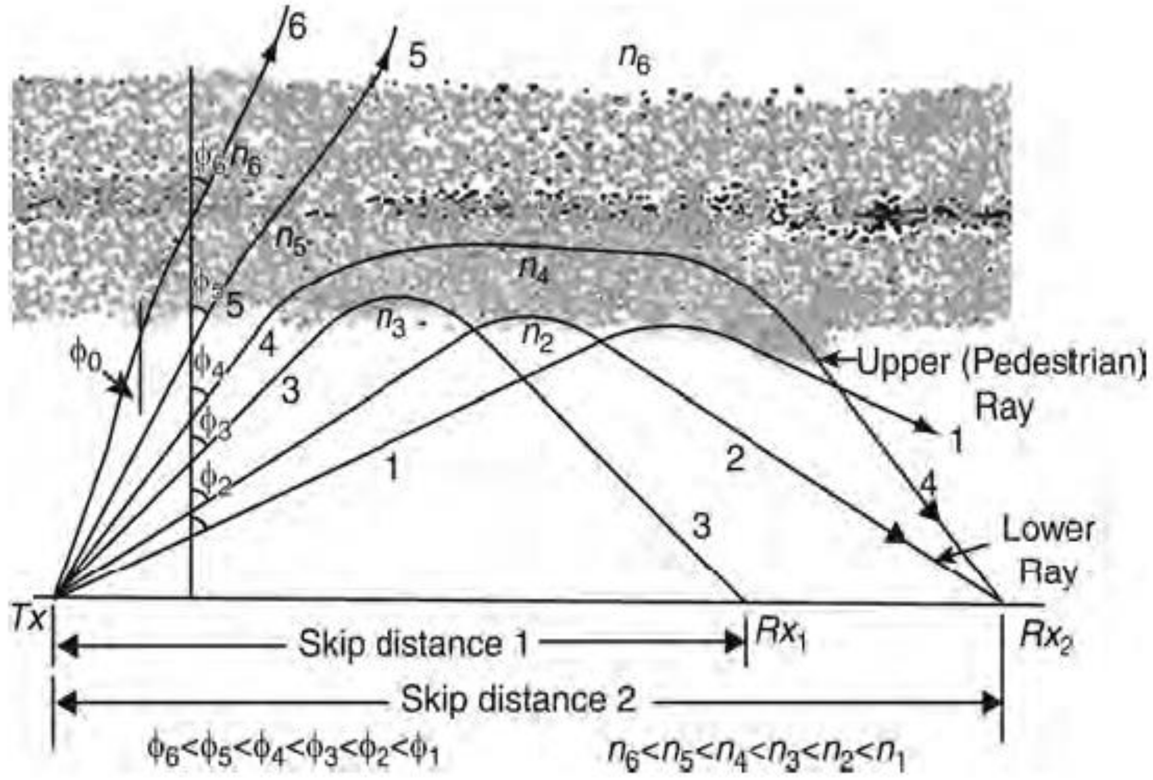
Multi-hop Propagation- Example

- 2 Hop transmission



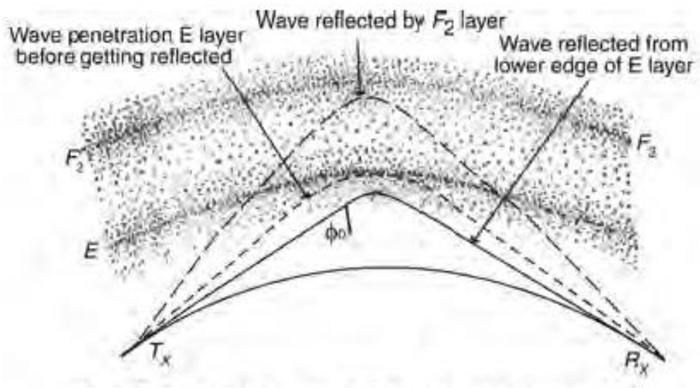
Need of Multi-hop Propagation

- Lower ray(LR) is preferred for communication
- Upper ray(UR) also called Pedersen ray
- The UR is weaker than the lower ray interms of its energy contents

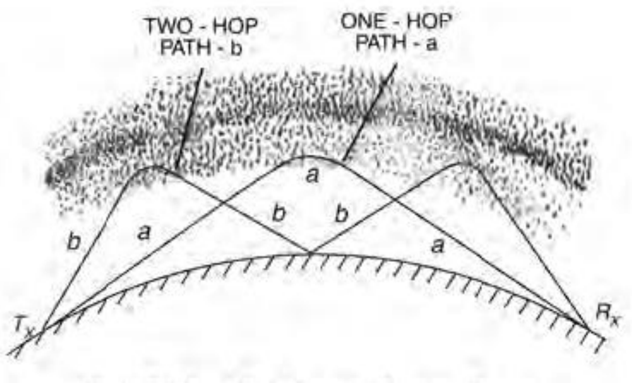


Multi-hop propagation modes :

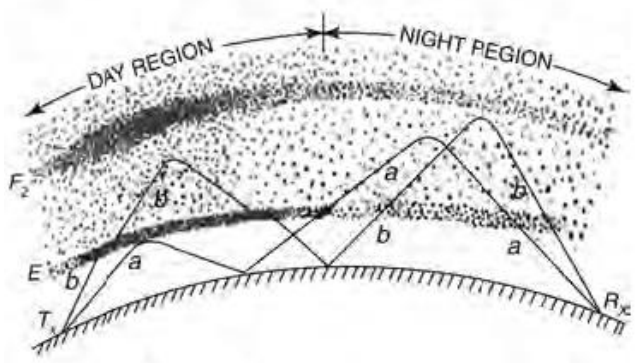
(a) single hop single layer, (b) single hop multi layer,(c) multi hop single layer, and (d) multi hop multi layer systems.



(b) single hop multi layer



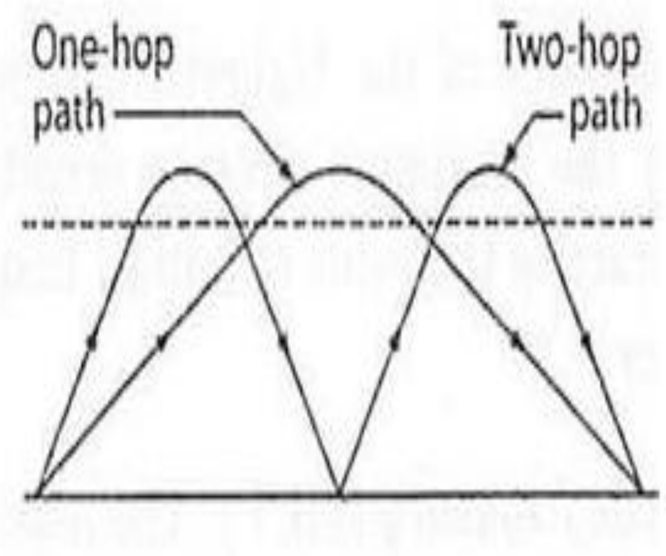
(a) single hop single layer/ 2 hops

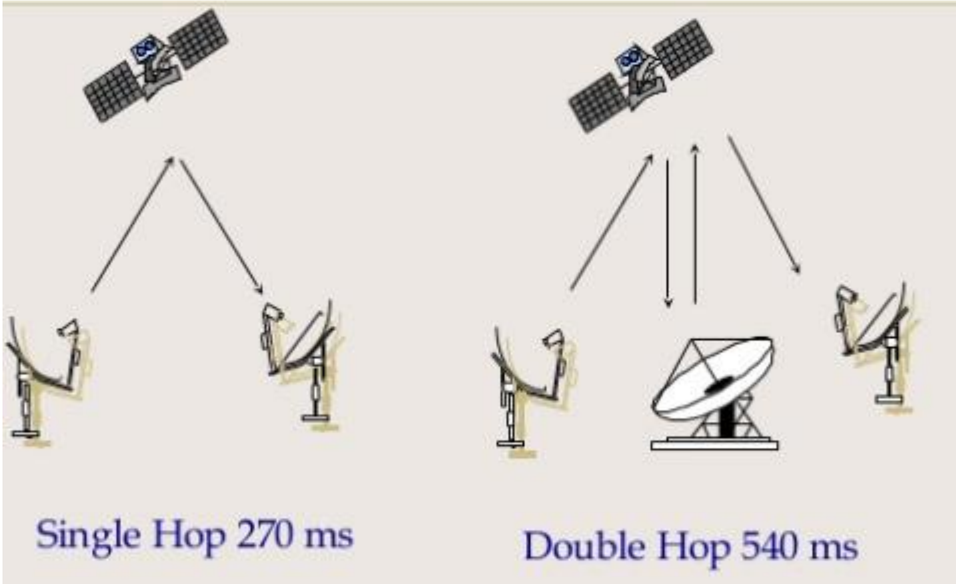


(d) multi hop multi layer systems.

Single Hop vs Multi-hop

- When the distance between the transmitter and receiver is larger than the skip-distance, the wave may follow different single-hop paths. The largest possible single-hop distance corresponds to the ray that leaves the transmitter tangentially to the earth surface.
- The maximum one-hop distance for E layer is about 2000 km, and for F_2 layer it is about 4000 km. Larger distance is possible only by means of two or more hops transmission.
- FIG. shows single and two-hop transmission paths.



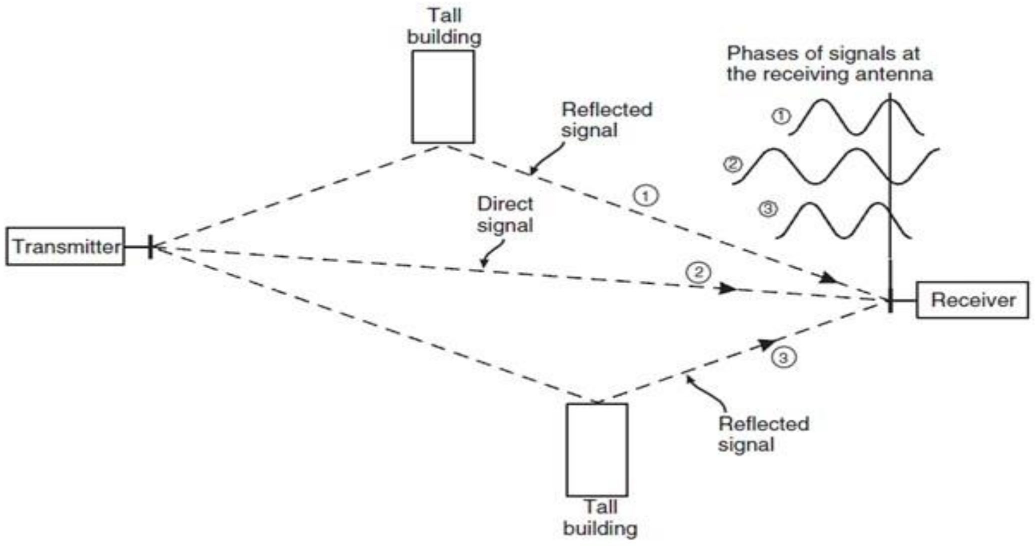


Fading

- Fading is the fluctuation of received signal strength, and this fluctuation may be rapid or slow, may be general or frequency-selective.
- This is due to the fact that signal may arrive the receiver from the transmitter by different paths.

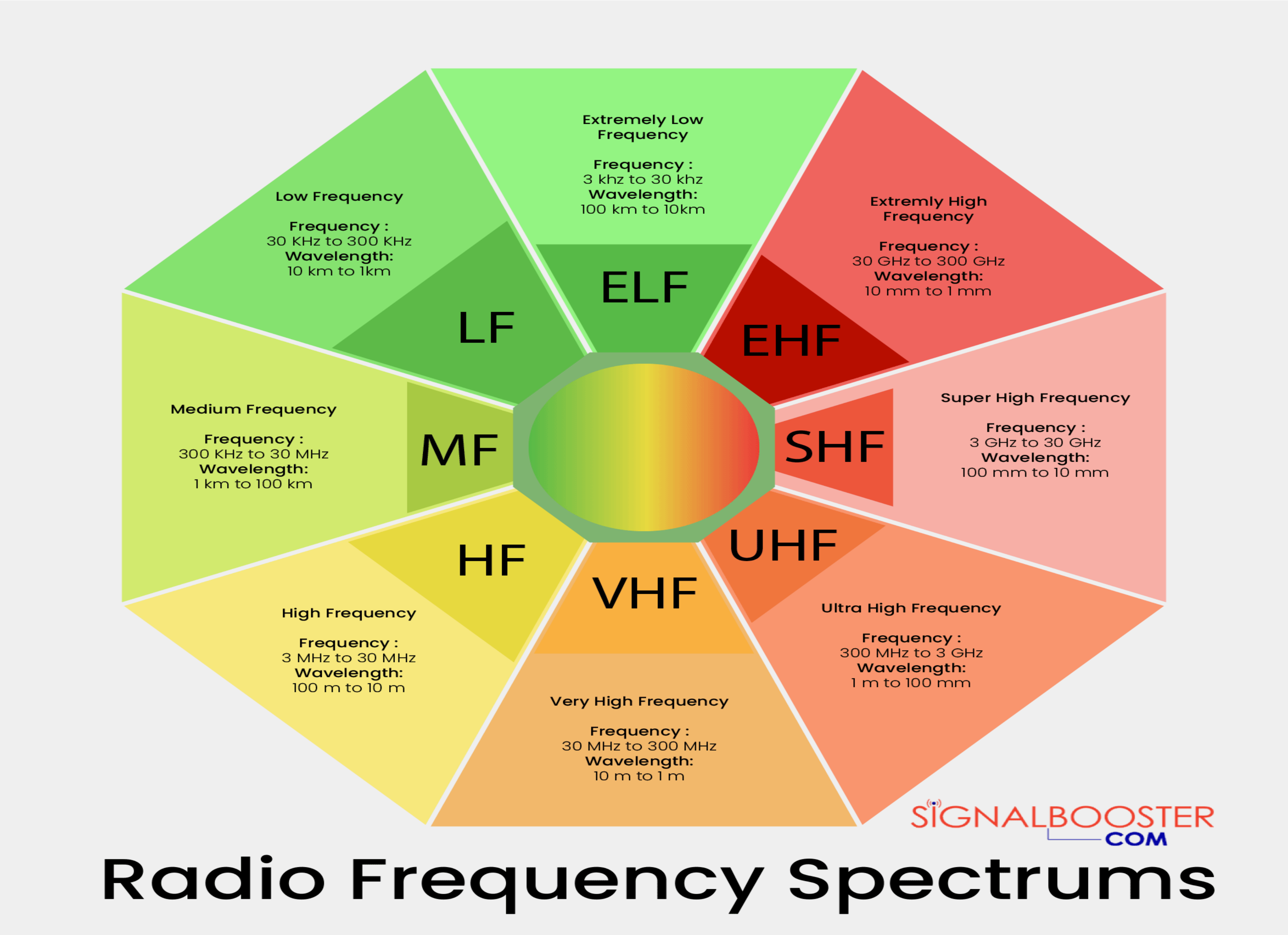
Fading (Cont'd)

- The signal received at any instant is the vector sum of all the waves received, and there will be variation of the resultant due to the variations of the waves of different path because of fluctuations in the layer.
- So fading is occurred due to interference between different rays. Fading may also occur due to in a single ray due to fluctuation of density and height of the layer reflecting the ray.



Wave Characteristics

- Different modes of propagation and Frequency ranges
- ITU – 12 Radio Frequency bands
- Wavelengths of RF bands
- Applications


Extremely Low Frequency
Frequency :
3 khz to 30 khz
Wavelength:
100 km to 10km
ELF
Low Frequency
Frequency :
30 KHz to 300 KHz
Wavelength:
10 km to 1km
LF
Extremly High Frequency
Frequency :
30 GHz to 300 GHz
Wavelength:
10 mm to 1 mm
EHF
Medium Frequency
Frequency :
300 KHz to 30 MHz
Wavelength:
1 km to 100 km
MF
Super High Frequency
Frequency :
3 GHz to 30 GHz
Wavelength:
100 mm to 10 mm
SHF
HF
UHF
VHF
High Frequency
Frequency :
3 MHz to 30 MHz
Wavelength:
100 m to 10 m
Ultra High Frequency
Frequency :
300 MHz to 3 GHz
Wavelength:
1 m to 100 mm
Very High Frequency
Frequency :
30 MHz to 300 MHz
Wavelength:
10 m to 1 m
SIGNALBOOSTER
.COM
Radio Frequency Spectrums

Radio Frequency Spectrums

- Radio wave frequencies range from Extremely Low Frequencies (ELF) 3 kilohertz (kHz) to Extremely High Frequencies (EHF) 300 gigahertz (GHz).
- EHF are often called the millimeter band because its wavelengths range from 1 to 10 mm.
  - Wavelengths in and around this band are called millimeter waves (mmW).
- Worldwide, 5G will use spectrum in the existing 4G LTE frequency range 600 MHz to 3 GHz (Ultra High Frequency, UHF) and even up to 6 GHz, as well as millimeter wave bands 24 to 86 GHz (Super High Frequency to Extremely High Frequency).
- Ultra High Frequency (UHF) spectrum is also being used by some Carriers for 5G.
- UHF band has a frequency range of 300 MHz to 3 GHz. It is already being used since years in many other applications such as TV broadcasting, cordless phones, Wi-Fi, GPS, and Bluetooth.

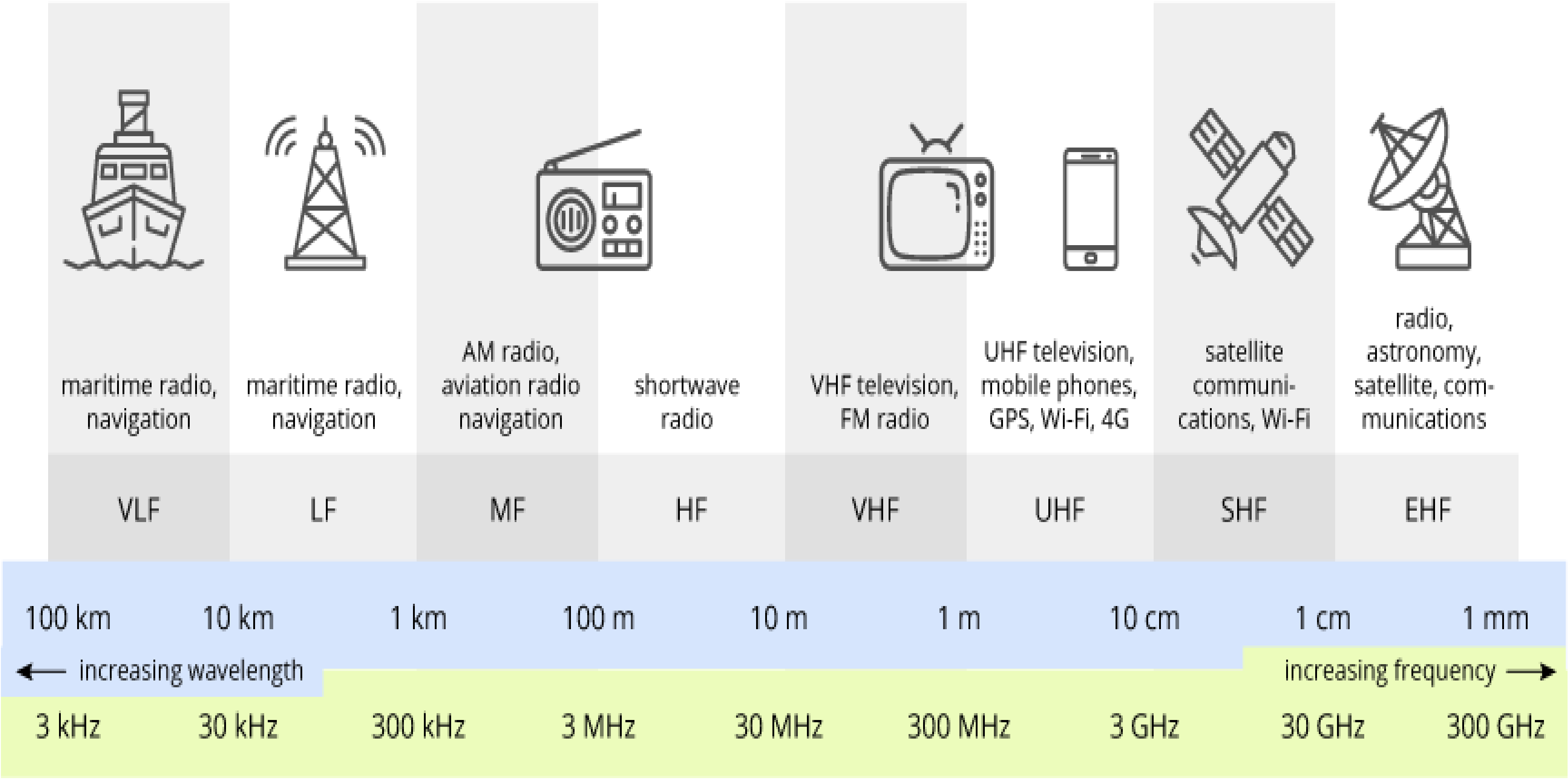
Radio Frequency Bands

- To prevent interference between different users, the generation and transmission of radio frequency bands is strictly regulated by national laws, coordinated by an international body, the International Telecommunication Union (ITU).

  - The ITU is a member of UN development group, coordinates the shared global use of the radio spectrum, promotes international cooperation in assigning satellite orbits, works to improve telecommunication infrastructure in the developing world, and assists in the development and coordination of worldwide technical standards.

- A radio frequency band is a small contiguous section of the radio spectrum frequencies, in which channels are usually used or set aside for use.
- For example, broadcasting, mobile radio, or navigation devices, will be allocated in non-overlapping ranges of frequencies. For each of these bands the ITU has a band plan which dictates how it is to be used and shared, to avoid interference and to set protocol for the compatibility of transmitters and receivers.

RF Bands



maritime radio, navigation
maritime radio, navigation
AM radio, aviation radio navigation
shortwave radio
VHF television, FM radio
UHF television, mobile phones, GPS, Wi-Fi, 4G
satellite communi- cations, Wi-Fi
radio, astronomy, satellite, com- munications
VLF
LF
MF
HF
VHF
UHF
SHF
EHF
100 km
10 km
1 km
100 m
10 m
1 m
10 cm
1 cm
1 mm
increasing wavelength
increasing frequency
3 kHz
30 kHz
300 kHz
3 MHz
30 MHz
300 MHz
3 GHz
30 GHz
300 GHz

RF Bands (Cont'd)

Band name	Abbreviation	ITU band number	Frequency	Wavelength	Example Uses
Extremely low frequency	ELF	1	3–30 Hz	100,000–10,000 km	Communication with submarines
Super low frequency	SLF	2	30–300 Hz	10,000–1,000 km	Communication with submarines
Ultra low frequency	ULF	3	300–3,000 Hz	1,000–100 km	Submarine communication, communication within mines
Very low frequency	VLF	4	3–30 kHz	100–10 km	Navigation, time signals, submarine communication, wireless heart rate monitors, geophysics
Low frequency	LF	5	30–300 kHz	10–1 km	Navigation, time signals, AM longwave broadcasting (Europe and parts of Asia), RFID, amateur radio
Medium frequency	MF	6	300–3,000 kHz	1,000–100 m	AM (medium-wave) broadcasts, amateur radio, avalanche beacons

RF Bands (Cont'd)

High frequency	HF	7	3–30 MHz	100–10 m	Shortwave broadcasts, citizens band radio, amateur radio and over-the-horizon aviation communications, RFID, over-the-horizon radar, automatic link establishment (ALE) / near-vertical incidence skywave (NVIS) radio communications, marine and mobile radio telephony
Very high frequency	VHF	8	30–300 MHz	10–1 m	FM, television broadcasts, line-of-sight ground-to-aircraft and aircraft-to-aircraft communications, land mobile and maritime mobile communications, amateur radio, weather radio
Ultra high frequency	UHF	9	300–3,000 MHz	1–0.1 m	Television broadcasts, microwave oven, microwave devices/communications, radio astronomy, mobile phones, wireless LAN, Bluetooth, ZigBee, GPS and two-way radios such as land mobile, FRS and GMRS radios, amateur radio, satellite radio, Remote control Systems, ADSB
Super high frequency	SHF	10	3–30 GHz	100–10 mm	Radio astronomy, microwave devices/communications, wireless LAN, DSRC, most modern radars, communications satellites, cable and satellite television broadcasting, DBS, amateur radio, satellite radio
Extremely high frequency	EHF	11	30–300 GHz	10–1 mm	Radio astronomy, high-frequency microwave radio relay, microwave remote sensing, amateur radio, directed-energy weapon, millimeter wave scanner, wireless LAN (802.11ad)
Terahertz or Tremendously high frequency	THz or THF	12	300–3,000 GHz	1–0.1 mm	Experimental medical imaging to replace X-rays, ultrafast molecular dynamics, condensed-matter physics, terahertz time-domain spectroscopy, terahertz computing/communications, remote sensing

VLF/ ELF Wave Propagation

- Range of VLF spreads over 3 kHz – 30 kHz.
- limits the bandwidth and hence the information contents and thus cannot be used for conventional communication.
- Applications :

  Submarine and mine 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 kilometres 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.
- 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.

LF Wave Propagation

- 30KHz-300KHz
- 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.
- For distances greater than 1000 km, mostly the sky wave mode is used.
- Fading in the normal sense does not occur.

MF Wave Propagation

- 300KHz -3000KHz
- 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.

HF wave propagation

- 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.
- 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 & Sub-millimetric and Optical Waves

❑ 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

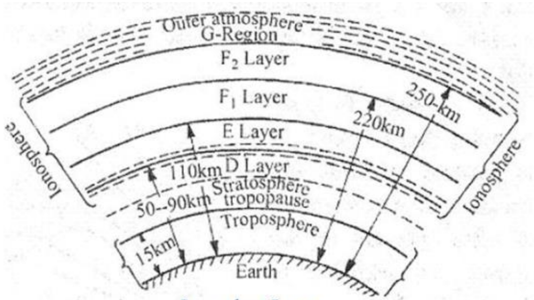
- Can propagate only as ground and direct wave.
- Atmospheric refraction causes bending of path.
- Heavy rain and dense fog will completely stop propagation.
- Well suited for space communication outside the troposphere.

Conclusions

- ✓Basics of propagation & Different Modes of propagation
- ✓Structure of ionosphere, Refraction and Reflection of sky wave by ionosphere.
- ✓Ray path, Critical frequency, MUF, LUF , OF, Virtual Height and skip distance
- ✓Relation between MUF & Skip distance for Flat Earth's Surface
- ✓Relation between MUF & Skip distance for Curved Earth's Surface
- ✓Ionospheric Abnormalities, Impact of solar activity
- ✓Multi-Hop propagation Wave characteristics

Conclusions (Cont'd)

- Radio wave signals are mainly used for communication purpose.
- Transmission of broadcast signals to the communication with aircrafts, every mode of communication and transportation is dependent on signals transmitted in radio wave frequency.
- The main objective of radio wave propagation is to transmit signals securely without any error.
- It is concluded that Radio wave propagation is an important branch of communication studies.



Ionosphere Layers

Conclusions(Cont'd)

- Long distance communication between two points on the earth is achieved through reflection of electromagnetic waves by ionosphere.
- Sky wave propagation takes place up to frequency of about 30 MHz. Above this frequency, EM waves essentially propagate as space waves.
- The reflections from the ionosphere are actually produced by refraction as the wave propagates through the ionosphere.
- The ionosphere is a concentrated region highly charged ions and electrons that collective form an ionized gas or plasma.
- The amount of refraction that occurs depends on three main factors:
    - the density of ionization of the layer
    - the frequency of the radio wave
    - the angle at which the wave enters the layer

Conclusion(Cont'd)

- Frequencies including the CF,MUF,LUF,OWF are all of great importance when determining which frequencies will provide the best performance for a short wave radio, HF radio communications link.
- The highest frequency, which is reflected from the ionosphere to the receiver is called as **critical frequency, fc**.
- In radio transmission **maximum usable frequency,MUF** is the highest radio frequency that can be used for transmission between two points via reflection from the ionosphere (sky wave or "skip" propagation) at a specified time, independent of transmitter power.
- The **lowest usable frequency , LUF** is defined as the **frequency at below which the signal falls below the minimum strength required for satisfactory reception.**
- The frequency, which is being used mostly for a particular transmission and which has been predicted to be used over a particular period of time, over a path, is termed as **optimum working frequency ,OWF.**
- MUF is a median frequency, defined as the highest frequency at which skywave communication is possible 50% of the days in a month, as opposed to the LUF which is the frequency at which communication is possible 90% of the days, and the Frequency of optimum transmission (FOT).

Conclusion(Cont'd)

For shorter distances, the earth can be assumed to be flat. In the figure, h is the height of the ionospheric layer, d is the skip distance, θ_i is the angle of incidence and θ_r is the angle of reflection.

- Critical Frequency and Maximum Usable Frequency

$$f_C = 9\sqrt{N_{max}}$$

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

- The relationship between the skip distance and MUF,

$$f_{MUF} = f_C\sqrt{\frac{d^2}{4h^2}+1} \quad \text{----→ (13)}$$

$$d_{skip} = 2h\left[\left(\frac{f_{MUF}}{f_C}\right)^2 - 1\right]^{1/2} \quad \text{----→ (15)}$$

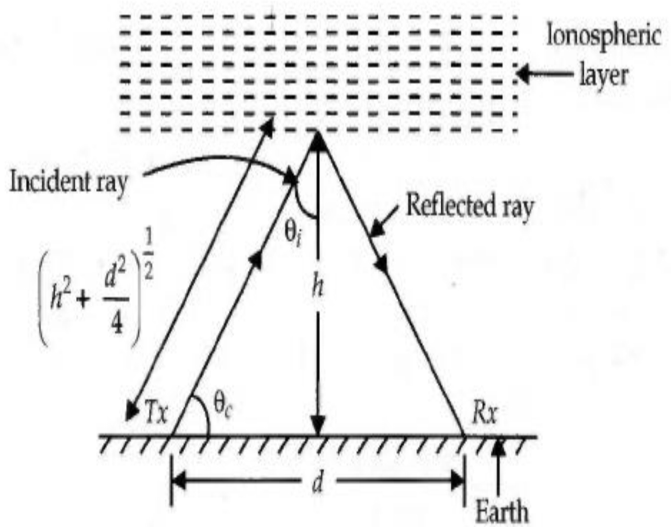


Fig. illustrates the ionized layer which is assumed to be thin with sharp ionization density gradient so as to obtain mirror like reflections.

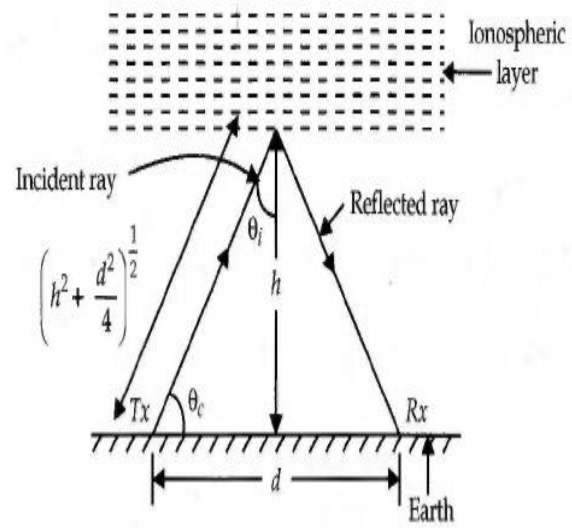
Conclusion(Cont'd)

The Relationship between MUF and skip distance

(a) Flat Earth case

$$f_{MUF} = f_C\sqrt{\frac{d^2}{4h^2}+1}$$

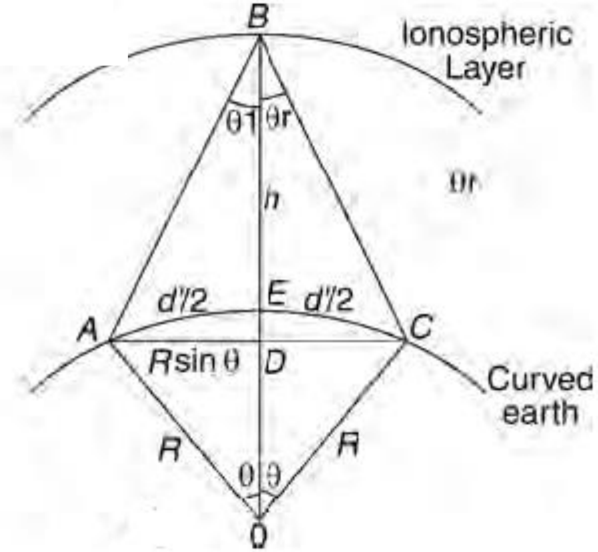
$$d_{skip} = 2h\left[\left(\frac{f_{MUF}}{f_C}\right)^2 - 1\right]^{1/2}$$



(b) Curved Earth case

$$f_{MUF} = f_C\left(1+\frac{d'^2/4}{\left(h+d'^2/8R\right)^2}\right)^{1/2}$$

$$d' = 2\left(h+\frac{d'^2}{8R}\right)\left[\left(\frac{f_{MUF}}{f_C}\right)^2-1\right]^{1/2}$$

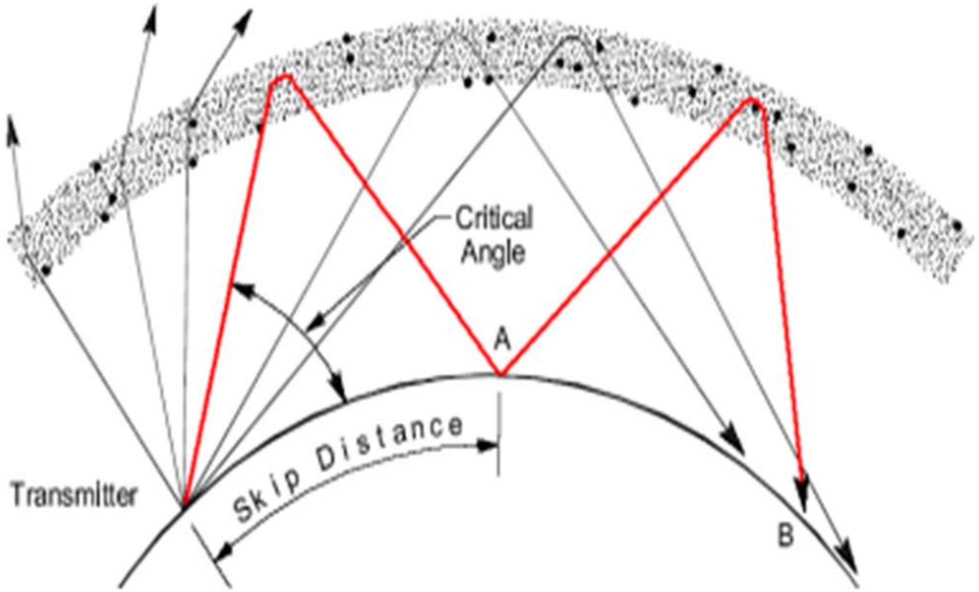


Conclusions (Cont'd)

- Ionospheric variations :
  - Normal
  - Abnormal
- To elaborate, the influence of solar activity can be summarized under different captions as given below.
  - Ionospheric Stroms
  - Sudden Ionospheric Disturbances (SID)
  - Sunspot cycle
  - Fading
  - Whistlers
  - Tides and winds

Conclusions (Cont'd)

- Single Hop vs Multi-Hop Propagation
- Need of Multi-Hop Propagation
- Fading



Recorded Video Lectures

LESSON1 Basics of propagation: Definition and General Different Modes of propagation

https://www.youtube.com/watch?v=wCS2O08ObQg&t=409s

LESSON 2 Structure of ionosphere & Refraction and Reflection of sky wave by ionosphere.

https://www.youtube.com/watch?v=8viNeTGoTd0&t=10s

LESSON 3 Ray path, Critical frequency, MUF, LUF , OF, Virtual Height and skip distance

https://www.youtube.com/watch?v=9BZuneS-OmE&t=29s

LESSON 4 Relation between MUF & Skip distance for flat Earth
https://www.youtube.com/watch?v=HBxWVkkh7eI&t=696s

LESSON 5 Ionospheric abnormalities, Impact of solar activity
https://www.youtube.com/watch?v=2MwVHhCW4JY&t=10s

LESSON 6 Multi-Hop propagation https://www.youtube.com/watch?v=vJrT08dtYzo

LESSON 7 wave characteristics https://www.youtube.com/watch?v=-i5aUdEM3J0&t=383s

LESSON 8 Relationship between MUF & skip distance for curved Earth
https://www.youtube.com/watch?v=CJNVUk7mOvg

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- http://www.tpub.com/neets/book10/40i.htm
- https://en.wikipedia.org/wiki/Maximum_usable_frequency

THANK YOU