Radio wave propagation (5p): Radio frequencies and their primary mode of propagation such as HF, VHF, UHF and Microwave. Ground waves, Space waves, Surface waves and Tropospheric waves, Ionospheric waves, Critical frequency, Maximum usable frequency, Skip distance, Virtual height, Radio noise of terrestrial and extra-terrestrial origin. Multiple fading of radio waves.

Radio frequencies

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

Propagation of Waves

The process of communication involves the transmission of information from one location to another. Modulation is used to encode the information onto a carrier wave, and may involve analog or digital methods. It is only the characteristics of the carrier wave which determine how the signal will propagate over any significant distance. Following describes the different ways that electromagnetic waves propagate.

Basics

An electromagnetic wave is created by a local disturbance in the electric and magnetic fields. From its origin, the wave will propagate outwards in all directions. If the medium in which it is propagating (air for example) is the same everywhere, the wave will spread out uniformly in all directions.

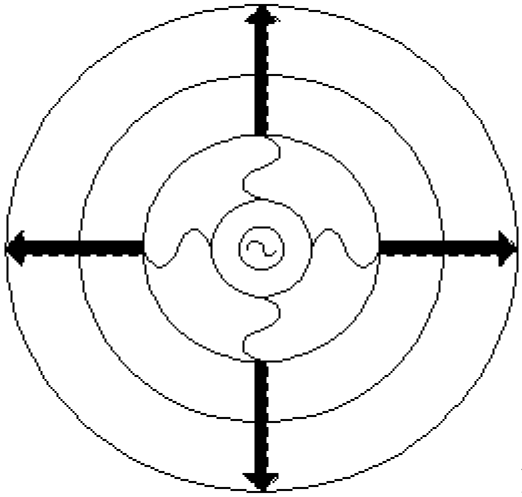


Fig1

A **plane wave** is an idealization that allows one to think of the entire wave traveling in a single direction, instead of spreading out in all directions.

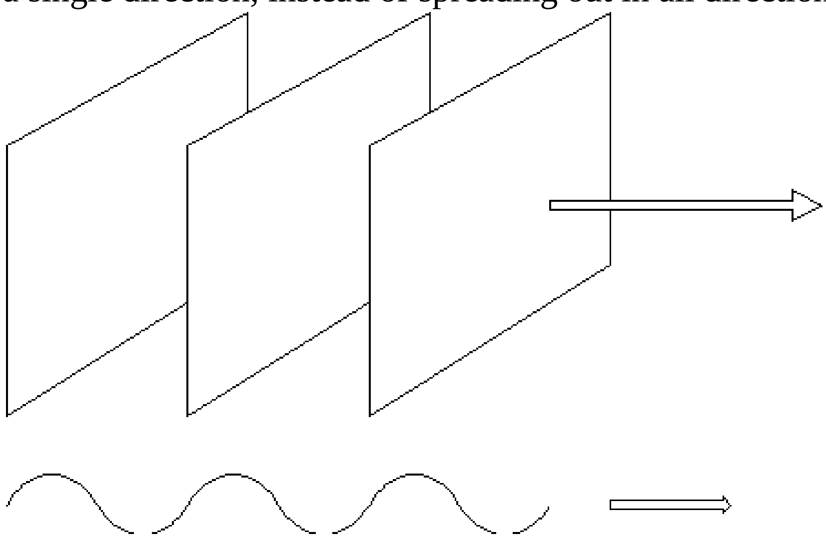


Figure 2

Electromagnetic waves propagate at the speed of light in a vacuum. In other mediums, like air or glass, the speed of propagation is slower. If the speed of light in a vacuum is given the symbol c_0, and the speed in some medium is c, we can define the index of refraction, n as:

$n = c_0 / c$

Here's a short table of the indices of refraction for common media:

substance	index of refraction
vacuum	1
air	1.0003
water	1.33
glass	1.55

Reflection

When a plane wave encounters a change in medium, some or all of it may propagate into the new medium or be reflected from it. The part that enters the new medium is called the transmitted portion and the other the reflected portion. The part which is reflected has a very simple rule governing its behavior. Make the following construction:

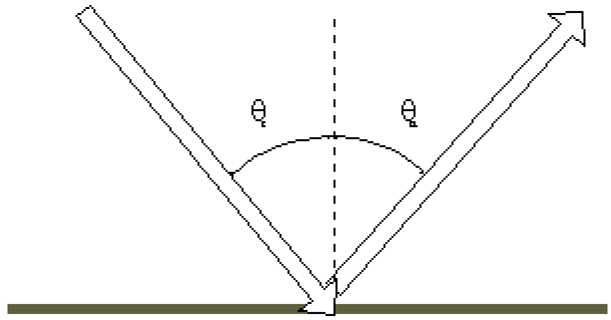


Figure 3

Angle of Incidence = the angle between the direction of propagation and a line perpendicular to the boundary, on the same side of the surface.

Angle of Reflection = the angle between the direction of propagation of the reflected wave and a line perpendicular to the boundary, also on the same side of the surface. Then the rule for reflection is simply stated as:

The angle of reflection = The angle of incidence

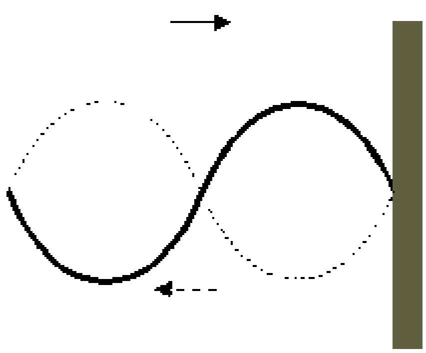


Figure 4

If the incident medium has a lower index of refraction then the reflected wave has a 180^0 phase shift upon reflection. Conversely, if the incident medium has a larger index of refraction the reflected wave has no phase shift.

Refraction

When the wave enters the new medium, the speed of propagation will change. In order to match the incident and transmitted wave at the boundary, the transmitted wave will change its direction of propagation. For example, if the new medium has a higher index of refraction, which means the speed of propagation is lower, the wavelength will become shorter (frequency must stay the same because of the boundary conditions). For the transmitted wave to match the incident wave at the boundary, the direction of propagation of the transmitted wave must be closer to perpendicular.

The relationship between the angles and indices of refraction is given by *Snell's Law*:

$$n_i \sin\theta_I = n_t \sin\theta_t$$

When the direction of propagation changes, the wave is said to refract. It is most useful to know in which direction the wave will refract, not necessarily by how much.

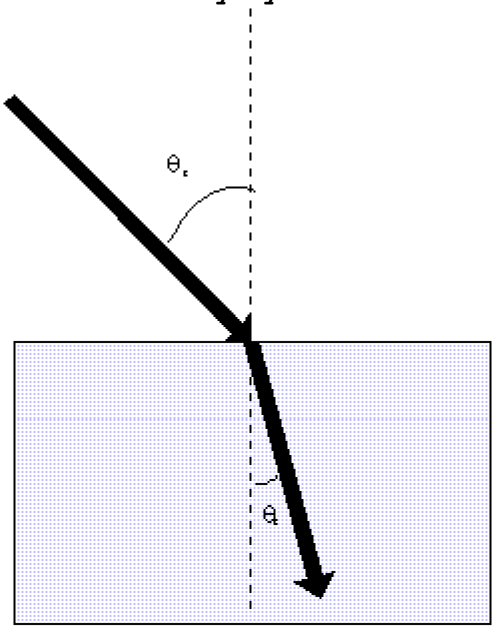


Figure 5

The transmitted wave will bend more towards the perpendicular when entering a medium with higher index of refraction (slower speed of propagation). Example: Why a pool is deeper than it looks.

When you look into a pool, the light from the bottom is refracted away from the perpendicular, because the index of refraction in air is less than in water. To the observer at the side of the pool, the light appears to come from a shallower depth. For the same reason, when you look at objects underwater through a mask, they will appear to be larger than they really are. The light from the object is spread outwards at the water-air interface of your mask. To you it will appear the object is closer or larger.

Interference

All electromagnetic waves can be superimposed upon each other without limit. The electric and magnetic fields simply add at each point. If two waves with the same frequency are combined there will be a constant interference pattern caused by their superposition. Interference can either be constructive, meaning the strength increases as result, or destructive where the strength is reduced.

The amount of interference depends of the phase difference at a particular point. It can be shown that constructive interference occurs for phase differences of 0-120^0, and 240-360^0. Thus destructive interference occurs from 120-240^0. For two identical waves, no phase shift results in total constructive interference, where the strength is maximum and 180^0 phase shift will create total destructive interference (no signal at all).

---

https://www.youtube.com/watch?v=nnzVk9Kzq8M
https://www.youtube.com/watch?v=Xz7l_gedRdg

Diffraction

Recall that the idealized plane wave is actually infinite in extent. If this wave passes through an opening, called an aperture, it will diffract, or spread out, from the opening. The degree to which the cropped wave will spread out depends on the size of the aperture relative to the wavelength. In the extreme case where the aperture is very large compared to the wavelength, the wave will see no effect and will not diffract at all. At the other extreme, if the opening is very small, the wave will behave as if it were at its origin and spread out uniformly in all directions from the aperture. In between, there will be some degree of diffraction.

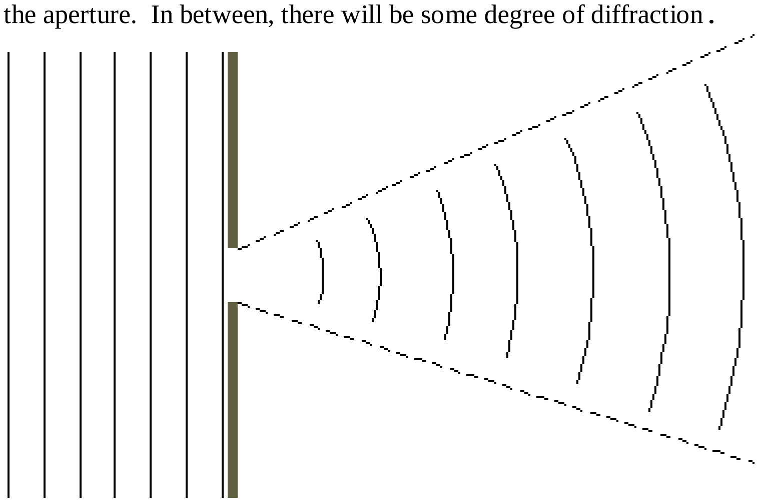


Figure 6

First consider a circular aperture. If a wave with wavelength λ encounters an opening with diameter D, the amount of diffraction as measured by the angle, θ ,at which the new wave diverges from the opening, measured from edge to edge, will be approximated by

$$\theta = \lambda / D$$

Modes of Propagation in Air

Line of Sight (LOS) Propagation

Among the modes of propagation, this line-of-sight propagation is the one, which we commonly notice. In the **line-of-sight communication**, as the name implies, the wave travels a minimum distance of sight. Which means it travels to the distance up to which a naked eye can see. Now what happens after that? We need to employ an amplifier cum transmitter here to amplify the signal and transmit again.

This is better understood with the help of the following diagram.

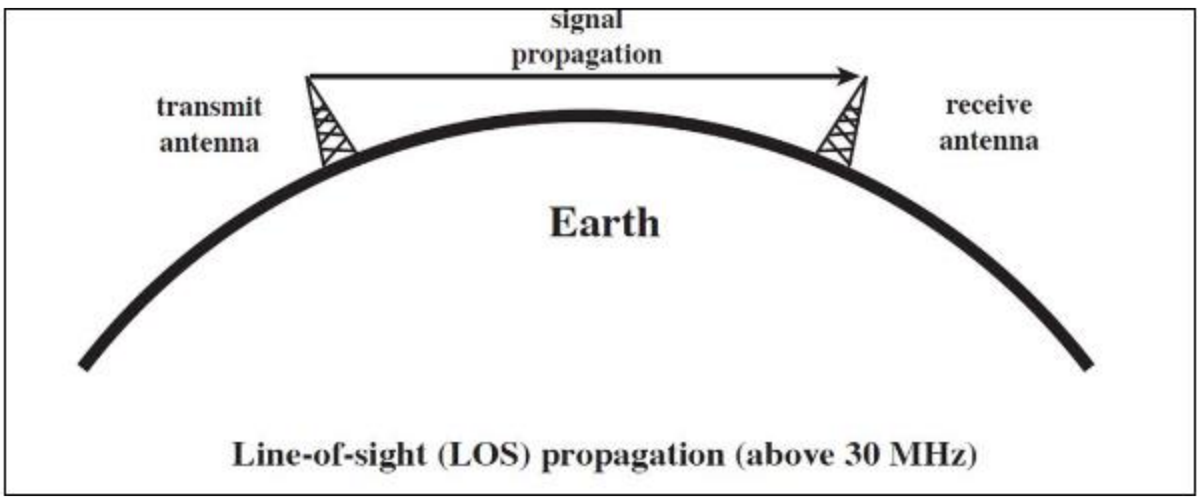


Figure 7

The figure depicts this mode of propagation very clearly. The line-of-sight propagation will not be smooth if there occurs any obstacle in its transmission path. As the signal can travel only to lesser distances in this mode, this transmission is used for **infrared** or **microwave transmissions**.

In the VHF band and up, the propagation tends to straighten out into line-of-sight(LOS)waves. However the frequency is still low enough for some significant effects.

1. **Ionospheric scatter**. The signal is reflected by the E-region and scattered in all directions. Some energy makes it back to the earth's surface. This seems to be most effective in the range of 600-1000 miles.

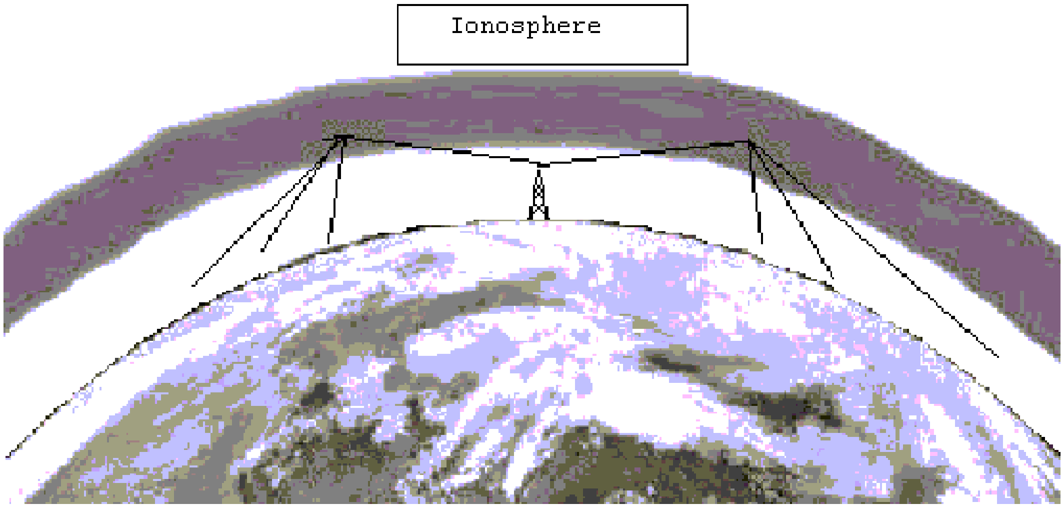


Figure 8

2. **Tropospheric scatter**. Again, the wave is scattered, but this time, by the air itself. This can be visualized like light scattering from fog. This is a strong function of the weather but can produce good performance at ranges under 400 miles.

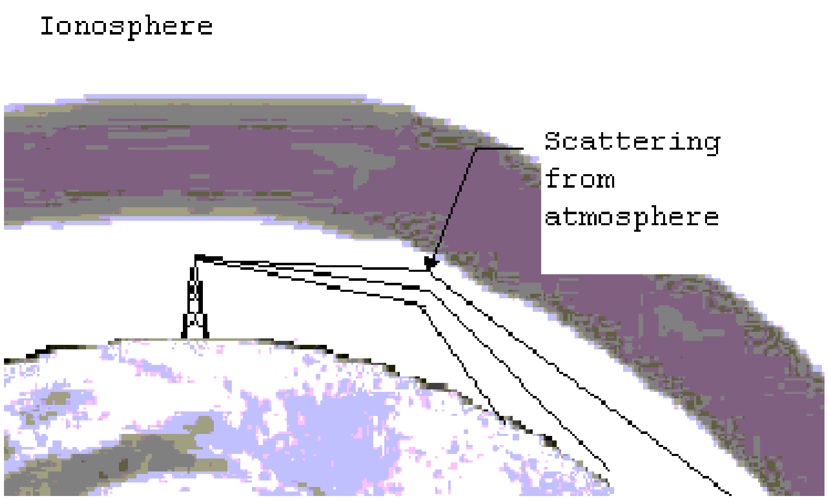


Figure 9

3. **Tropospheric ducting**. The wave travels slower in cold dense air than in warm air. Whenever inversion conditions exist, the wave is naturally bent back to the ground. When the refraction matches the curvature of the earth, long ranges can be achieved. This ducting occurs to some extend always and improves the range over true the line-of-sight by about 10 %.
4. **Diffraction**. When the wave is block by a large object, like a mountain, is can diffract around the object and give coverage where no line-of-sight exists.

Beyond VHF, all the propagation is line-of-sight. Communications are limited by the visual horizon. The line-of-sight range can be found from the height of the transmitting and receiving antennas by:

$$R = \sqrt{13h_t} + \sqrt{13h_R}$$

where h_t and h_r are the heights of the antennas in meters, and R will be in km (the conversion factor is already taken into account in the factor 13).

Ground Wave

Ground wave propagation of the wave follows the contour of earth. Such a wave is called as **direct wave**. The wave sometimes bends due to the Earth's magnetic field and gets reflected to the receiver. Such a wave can be termed as **reflected wave**.

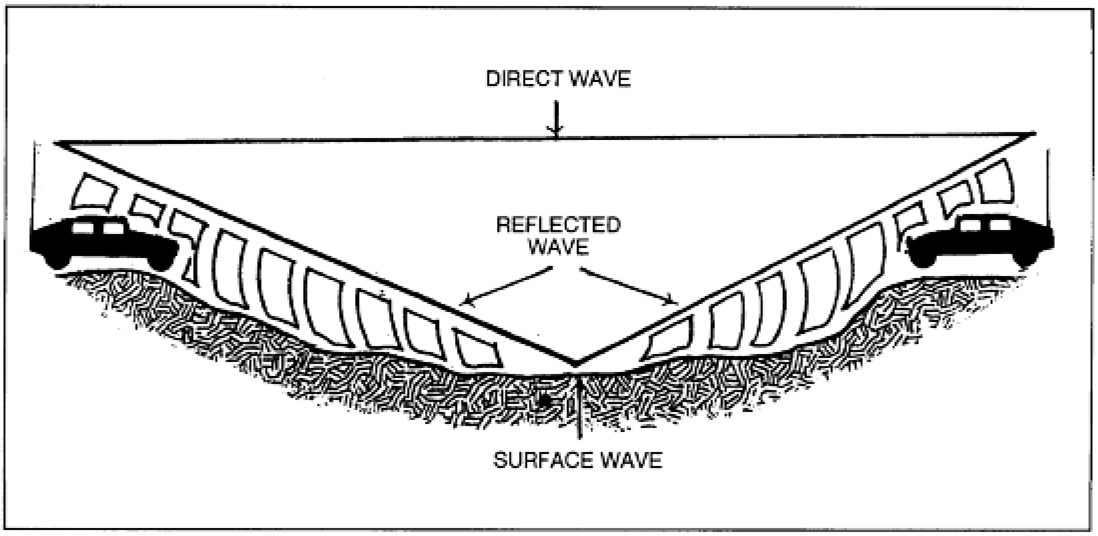


Figure D-2. Components of ground wave.

Figure 10

The above figure depicts ground wave propagation. The wave when propagates through the Earth's atmosphere is known as **ground wave**. The direct wave and reflected wave together contribute the signal at the receiver station. When the wave finally reaches the receiver, the lags are cancelled out. In addition, the signal is filtered to avoid distortion and amplified for clear output.

Radio waves in the VLF band propagate in a ground, or surface wave.
https://www.youtube.com/watch?v=V4zuFsME6pg

Sky Waves

Radio waves in the LF and MF ranges may also propagate as ground waves, but suffer significant losses, or are attenuated, particularly at higher frequencies. But as the ground wave mode fades out, a new mode develops: the sky wave. Sky waves are reflections from the ionosphere. While the wave is in the ionosphere, it is strongly bent, or refracted, ultimately back to the ground. From a long distance away this appears as a reflection. Long ranges are possible in this mode also, up to hundreds of miles. Sky waves in this frequency band are usually only possible at night, when the concentration of ions is not too great since the ionosphere also tends to attenuate the signal. However, at night, there are just enough ions to reflect the wave but not reduce its power too much.

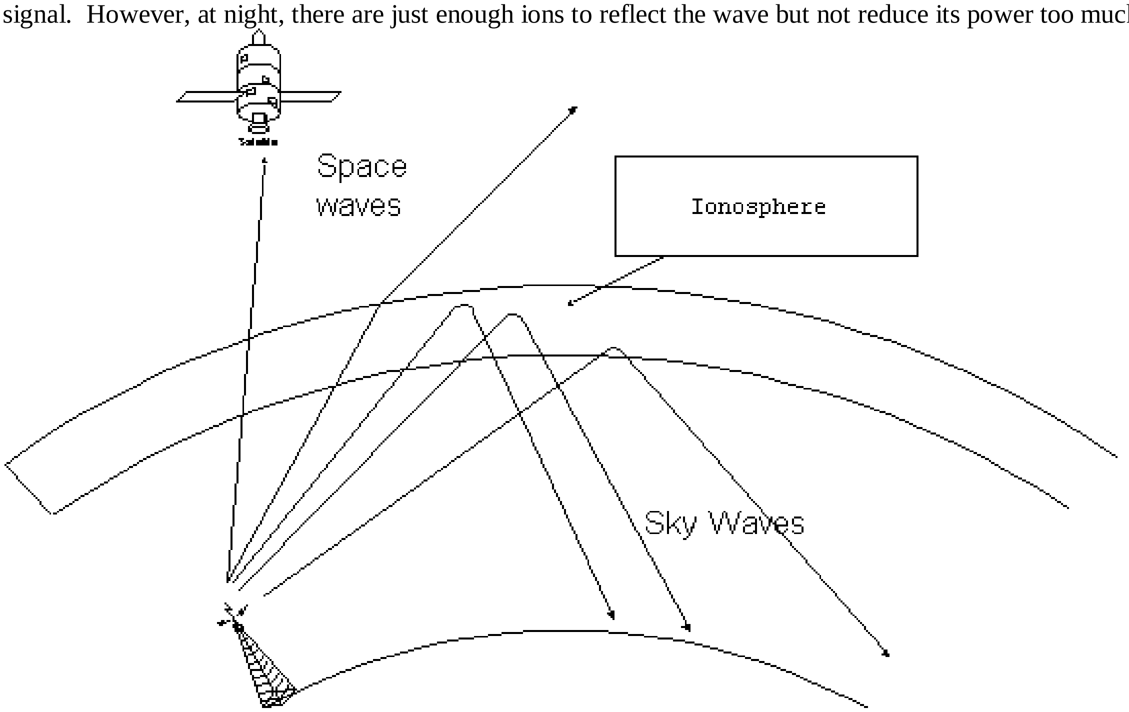


Figure 11

The HF band operates almost exclusively with sky waves. The higher frequencies have less attenuation and less refraction in the ionosphere as compared to MF. At the high end, the waves completely penetrate the ionosphere and become space waves. At the low end, they are always reflected. The HF band operates with both these effects almost all of the time. The characteristics of the sky wave propagation depend on the conditions in the ionosphere which in turn are dependent on the activity of the sun. The ionosphere has several well-defined regions in altitude.

https://www.youtube.com/watch?v=voh5UcC5wVM

Critical Frequency

https://www.youtube.com/watch?v=VqgcHBtYorM

As we increase the frequency of the transmitted signal at vertical incidence, the wave is returned to earth from successively higher ionospheric layers. As the increase in frequency continues, we reach a frequency that will penetrates the F2 layer and won't return to earth. The highest frequency at which a vertical signal will be returned to earth is known as the *critical frequency*. Frequencies higher than this critical frequency pass into space. Since the critical frequency increases with altitude, a signal that has passed through the E layer might be returned from the F1 or F2 layer. The critical frequency also varies, for a given layer, at different locations on the earth's surface. Generally, it's higher near the equator, where more of the sun's radiation is intercepted by the earth's atmosphere.

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. This is reflected back and can be received by a receiver on the same site as the transmitter. The pulse may be reflected back to earth, and the time measured to give an indication of the height of the layer. As the frequency is increased a point is reached where the signal will pass right through the layer, and on to the next one, or into outer space. The frequency at which this occurs is called the critical frequency.

The equipment used to measure the critical frequency is called an ionosonde. In many respects it resembles a small radar set, but for the HF bands. Using these sets a plot of the reflections against frequency can be generated. This will give an indication of the state of the ionosphere for that area of the world.

The critical frequency of a layer is the highest frequency that will be returned at vertical incidence; at larger incidence angles higher frequencies can be returned but, the penalty is a zone out from the transmitter, known as the skip distance, within which a signal cannot be received. Nevertheless, it is useful now to determine an expression for the highest frequency for return at a given angle of incidence: that is called the maximum usable frequency (MUF).

Maximum Usable Frequency, MUF

Maximum usable frequency (MUF). The MUF is the highest frequency that allows reliable long-range HF radio communication between two points by ionospheric refraction. The highest frequency that can be refracted depends on the angle of incidence, and hence, for a given layer height, on the horizontal length of the hop. The maximum frequency that can be refracted back for a given transmission path is the MUF for that path. The MUF is closely related to the critical frequency. Like the critical frequency, it changes with the time of day, season, solar activity, and geographic location. There is a range of usable frequencies, between the MUF and the lowest usable frequency (LUF), that needs to be predicted for operator use. The MUF and LUF vary with solar activity, season, and time of day.

When a signal is transmitted using HF propagation, over a given path there is a maximum frequency that can be used. This result from the fact that as the signal frequency increases it will pass through more layers and eventually travelling into outer space. As it passes through one layer it may be that communication is lost because the signal then propagates over a greater distance than is required. Also when the signal passes through all the layers communication will be lost.

It is possible to calculate the relationship more exactly:

$$MUF = Cf/\cos\theta$$

Where:

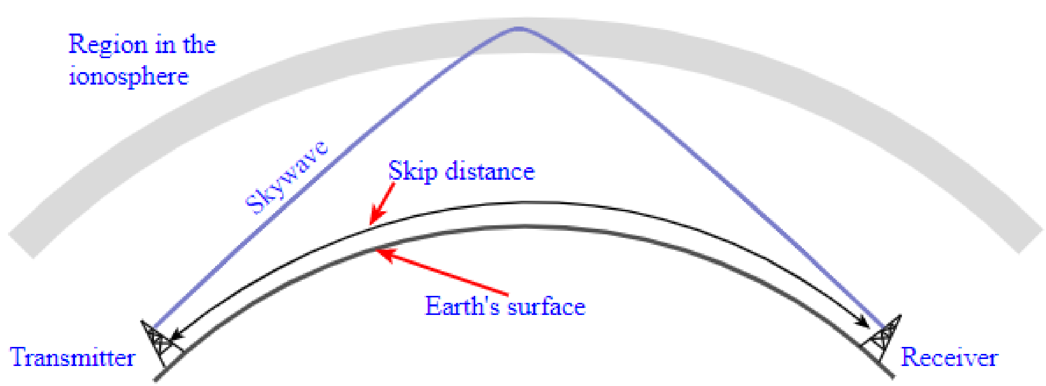
MUF=Maximum Usable Frequency
Cf=critical frequency
θ = the angle of incidence.

The factor sec θ is called the MUF factor and it is a function of the path length if the height layer is known. By using typical figures for the heights of the different ionospheric regions the factors may be determined.

Skip distance

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.

The signals leave the antenna and travel away from it, eventually reaching the ionosphere. Normally they will leave the earth at an angle called the angle of radiation. Whether it is low, i.e. almost parallel to the Earth, or high, i.e. at a high angle upwards, they will reach the ionosphere at some point.



Skip distance

Figure 12

Virtual height

https://www.youtube.com/watch?v=C9gNQFw1-Vc

The point of the ionosphere from which a radio wave appears to have been refracted is called the *virtual height* of the ionosphere. Thus, virtual height is the altitude that refraction occurs. (See point **h** in figure 13.)

Since the strength of solar radiation varies with season and time of day the layers show considerable changes with time. Note that the altitudes of the layers are described as virtual heights which can be quite different from their actual heights.

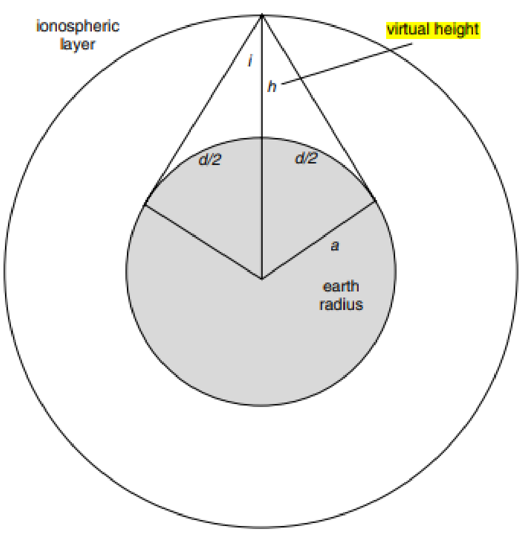
Thus when trying to establish the height of an ionospheric layer using the delay between transmission and reception of a pulse, the height will be overestimated when assuming that the signal travels at the speed of light; that is why it is referred to as virtual height.

Figure 13 shows the geometry of sky wave propagation, in which the limitations imposed by earth curvature are evident. It is readily shown that

$$\theta = \cos^{-1}\frac{a}{a+h}$$

so that

$$d = 2a\cos^{-1}\frac{a}{a+h}$$



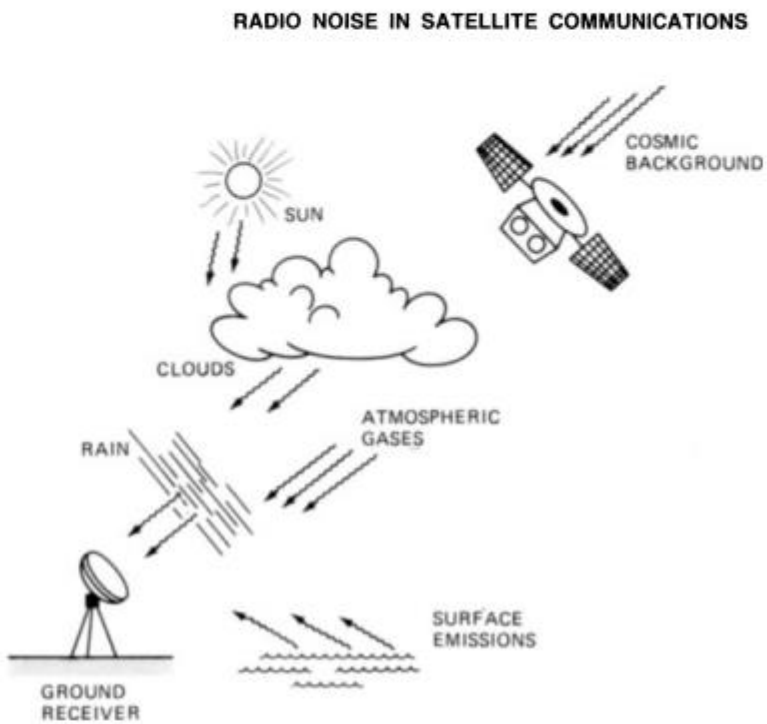
The path of the sky wave at maximum range

Figure 13

Radio noise

There are several natural and man-made sources of unwanted external noise which can be introduced in the radiowave transmission of a space communications link. Any natural absorbing medium in the atmosphere which interacts with a radiowave will not only produce a signal amplitude reduction (attenuation), but will also be a source of thermal noise power radiation. The noise associated with these sources, referred to as radio noise, or sky noise, will directly add to the system noise through an increase in the antenna temperature of the receiver.

Radio noise is emitted by all matter, both terrestrial and extraterrestrial. Terrestrial sources are both natural, such as gaseous atmospheric constituents (oxygen and water vapor), and hydrometeors (clouds and rain), and man-made, such as emission from electric devices and from other communications systems.



Natural sources of radio noise on the downlink of a space communications link.

Figure 14

Multiple fading of radio waves.

https://www.youtube.com/watch?v=vE2PjzLB_6U

Multipath fading occurs when signals reach a receiver via many paths & their relative strengths & phases change**.** Multipath fading affects most forms of radio communications links in one form or another.

Multipath fading can affect signals on frequencies from the LF portion of the spectrum and below right up into the microwave portion of the spectrum.

Multipath fading occurs in any environment where there is multipath propagation and the paths change for some reason. This will change not only their relative strengths but also their phases, as the path lengths will change.

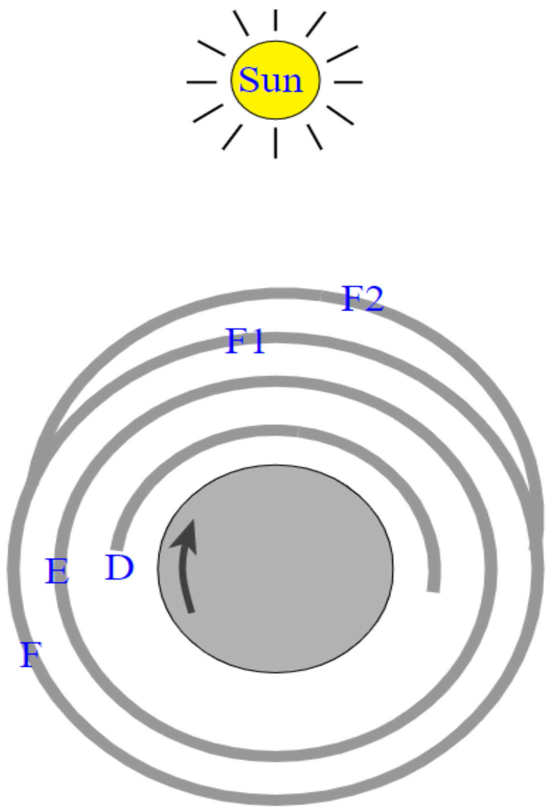
Multipath fading may also cause distortion to the radio signal. As the various paths that can be taken by the signals vary in length, the signal transmitted at a particular instance will arrive at the receiver over a spread of times. This can cause problems with phase distortion and inter-symbol interference when data transmissions are made. As a result, it may be necessary to incorporate features within the radio communications system that enables the effects of these problems to be minimised.

Multipath radio fading is factor that appears on most signals to a greater or lesser degree. As radio signals tend to reach a receiver via multiple paths regardless of how good the path appears to be there are always likely to be reflections from other objects. The only exception is in outer space where there are very few significant objects that are likely to cause major issues.

Critical angle. The critical angle of a given frequency is the highest angle at which you can send a radio wave into the ionosphere and have it return to earth. Unlike the critical frequency, the critical angle is not applicable to any single ionospheric layer. The critical angle applies to the refraction of a single frequency from any part of the ionosphere. When radio electromagnetic energy is radiated from an antenna, it travels as a wave-front that's like the contour of a balloon.

Waves radiate from the antenna at many different angles. The wave front that's at the right angle of radiation is useful to sky-wave communications. Waves above the critical angle will pass through the ionosphere. Those angled too low and will be absorbed before refraction can occur.

Ionospheric Regions:



D Region

When a sky wave leaves the Earth's surface and travels upwards, the first region of interest that it reaches in the ionosphere is called the D layer or D region.

It is present at altitudes between about 60 and 90 kilometres and the radiation within it is only present during the day to an extent that affects radio waves noticeably. It is sustained by the radiation from the Sun and levels of ionisation fall rapidly at dusk when the source of radiation is removed.
The D region attenuates signals because the radio signals cause the free electrons in the region to vibrate. As they vibrate the electrons collide with molecules, and at each collision there is a small loss of energy. With countless millions of electrons vibrating, the amount of energy loss becomes noticeable and manifests itself as a reduction in the overall signal level.

E Region

The E region or E layer is above the D region. It exists at altitudes between about 100 and 125 kilometres. Instead of attenuating radio communications signals this layer chiefly refracts them, often to a degree where they are returned to earth. As such they appear to have been reflected by this layer. However this layer still acts as an attenuator to a certain degree.

At the altitude where the E layer or E region exists, the air density is very much less than it is for the D region. This means that when the free electrons are excited by radio signals and vibrate, far fewer collisions occur. As a result the way in which the E layer or E region acts is somewhat different. The electrons are again set in motion by the radio signal, but they tend to re-radiate it. As the signal is travelling in an area where the density of electrons is increasing, the further it progresses into the region, the signal is refracted away from the area of higher electron density. In the case of HF signals, this refraction is often sufficient to bend them back to earth. In effect it appears that the region has "reflected" the signal.

F Region

The most important region in the ionosphere for long distance HF radio communications is the F region. During the daytime when radiation is being received from the Sun, it often splits into two: the lower one being the F1 region and the higher one, the F2 region. Of these the F1 region is more of an inflection point in the electron density curve (seen above) and it generally only exists in the summer.

Typically the F1 layer is found at around an altitude of 300 kilometres with the F2 layer above it at around 400 kilometres. The combined F layer may then be centred around 250 to 300 kilometres. The altitude of the all the layers in the ionosphere layers varies considerably and the F layer varies the most. As a result the figures given should only be taken as a rough guide. Being the highest of the ionospheric regions it is greatly affected by the state of the Sun as well as other factors including the time of day, the year and so forth.

The F layer acts as a "reflector" of signals in the HF portion of the radio spectrum enabling world wide radio communications to be established. It is the main region associated with HF signal propagation.

Question For Practice

1. Which frequency band is used for weather Radars?
2. What is the formula to calculate refractive index of a medium?
3. What is the refractive index of Air?
4. What is snell's Law?
5. What is Reflection and Refraction?
6. What should be the phase difference for total constructive and total destructive interference?
7. Why a pool is deeper than it looks?
8. Write formula to estimate range for line of sight communication.
9. Define Critical Frequency. What is relation between Critical frequency and Maximum usable frequency?
10. If an EM wave whose critical frequency is 30 MHz is incident with an angle of 60°. Calculate its MUF.
11. Communication through LOS can be increased by decreasing the height of antenna. (True or False with Reason)
12. Define MUF.
13. What is Multipath fading?
14. Multipath fading is more in outer space. (True or False)
15. Calculate range of line of sight communication for standard atmosphere when ht = 52 m and hr is 13 m.
16. In which of the following modes of propagation the ionosphere acts as the reflecting surface for the waves?
    a) Ground wave
    b) Sky wave
    c) Space wave
    d) LOS
17. Which of ionosphere layer disappears during night time in ionosphere?
18. Which layers of ionosphere regions are present in the night time?
19. At what height the Ionosphere lies above the earth surface?
20. Ground wave propagation is also known as __________.
21. ------Frequency band is used for ground to aircraft communications
22. What is the value of maximum usable frequency when the incident angle is 0° and the critical frequency is 10 MHz?

23. Calculate range of line of sight communication for standard atmosphere when ht = 52 m and hr is 13 m.
24. Which of the following frequency is greater than the critical frequency?
    a) MUF
    b) LUF
    c) Optimum frequency
    d) VLF
    Write the Reason.
25. Define Interference.
26. What is skip distance?
27. Which of the following statements is false? With Reason.
    a) MUF is always greater than or equal to critical frequency depending on the incident angle
    b) Optimum frequency is the frequency at which optimum reflection of wave takes place
    c) Beyond the MUF, the entire wave gets reflected back
    d) Below LUF, the entire power of wave gets absorbed

28. When a wave is incident normally then the acceptable highest frequency at which signal can be returned is the ______

a) critical frequency

b) MUF

c) optimum frequency

d) dominating frequency

29. What is the value of maximum usable frequency when the incident angle is 60° and the critical frequency is 4.5MHz?

a) 4.5MHz

b) 2.25MHz

c) 9MHz

d) 18MHz

30. Which of the following is true when a ray is incident normally in an Ionosphere region?

a) MUF is equal to critical frequency

b) MUF is greater than critical frequency

c) MUF is less than critical frequency

d) MUF is zero

31. What is ionosphere. Write short note on different layers of ionosphere.

32. The effective height of a layer of ionized gas in the atmosphere by which the radio waves are reflected around earth's curvature is called Virtual height.

a) True

b) False

33. The differences in the virtual height and actual height are affected by the electron density in the ionosphere region.

a) True

b) False

34. If wave exceeds the MUF then it is not reflected back.

a) True

b) False