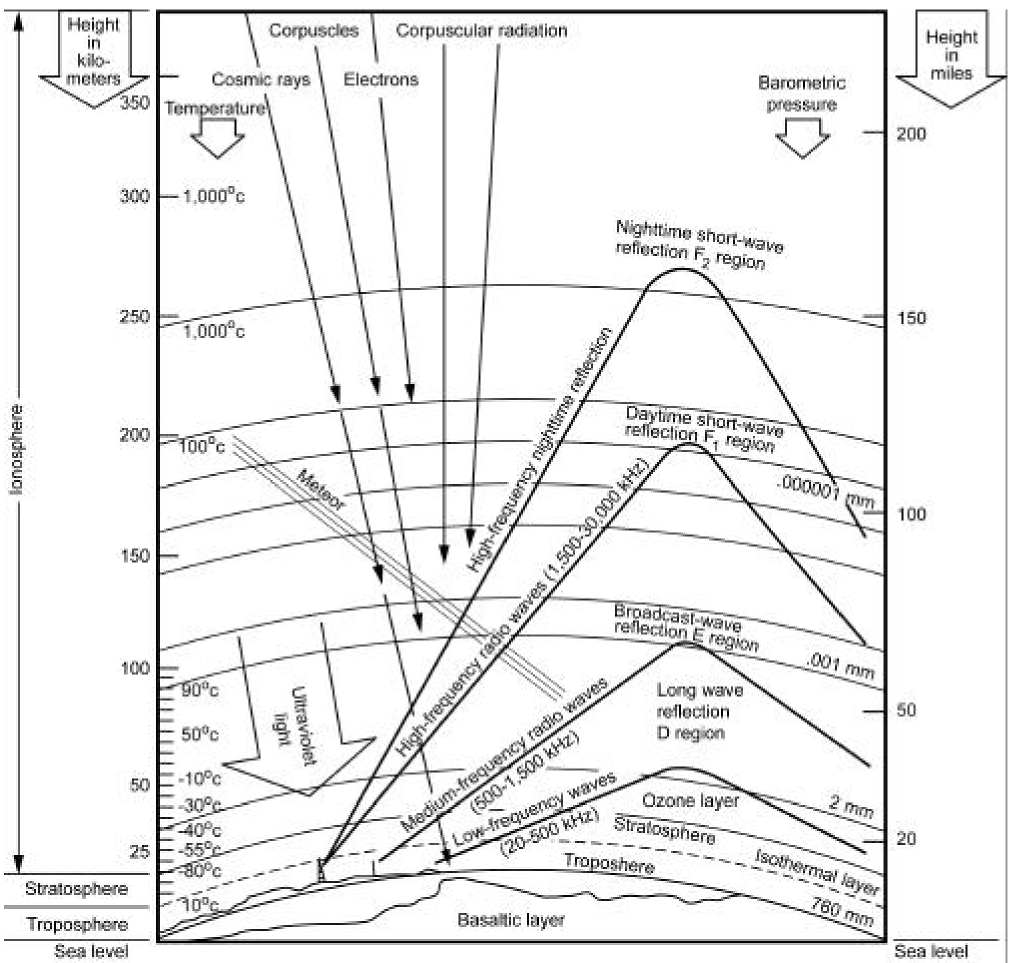
The Earth's Atmosphere

Introduction

Wave propagation deals with the properties and the nature of the atmosphere through which radio waves must travel from the transmitting antenna to the receiving antenna. The atmosphere is a gaseous mass that envelops the earth. It is not uniform because it varies with the altitude, temperature, geographic location, time of day or night, season, and year. Knowledge of the composition and properties of the atmosphere aids in the solution of problems that arise in planning radio communication paths and in predicting the reliability of communications. The earth's atmosphere is divided into three regions: the troposphere, the stratosphere, and the ionosphere. Refer to the diagram below for an idea of their location and heights above the earth.



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The Earth's Atmosphere, Continued

Troposphere

The troposphere is that portion of the earth's atmosphere extending from the surface of the earth to a height of approximately 6.8 miles. Within the troposphere, the bending of radio waves by refraction causes the radio horizon to exceed the optical horizon. Tropospheric refraction (reflection caused by sudden changes in the characteristics of air in a lower atmosphere) effects the received signal at distances beyond the radio horizon.

Stratosphere

The stratosphere is that portion of the earth's atmosphere lying between the troposphere and the ionosphere, from 6.8 miles to 30 miles above the earth. The temperature in this region is nearly constant.

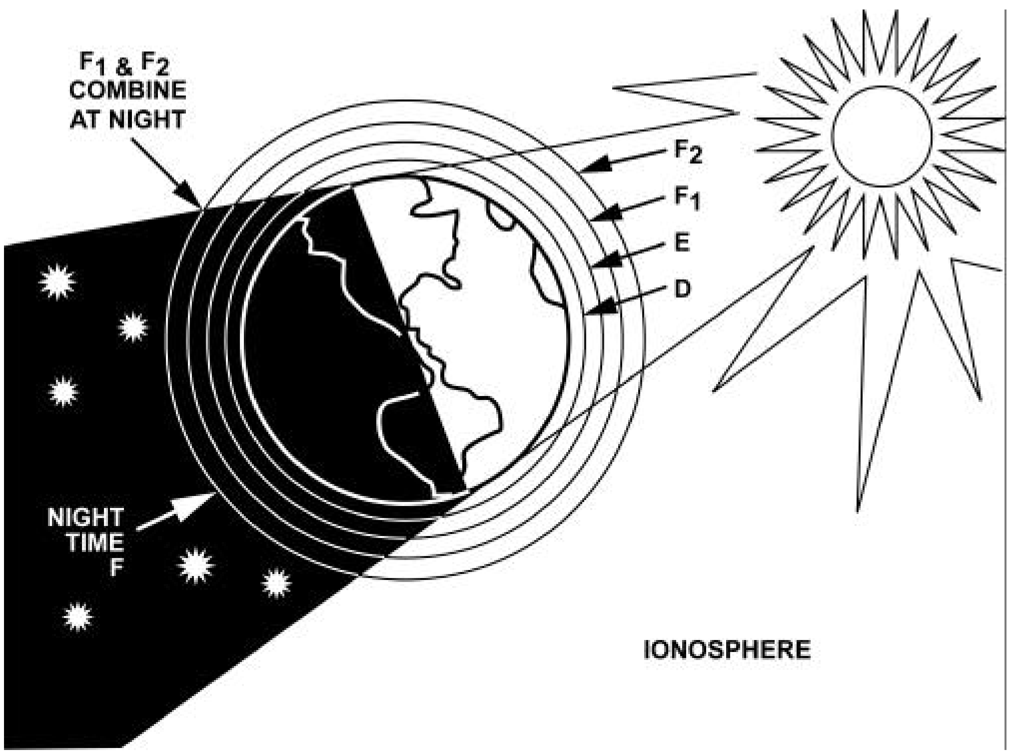
Ionosphere

The ionosphere is that portion of the earth's atmosphere above the lowest level at which ionization (splitting of molecules into positive and negative charges or ions) of low pressure gases will effect the transmission of radio waves. It extends from 30 to 250 miles above the earth. The ionosphere is composed of several distinct layers in which ionization occurs at different levels and intensities.

The Ionosphere

Definition

The ionosphere is that portion of the earth's atmosphere containing ionized gases. There are four distinct layers of the ionosphere. In the order of increasing heights and intensities, they are the "D", "E", "F_1", and "F_2" layers. The four layers are present only during the day when the rays of the sun are directed toward that portion of the atmosphere. During the night, the "F_1" and "F_2" layers merge into a single "F" layer and the "D" and "E" layers fade out. The actual number of layers, their heights above the earth, and their relative intensity of internal ionization vary from hour to hour, day to day, month to month, season to season, and year to year. The relative distribution of these layers is shown in the diagram below:



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"D" Region

The "D" region exists only during daylight hours and has little effect in bending the path of high frequency radio waves. The main effect of the "D" region is its ability to attenuate or decrease the intensity of high-frequency waves when the transmission path lies in sunlit regions.

"E" Region

The "E" region is used during the day for high-frequency radio transmission over distances greater than 1,500 miles. The intensity of this layer decreases during the night, rendering it useless for radio transmissions.

"F" Region

The "F" region exists at heights up to 240 miles above the surface of the earth and is ionized at all hours of the day and night. The "F" region is comprised of two well-defined layers during the day and one during the night. At night, the "F" layer lies at a height of about 170 miles and is useful for long-range radio communication (over 1,500 miles).

"F_1" and "F_2" Regions

During the day, air warmed by sunlight causes the "F" region to split into two distinct layers, the "F_1" layer and the "F_2" layer. The " F_2" layer is the most useful of all layers for long-range radio communication, even though the degree of ionization varies appreciably from day to day as compared with other layers.

Ionosphere Characteristics

Critical Frequency

Primarily the ionization density of each ionospheric layer determines the range of long-distance radio transmission. The higher the frequency, the smaller the radio waves, and a greater density of ionization is required to refract the waves back to earth. The upper ("E" and "F") layers refract the higher frequencies because they are the most highly ionized. The "D" layer, which is the least ionized, does not refract frequencies above approximately 500 KHz. Thus, at any given time and for each ionized layer, there is an upper frequency limit at which waves sent vertically upward are reflected directly back to earth. This limit is called the critical frequency. Waves that are directed vertically at frequencies higher than the critical frequency pass through the ionized layer out into space. All waves directed to the ionosphere at frequencies lower than the critical frequency are refracted back to the earth.

Critical Angle

Radio waves used in communication generally are directed to the ionosphere at some oblique angle are called the angle of incidence. Waves at frequencies above the critical frequency can be returned, if propagated at angles of incidence lower than the critical angle. At the critical angle and any angle larger than the critical angle, the wave will pass through the ionosphere if the frequency is higher than the critical frequency. As the angle becomes smaller, an angle is reached at which the wave is bent back to the earth by refraction. The distance between the transmitting antenna and the point at which the wave first returns is called the skip distance.

Variations of the Ionosphere

Definition

The movements of the earth around the sun and changes in the sun's activity contribute to ionospheric variations. There are two main classifications of these variations:

- Regular variations: predictable behavior of the sun
- Irregular variations: abnormal behavior of the sun

Regular Variations

The regular variations are divided into four classes:

Class	Predictable Behavior
Daily	The rotation of the earth
Seasonal	The north and south progression of the sun
27-Day	The rotation of the sun on its axis
11-Year	The average cycle of sunspot activity

Irregular Variations

The transient or momentary ionospheric variations, though unpredictable, have important effects on radio propagation. Some of the major effects are:

- Sporadic E
- Sudden ionospheric disturbance
- Ionosphere storms
- Nuclear detonations

Sporadic E

When it is excessively ionized, the "E" layer often completely blanks out reflections from the higher layers. This effect may occur during the day or night.

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Variations of the Ionosphere, Continued

Sudden Ionospheric Disturbance	Sudden ionospheric disturbances (SID) are ionization abnormalities of the "D" layer. The most common causes of these disturbances are solar anomalies, such as sunspots or solar flares.
Ionosphere Storms	These storms may last from several hours to several days, and usually extend over the entire earth. During these storms, sky wave transmission above approximately 1.5 MHz shows low intensity and is subject to a type of rapid blasting and fading, known as flutter fading.
Sunspots	Sunspots are caused by magnetic storms on the surface of the sun and can last for weeks. Sunspots that disappear from view behind the sun will often predictably reappear two weeks later as that portion of the sun comes back into view. Sunspots generally follow an 11-year cycle, but can vary daily. Sunspots cause an increase in ionization that will allow the "E" and "F" layers to refract higher frequencies while causing more absorption by the "D" layer.
Solar Flares	Solar flares are large, sudden releases of energy on the sun, which can last from a few minutes to several hours. Usually occurring near sunspots, they can have energy outputs equivalent to the explosion of a billion H-bombs. Solar flares have both immediate and delayed effects on HF communications. The immediate effect is a large increase of solar noise and the start of a SID. These effects, like their originators, can last from a few minutes to several hours. The delayed effects can occur from 30 minutes to 72 hours after the solar flare, and include polar cap absorption and ionospheric storms. In either case, the result is total absorption of all frequencies above 1 MHz, causing receivers to go dead.
Nuclear Effects	The physical properties of the ionosphere can also be greatly altered during a nuclear exchange. Intense dust clouds formed by surface bursts would cause the "D" layer to become highly ionized from gamma ray radiation caused by low altitude air defense bursts (10 to 35 miles). Bursts, especially those at high altitude (greater than 250 miles) would damage unshielded radio equipment through an effect known as electromagnetic pulse (EMP). Ground wave communications between surviving equipment would be hindered in the direction of surface bursts due to the great amount of dirt in the air and/or the changes in electrical properties of the earth.

Ground Wave Propagation

Definition

Ground wave propagation refers to radio transmissions that do not utilize waves that have been refracted from the ionosphere. The field intensity of ground waves depends on the transmitter power, the characteristics of the transmitting antenna, and the frequency of the waves. Additionally, the diffraction of the waves around the curvature of the earth, the conductivity and dielectric constant of the local terrain, the nature of the transmission path, and local weather conditions also effect the intensity of ground waves. The ground wave is comprised of three distinctly different components: the direct wave, the ground-reflected wave, and the surface wave. The three components are identified in the diagram at the bottom of this page.

Direct Wave

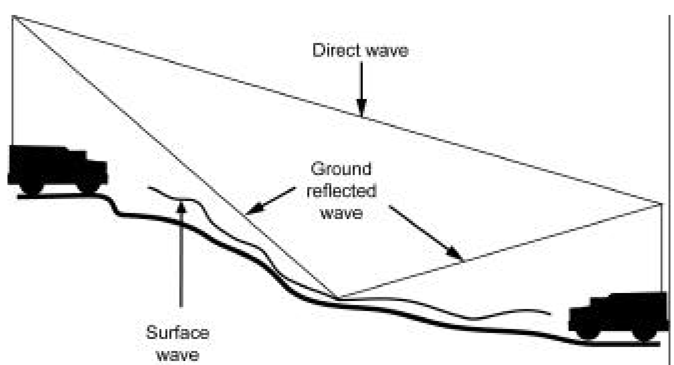
The direct wave is that component of the entire wave front that travels directly from the transmitting antenna to the receiving antenna. This component is limited to the line-of-sight distance between the transmitting and receiving antennas, plus a small, additional distance caused by the curvature of the earth. Increasing the height of the transmitting antenna or the receiving antenna (or both) can extend this distance.

Ground-Reflected Wave

The ground-reflected wave is the portion of the radiated wave that reaches the receiving antenna after being reflected from the surface of the earth. When both the transmitting and receiving antennas are on or close to the ground, the direct and ground-reflected components of the ground wave tend to cancel each other out.

Surface Wave

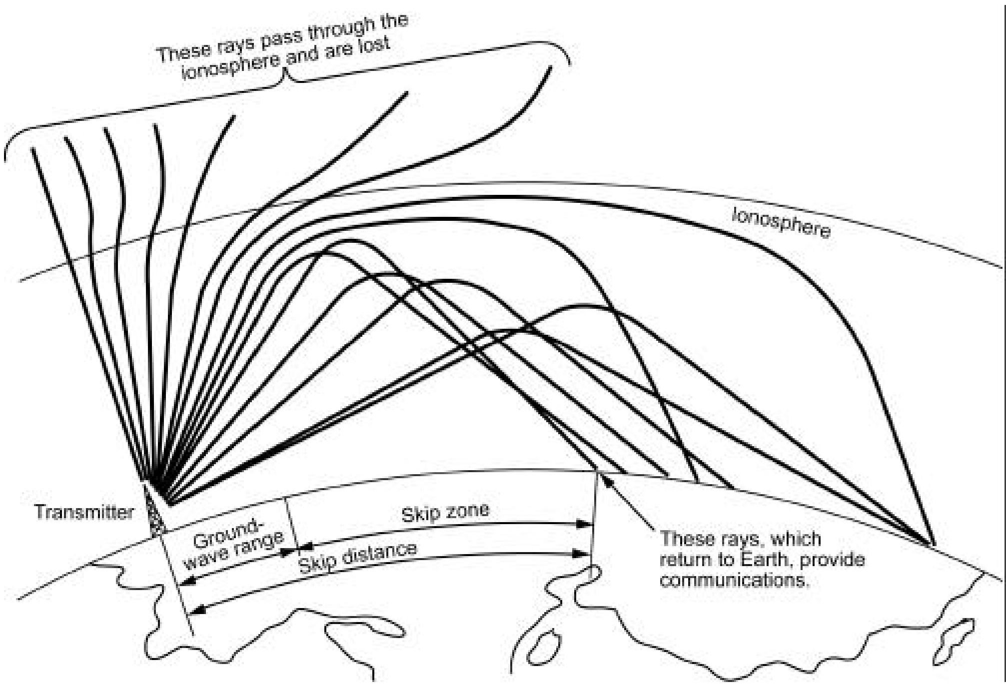
The surface wave, which follows the curvature of the earth, is the component of the ground wave that is effected by the conductivity and dielectric constant of the earth.



Sky Wave Propagation

Sky Wave Transmission Paths

Sky wave propagation refers to those types of radio transmissions that depend on the ionosphere to provide signal paths between transmitters and receivers. Sky wave transmissions are by far the most important method for long distance radio communications. The various sky wave transmission paths are identified in the diagram below:



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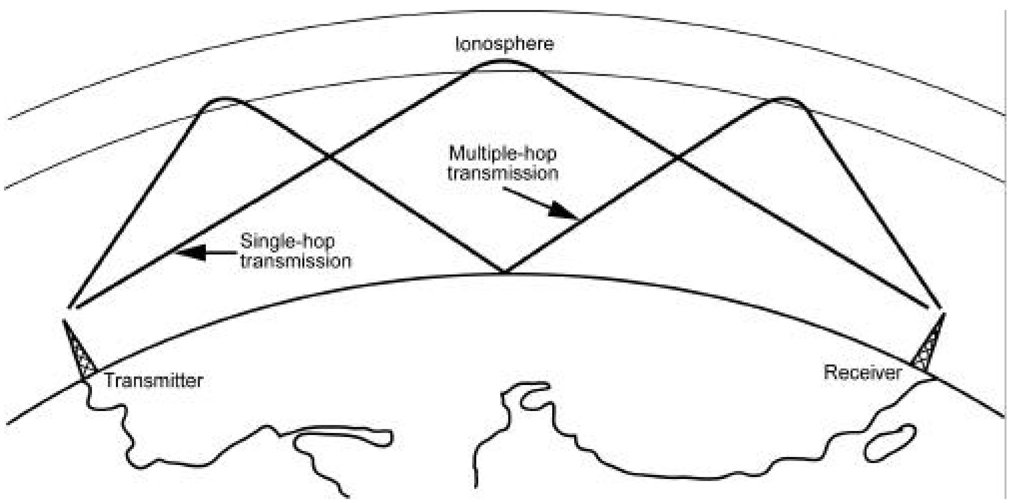
Sky Wave Modes

The area where the wave returns to the earth depends on the height of the ionized layer and the amount of bending the wave encounters while traversing the layer. This bending is a function of the frequency of the wave as compared to the ion density of the layer. Upon return to the earth's surface, part of the energy enters the earth to be rapidly dissipated, but part is reflected back into the ionosphere where it may reflect downward again at a still greater distance from the transmitter. This means of traveling in hops, bouncing between the ionosphere and the surface of the earth, is known as multi-hop transmission and enables transmissions to be received at long distances from the transmitter. The diagram below illustrates this means of travel for paths involving one, two, or three reflections from the ionosphere (single, double, and triple hop modes or paths).



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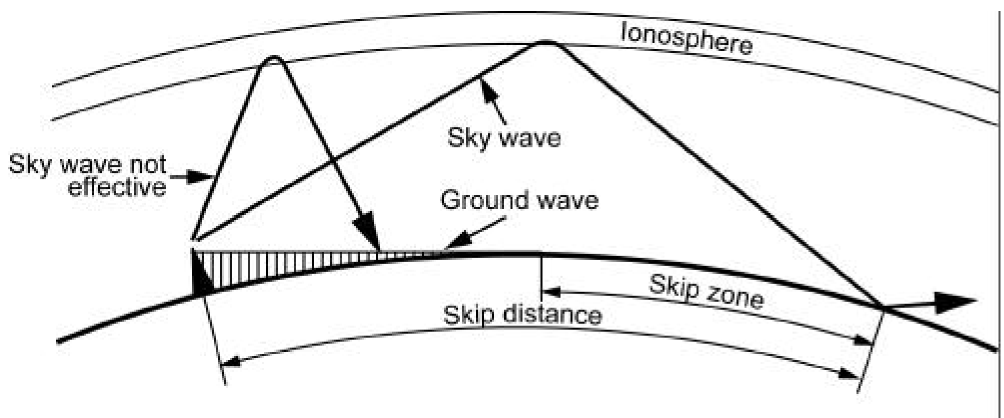
Sky Wave Propagation, Continued

Skip Zone

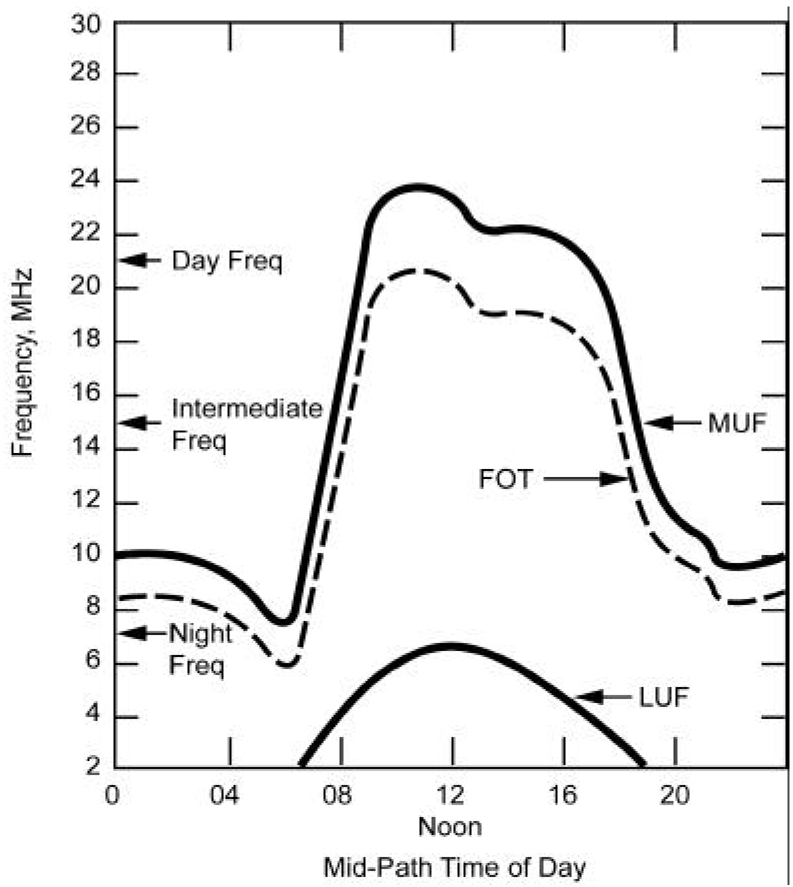
The skip zone is that area where no usable signal can be received from a given transmitter operating at a given frequency. This area is bounded by the outer edge of the usable ground-wave propagation and the point nearest the antenna at which the closest sky wave returns to earth. The greater the distance between those two points, the larger the skip zone. Refer to the diagram below for the skip zone and its relation to the ground wave. If the ground wave extends to the point where skip waves begin, there is no skip zone. In this case, both the sky wave and the ground wave may arrive at the antenna with nearly the same field intensity, but at randomly different phases. When this occurs, the sky wave component alternately reinforces and cancels the ground wave component, causing blasting (during reinforcement) and fading (during cancellation) of the signal.



Maximum Usable Frequency (MUF)

Definition

An important concept associated with sky wave propagation is called the maximum usable frequency (MUF). The MUF is the highest frequency at which a radio wave will reflect from an ionospheric layer for a given elevation or propagation path. Frequencies higher than the MUF will penetrate the layer and escape into space. The diagram below depicts a chart used to determine specific frequencies and their usefulness depending on the time of day.



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Maximum Usable Frequency (MUF), Continued

Predictions

It is important at this point to discuss propagation predictions and their statistical nature. The science of predicting ionospheric conditions and selecting frequencies to use for a given path is well developed, but subject to the same accuracy problems as prediction of the local weather. It is impossible to predict with

- Absolute accuracy the best choice of frequency to use for a given propagation path.
- Reasonable accuracy what the MUF will be for a given communication path at a particular time of day.

These predictions are usually based on a statistical reliability of 50 percent.

Example

Assume the MUF for a certain propagation path is predicted to be 12 MHz during the time period of 1200 to 1500 hours for the month of November. This actually means the MUF will be lower than 12 MHz 15 days of the month and higher than 12 MHz the other 15 days of the month. The median MUF for the entire month will be 12 MHz. It also means that on a given day when the MUF is actually 12 MHz, frequencies slightly higher than 12 MHz may be used with greatly reduced reliability.

Frequency Selection

When there is a choice of frequencies to use, it is always best to use a higher frequency. This is especially true when communicating over distances greater than 650 miles. This reduces absorption from any lower layer and minimizes multi-path fading. However, it is generally undesirable to operate at or near the MUF since this frequency is reflected only 50 percent of the time. To allow for day-to-day changes in the MUF and the critical frequency, it is customary to use a frequency that is about 85 percent of the MUF. This lower frequency is known as the frequency of optimum transmission (FOT). It is based on the statistical fact that the FOT lies below the daily variations of the actual MUF about 90 percent of the time. It is not always the frequency for minimum path loss or for minimum fading, and there are times when a frequency 10 percent lower or higher than the FOT will be more reliable. Based on statistics, the FOT represents the best choice for a given path length, time of day, season, and sunspot number.

Lowest Usable Frequency (LUF)

Definition

As the frequency for transmission over any given sky wave path is increased, a value will be reached at which the radio signal just overrides the level of atmospheric and other radio noises. This is called the lowest usable frequency (LUF) because frequencies lower than the LUF are too weak for useful communications. For a given transmitter power as the operating frequency is decreased, the average signal level at the receiver will decrease due to increased ionospheric absorption. The average level of natural atmospheric noise (lightning discharge) and manmade noise (electrical equipment) existing in the vicinity of the receiver increases at lower frequencies. Thus, if the frequency of transmission is reduced much below the critical frequency, the received signal strength decreases while the received noise increases until finally the signal is generally unusable.

Frequency Selection

The LUF depends upon the power of the transmitter, path loss, total noise level at the receiving location, receiving antenna gain and directivity, and noise generated within the receiver itself. Because ionospheric absorption is highest when the "D" layer reaches its peak, the LUF generally peaks around noon. A frequency for day use must be chosen sufficiently above the LUF to ensure a reliable signal-to-noise ratio.

Fading Loss

Definition

When a radio signal is received over a long distance path, a periodic increase and decrease of received signal strength may result. This phenomenon is most common in the high frequency range. Most modern radios have internal circuitry that eliminates the "blasting" caused by increased signal strength, so this lesson will concentrate on the "fading" caused by decreased signal strength.

Cause and Prevention

The precise origin of fading is seldom understood. There is little common knowledge of what precautions can be taken to reduce or eliminate the troublesome effects of fading. Suggested methods for reducing fading are

- Increase transmitter power and antenna gain
- Use two or more receiving antennas spaced some distance apart with both feeding into the same receiver (space diversity reception)
- Select the proper frequency
- Know the capabilities and limitations of the transmitting and receiving equipment

Fading associated with sky wave paths is the greatest single detriment to reliable communications.

Types of Fading

Four Classes

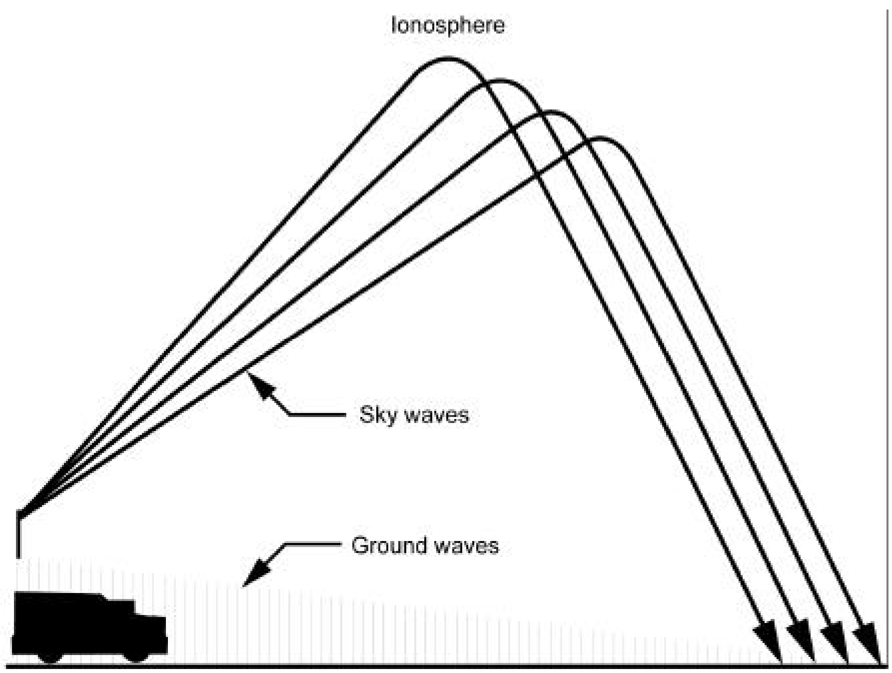
The many types of fading can be categorized into four principal classes:

- Interference
- Polarization
- Absorption
- Skip

Most cases of rapid fading are caused by a combination of the first two types while the latter two types normally cause gradual fading.

Interference Fading

Interference fading is caused by phase interference of two or more waves from the same source arriving at the receiver over slightly different paths. If the paths are of different lengths and their relative lengths vary for some reason, such as fluctuations in the height of the ionosphere layers, the relative phases of the waves arriving over the different paths vary with time, causing alternate reinforcement and cancellation of the field intensity. This concept is illustrated in the diagram below. Because of irregularities in the ionosphere, one downcoming sky wave is really the summation of a great number of waves of small intensity and of random relative phases, and thus the resultant field intensity can vary greatly.



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Types of Fading, Continued

Polarization Fading

Additional variation in the field intensity effecting the receiving antenna occurs when the polarization of the downcoming wave changes in relation to the polarization of the receiving antenna. This variation is called polarization fading. The polarization of the downcoming sky wave is changing constantly. This is due mainly to the combination of the two oppositely polarized components—the ordinary and the extraordinary wave—at random amplitudes and phases.

The polarization of the downcoming sky wave is generally elliptical. Elliptical polarization means that as the wave travels along the signal path, the electric and magnetic fields remain at right angles to each other and to the direction of propagation, rotating about the signal path in a corkscrew fashion. This results in random and constantly changing values of the amplitude and orientation of the electric field with respect to the receiving antenna. The state of polarization of sky waves varies more rapidly than the higher frequency, which accounts in part for the rapid fading on the higher frequencies.

Absorption Fading

Absorption fading is caused by short-term variations in the amount of energy lost from the wave because of absorption in the ionosphere. In general, the time period of this type of fading is much longer than that of other types since the ionospheric absorption usually changes slowly. In extreme cases, sudden ionospheric disturbances can account for this type of fading, although it is usually classified as an irregular disturbance rather than fading.

Another example of this type of fading is the reflection and absorption of radio waves by objects close to the receiver, such as when a vehicle is passing under a bridge or near a heavy steel structure and can no longer receive radio signals. Radiation from wires, fences, and steel structures can cause an interference pattern that is relatively fixed in space, and can be detected only by moving the receiving equipment around the radiating structure. Therefore, care must be exercised when selecting communication sites with nearby structures that could produce these effects.

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Types of Fading, Continued

Skip Fading

Skip fading is observed at places near the limit of the skip distance, and is caused by the changing angle of refraction. Near sunrise and sunset when the ionization density of the ionosphere is changing, the MUF for a given transmission path may fluctuate about the actual operation frequency. When the skip distance extends out past the receiving station, the received signal level drops abruptly and then increases just as abruptly when the skip distance moves back in. This may take place many times before conditions reach a steady state.

Wave Propagation

Definition

The effects of the atmospheric layers on wave propagation—as described in the previous lessons—are complicated further by variations in frequency of the transmitted wave. The propagation principles for frequencies at the low end of the frequency spectrum are drastically different than those at the high end of the spectrum. (For ease of identification, frequencies are usually classified in the ranges shown on page 1-7). It is also important to remember that radio waves travel by means of ground waves, sky waves, or a combination of both.

Low Frequency

At low frequencies (.03 to .3 MHz), the ground wave is extremely useful for communication over greater distance. The ground wave signals are quite stable and show little seasonal variation.

Medium Frequency

In the medium-frequency band (.3 to 3.0 MHz), the range of the ground wave varies from about 15 miles at the low end of the band to about 400 miles at the high end. Sky wave reception is possible during day or night at any of the lower frequencies in this band. At night, the sky wave gives reception at a distance up to 8,000 miles.

High Frequency

In the high-frequency band (3.0 to 30 MHz), the range of the ground wave decreases with an increase in frequency and the sky waves are greatly influenced by ionospheric conditions.

Very High Frequency

In the very-high-frequency band (30 to 300 MHz), there is no usable ground reflected and no surface wave, only a slight refraction of sky waves by the ionosphere at the lower frequencies. The direct wave provides communication if the transmitting and receiving antennas are elevated sufficiently above the surface of the earth. Transmission over any greater range is unpredictable and will last only for short periods of time because of sporadic conditions in the ionosphere.

Ultra High Frequency

In the ultra-high-frequency band (300 to 3,000 MHz), the direct wave must be used for all radio transmissions. Communication is limited to a short distance beyond the horizon. Lack of static and fading in these bands make line-of-sight reception very good. Highly directive antennas can be built into a space to concentrate RF energy into a narrow beam, increasing the signal intensity.