UNDERSTANDING VHF PROPAGATION

Educational Note

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1 OVERVIEW OF VHF

1.1 Definition of VHF

The International Telecommunications Union (ITU) designates VHF (very high frequency) as frequencies from 30 to 300 MHz. VHF therefore lies directly above HF (high frequency: 3-30 MHz) and directly below UHF (ultra-high frequency: 300-3000 MHz).

These categories are somewhat artificial, and propagation modes do not change abruptly at the edges of these frequency ranges. While there are substantial differences between common propagation modes at HF and VHF, many "VHF" propagation modes often carry signals in the low UHF range as well. Furthermore, propagation can also vary substantially even within the ITU-defined VHF frequency range of 30 to 300 MHz: for example, some modes may only be encountered at the lower end of this frequency range.

Unless otherwise noted, in this educational note "VHF" will be used to refer to signals in the range of approximately 50 to 500 MHz.

1.2 Applications of VHF

Signal at VHF are used in a very wide range of applications. Almost all modern radio and television broadcasting takes place at the lower and upper ends of VHF, respectively. Most non-cellular local two-way voice communications are based on VHF. VHF is often used for transferring data, particularly telemetry or other measurement data. Some of the navigational aids used in aviation, such as Very High Frequency Omni-Directional Range (VOR) and Instrument Landing System (ILS) also operate at VHF frequencies. In addition, VHF is used for many aerospace and defense applications. For example, several types of radar operate at VHF, such as “anti-stealth” radars which use longer VHF wavelengths in order to minimize the effectiveness of stealth technology.

Figure 1: Common VHF applications

1.3 VHF compared to HF

There are several important practical differences between propagation at HF and at VHF. Due to the shorter wavelengths of VHF signals, VHF antennas are usually physically smaller than HF antennas. This makes VHF more suitable for mobile or portable use, either with hand-held radios or on platforms such as land vehicles, ships, and aircraft. The wider frequency range of VHF allows the use of much wider bandwidths than HF, and this in turn increases the achievable data rates on VHF compared to HF. Atmospheric noise is usually lower at VHF compared to HF, but man-made noise sources are often more common at VHF. VHF penetrates buildings better than HF, and this is one of the reasons why VHF is more often used in broadcasting. VHF signals are however more susceptible to multipath: this is covered in more detail in section 2.3.2.

Because of these differences between HF and VHF propagation, HF is most often used for longer distance communications – HF can provide global communications coverage under the proper conditions. VHF is generally better suited for local applications, typically within a radius of roughly 100 kilometers or less, although section 3 of this educational note describes circumstances in which various VHF propagation modes can be used for communications over much larger distances.

1.4 Why study VHF propagation?

As with other frequency ranges, VHF application or mission planning requires knowledge of how signals propagate in order to select the equipment, antennas, power levels, etc. necessary to meet availability, coverage, and reliability requirements. There is also a very common misconception that VHF propagation is essentially "line of sight," and this educational note will illustrate why this assumption is usually incorrect. There are many different VHF propagation modes, and these propagation modes tend to be much more dependent on the local environment than HF propagation modes. Common VHF propagation modes are discussed in section 2.

In addition to the various standard modes of VHF propagation, there are also numerous "uncommon" propagation modes which can cause VHF signals to travel for much longer distances than would be expected using pure line of sight propagation. These uncommon modes can allow much longer communication distances and also have significant implications with regard to radio frequency interference, direction finding, signals intelligence, etc. The most important uncommon VHF propagation modes are discussed in much more detail in section 3 of this educational note.

2 COMMON VHF PROPAGATION MODES

2.1 About line of sight

Pure line of sight propagation at VHF is rare in terrestrial environments, especially at distances of several kilometers or more. The reason for this is that signals in a terrestrial environment usually encounter numerous objects along the path between a transmitter and a receiver. Depending on the shape, orientation, composition, and other properties of these objects, the direction, amplitude, phase, and/or polarization of a signal may be changed when a signal interacts with these objects.

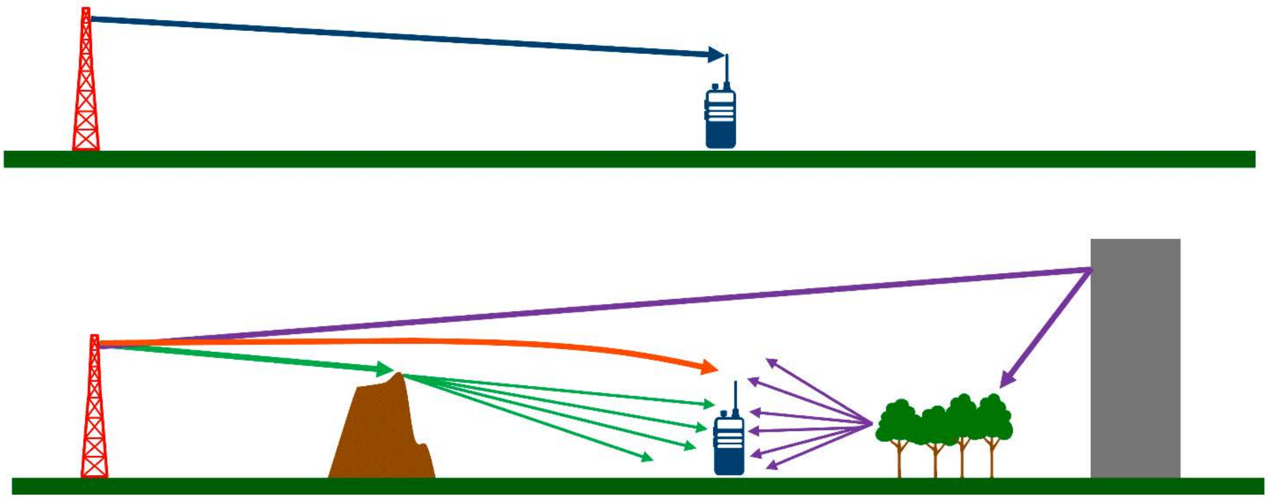

Figure 2: Pure line of sight versus typical propagation environments

Furthermore, the longer the path, the more obstacles a signal encounters and the greater the effects of interactions with these objects.

The four most important common VHF propagation modes, in rough order of importance, are refraction, reflection, diffraction, and scattering. Refraction arises from interactions with the troposphere, that is, with gases in the atmosphere, while reflection, diffraction, and scattering are caused by interaction with solid objects. The size, density, number, arrangement, and other properties of the encountered objects is what determines the relative contribution of each modes.

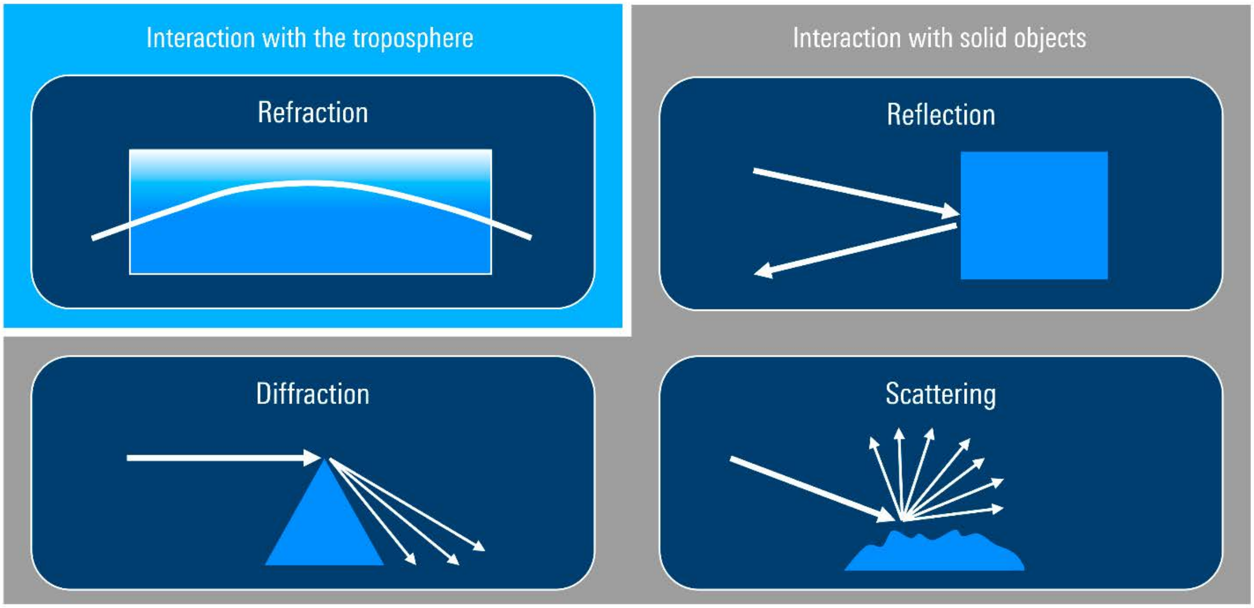

Figure 3: Common VHF propagation modes

2.2 About refraction

The most important of the common VHF propagation modes is refraction. Refraction is a change or "bend" in the direction of a wave caused by different propagation velocities in different media. The direction of the "bend" and the amount of bending are a function of the difference in **refractivity** between these two media: waves are bent towards the region with higher refractivity. The amount of bending depends on the nature of the boundary between the two media. When the boundaries are gradual, the bending is also gradual. On the other hand, more distinct boundaries cause much sharper refraction. This is illustrated in Figure 4.

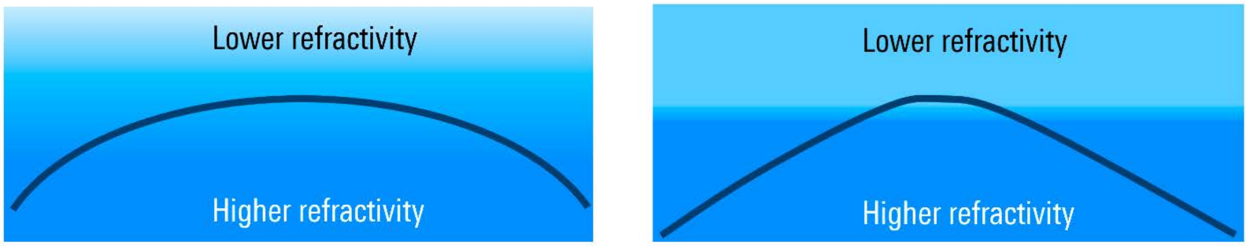

Figure 4: Degree of bending is a function of boundary between media

2.2.1 Refractive index

The amount of refractivity of a medium is quantified as its refractive index (N). The refractive index represents the "bending power" of a medium. For VHF signals in terrestrial applications, the "medium" is the atmosphere, or more specifically, the troposphere, which is the lowest level of the atmosphere and where most weather occurs.

Tropospheric refraction is largely independent of frequency. This is different from ionospheric refraction (most often seen at HF), which often has a very strong frequency dependence. In the troposphere, the refractive index is a function of three variables: air temperature, air pressure, and humidity. Atmospheric pressure always decreases with increasing altitude, and both temperature and humidity normally decrease with altitude. Thus, the refractive index of the troposphere generally decreases steadily with increasing altitude. This gradual decrease in the refractive index of the troposphere is very important for longer-distance VHF signal propagation.

2.2.2 Tropospheric refraction and the radio horizon

The communications distances achievable by pure line of sight propagation at VHF would be limited by the curvature of the Earth: reception beyond the so-called optical or geometric horizon would not be possible. However, since the refractive index of the troposphere is larger at lower altitudes, VHF signals passing through the troposphere are refracted towards the surface of the Earth. This downwards refraction causes VHF signals to follow the curvature of the Earth, thus extending the radio horizon beyond the optical horizon (Figure 5).

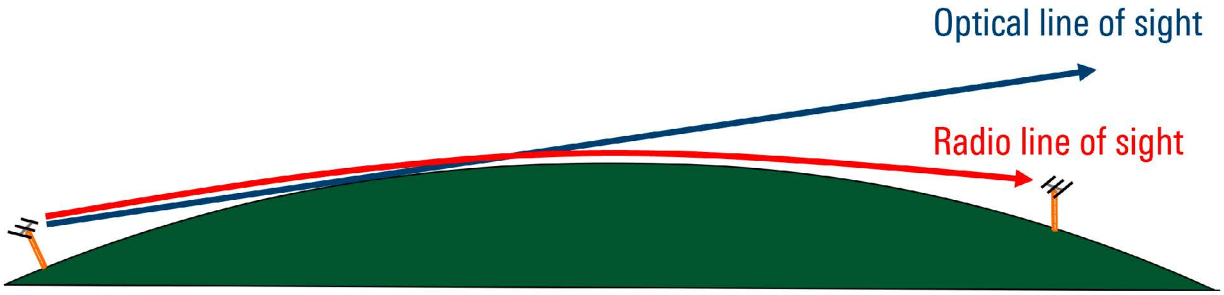

Figure 5: Optical and radio line of sight at VHF

Under ideal circumstances, this refraction extends the VHF radio horizon by approximately one-third, and therefore this phenomenon is sometimes referred to as "line of sight plus one-third". Note that this assumes a standard atmosphere and an unobstructed path: the actual extension of the radio horizon due to refraction may be significantly smaller under non-ideal, non-standard conditions.

2.3 About reflections

Like refraction, reflection is a change of radio wave direction at the boundary of two different media with different propagation speeds. Unlike refraction, which involves two air masses, reflection generally occurs at the boundary between air and a solid object, and this change in direction is more of a sharp angle than a gradual "bend." Reflection also tends to be "specular," which simply means that the incident and reflected angles are equal (Figure 6).

Radio frequency reflection is similar to optical reflection in that reflection is greatest when the reflector is large and smooth (or flat) compared to the wavelength. A rough surface usually produces more scattering than reflection: this is discussed in section 2.5.

In addition, reflection is not lossless – even the best reflectors absorb some of the incident signal. At VHF, reflections can sometimes be used advantageously, such as when passive objects are used as "repeaters." But most often, reflections are undesirable since they can create a phenomenon called multipath. Both of these situations are described in the following sections.

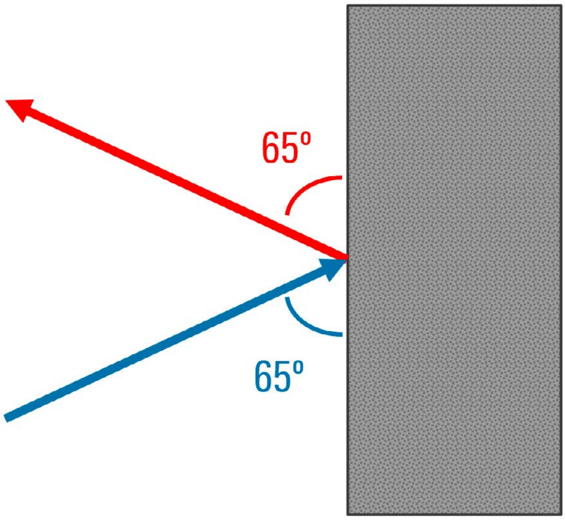

Figure 6: Specular reflection

2.3.1 Extending range using reflections

At VHF frequencies and higher, it is sometimes possible to advantageously use a large object as a reflector in order to extend range. Figure 7 shows signals being "bounced" over or around a hill using a nearby mountain as a reflector.

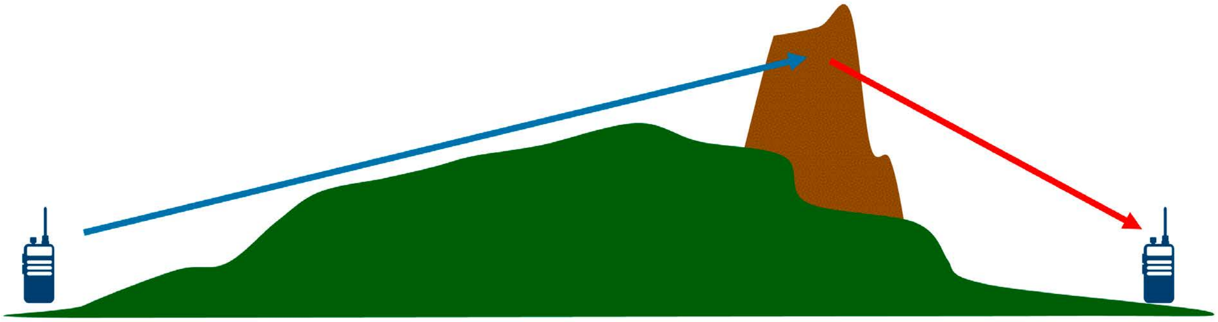

Figure 7: Using a reflector to extend range

As stated above, the larger and smoother the reflector, the better the results. Another important consideration when using an object as a reflector is that the reflected signal strength is often best when the reflector is located near one of the stations. Perhaps somewhat counterintuitively, the worst performance is often seen when the reflector is located halfway between the two stations.

2.3.2 Reflections and multipath

In most cases, reflections are undesirable. Even where a direct "line of sight" exists, reflections can create additional paths – usually of different lengths – between the transmitter and receiver. This is commonly referred to as a **multipath**. Although it is theoretically possible that multiple reflected signals could be received in phase and add constructively, this is quite rare, and multipath normally reduces signal strength and/or distorts the received signal.

Since multipath arises due to reflections, it is a much more serious issue in urban areas due to the large number of reflections from buildings, etc. In addition to impacting received signal quality, multipath also complicates direction finding at VHF frequencies, since it makes it difficult to obtain unambiguous bearings. In addition, multipath can create serious problems for direction-based services such as aeronautical navigational aids. For example, multipath caused by reflectors near or on an airport can distort the ILS localizer signals used for runway alignment during landing.

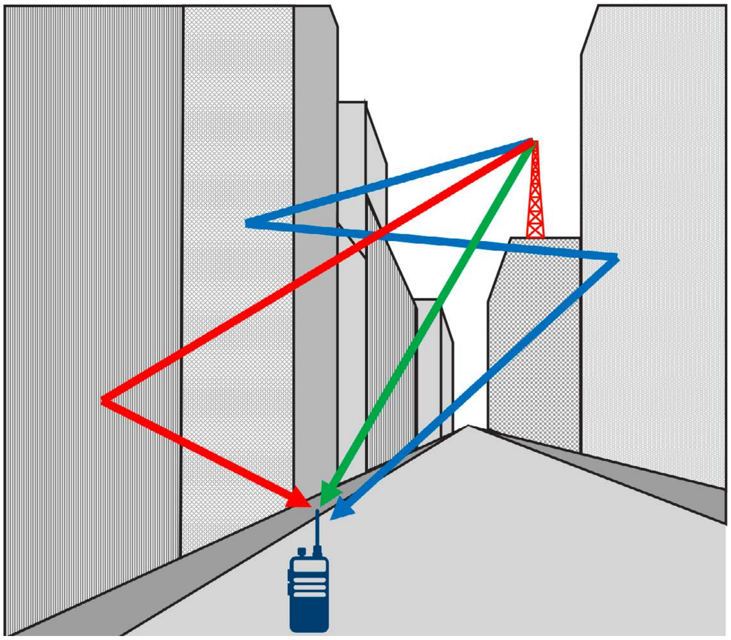

Figure 8: Multipath in an urban environment

2.4 About diffraction

Diffraction is different from refraction or reflection in that diffraction causes a change of direction by moving **past** rather than **through** or **against** a boundary. Diffraction most often occurs when a signal encounters a sharp or “knife” edge on an object. The "sharpness" of an object is a function of its edge dimensions compared to the wavelength of the signal encountering it.

Diffraction can propagate a signal into a “shadow area” or “shadow zone” created by an obstacle, and thus diffraction can enable reception in locations where a direct line of sight is not available. Diffracted signals do however suffer from diffraction loss or attenuation, and this loss increases with increasing frequency. It is also worth noting that it is possible for a signal to be diffracted over multiple objects along its path.

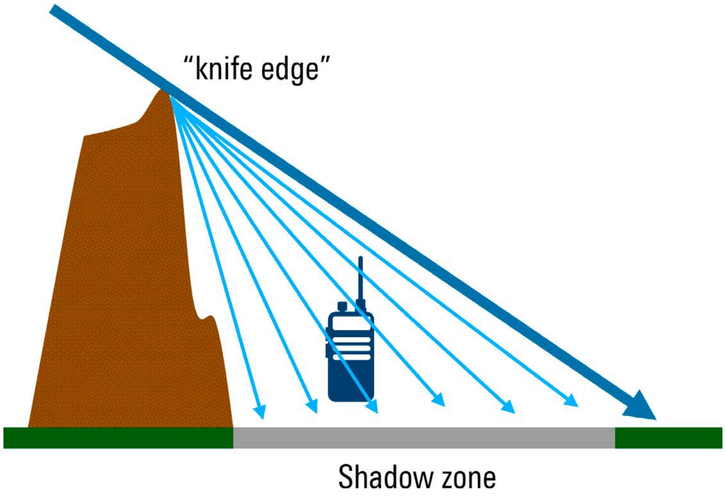

Figure 9: Diffraction allows reception in areas without line of sight

2.5 About scattering

Scattering is a special case of reflection in which multiple reflections occur in many, essentially random, directions. Often what determines whether a signal is reflected or scattered is the surface of the object. Rough or irregular surfaces usually create scattering rather than the specular reflection described in section 2.3. Scattering is normally caused by objects with a size on the order of a wavelength or less and the "scattering power" of an object is also very dependent on the wavelength of the signal. Unlike the other common VHF propagation modes previously discussed, scattering from objects at VHF frequencies is almost always undesirable. There are some less common forms of scattering that occur with non-solid objects, such as ionoscatter in the ionosphere and troposcatter in the troposphere, but these modes will not be discussed in this educational note.

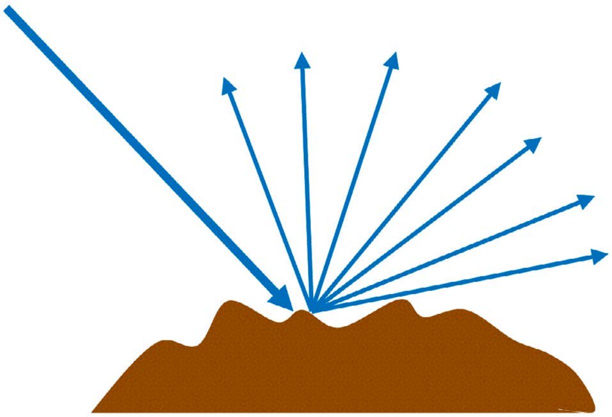

Figure 10: Scattering as a special form of reflection

3 UNCOMMON VHF PROPAGATION MODES

3.1 About uncommon VHF propagation modes

In addition to the "common" types of propagation described in the previous section, there are several **uncommon** propagation modes at VHF. “Uncommon” refers to modes that are either uncommon in **appearance**, that is, they do not occur on a regular or predictable basis, and/or modes that are uncommon in **use**, that is, modes which are not widely used in modern applications.

Despite being uncommon, these modes are important for several reasons. One of these reasons is that some of these modes can in fact support long-distance communications at VHF using only “natural” infrastructure instead of man-made technologies such as satellites, active repeaters, etc.

Even when uncommon modes cannot be reliably used for communications, they can intermittently and unpredictably lead to signal reception well outside of normal VHF ranges. This can have significant implications for direction finding and signals intelligence applications, especially when attempting to use received signal strength to estimate the proximity of that signal's source.

Although there are many uncommon propagation modes at VHF, this paper will address only the four most important uncommon modes: tropospheric ducting, sporadic E, meteor burst, and EME.

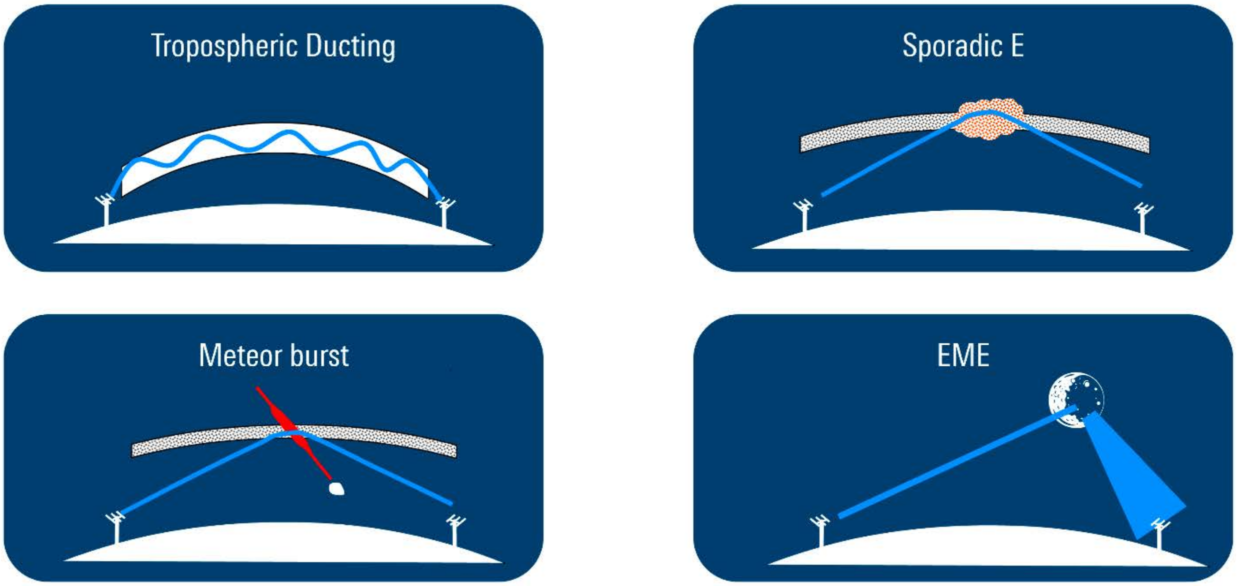

Figure 11: Most important uncommon VHF propagation modes

3.2 Tropospheric ducting

3.2.1 About temperature inversions

Section 2.2.1 discussed how the refractive index of the troposphere normally decreases with altitude. Recall that atmospheric pressure decreases steadily as altitude increases, and air temperature also normally decreases with altitude: that is, higher air layers are normally colder than lower air layers. However, some weather patterns can cause warmer air to be present over colder air, and this is referred to as a **temperature inversion** (Figure 12). These inversions can cause large and abrupt changes in the troposphere's refractive index and lead to the formation of tropospheric ducts.

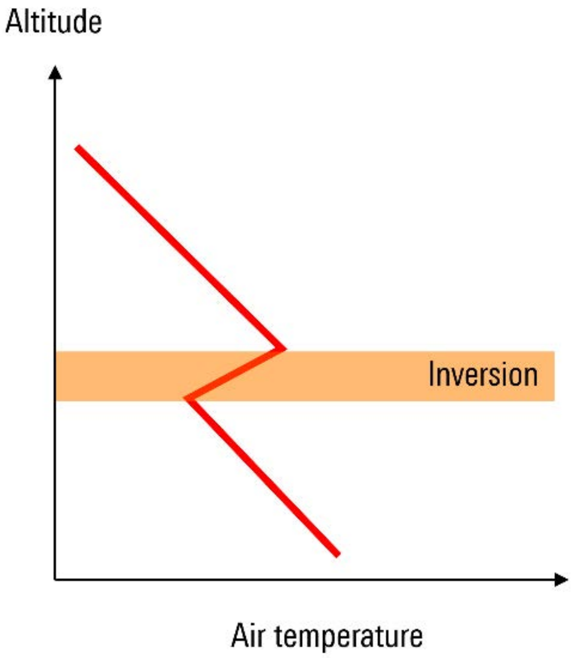

Figure 12: Temperature inversion

3.2.2 Properties of tropospheric ducting

Tropospheric ducting occurs when signals are refracted back and forth between two boundaries in a way similar to how signals travel along a waveguide. This is illustrated in Figure 13. Signals that are propagated via ducting often have very high signal strengths. Ducts are essentially two dimensional, and therefore ducted signal strength decreases more or less linearly with distance. Contrast this to propagation in three dimensions in which power decreases by the **square** of the distance.

Ducts are capable of carrying VHF and higher frequency signals for very long distances – up to 1500 kilometers or more in some cases. Ducts tend to build up and fade away gradually, but once formed, ducts typically persists for at least a couple of hours and may last up to several days.

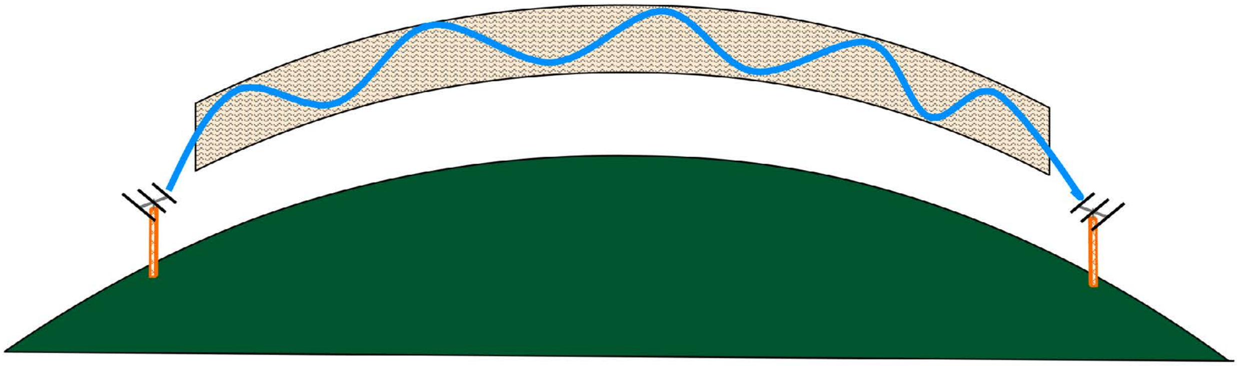

Figure 13: Principle of tropospheric ducting

3.2.3 Ducts and frequency

Tropospheric ducting can propagate signals with frequencies from the lower VHF range up to UHF and above. Similar to the way in which a waveguide functions, the width of the inversion or duct determines the frequencies that can be propagated through the duct: the thinner the inversion layer or duct, the higher the minimum frequency of signals that it can propagate.

It is not uncommon for ducts to become thicker over time, and this increased thickness then allows the propagation of lower-frequency signals. In other words, a newly formed duct may start by propagating only higher frequency signals and then later begin propagating lower frequency signals.

3.2.4 Ducting and weather

Tropospheric ducting can often be predicted or forecasted using standard meteorological information. For example, if a region of warm air intersects a region of cooler air and slides above it, this can create a temperature inversion and ducting. Note however that stable air masses are needed for the creation of temperature inversions and ducts. If the atmosphere becomes unsettled or "well mixed," such as following a storm, then formation of ducts becomes much less likely. Ducts may also move with the weather – in North America this movement follows the prevailing west to east weather pattern.

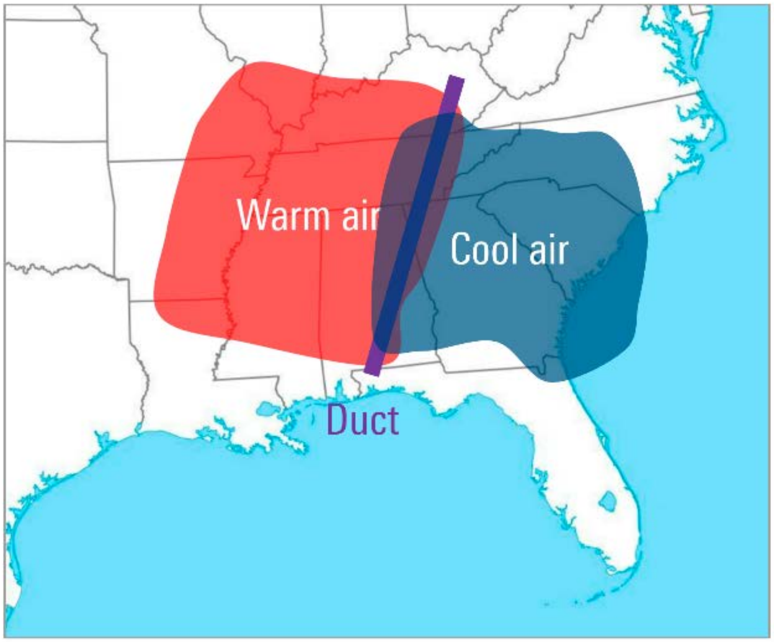

Figure 14: Duct formed at intersection of different air masses

3.2.5 Types of tropospheric ducts

Depending on how they are formed, ducts can be classified as either **surface ducts** or as **elevated ducts**.

3.2.5.1 Surface ducts

Surface ducts are created by a single discontinuity in the troposphere's refractive index. This discontinuity forms the top boundary of the duct and the Earth's surface forms the lower boundary. Generally speaking, surface ducts do not propagate signals well over land. The land surface of the Earth is lossy and irregular, and both natural and man-made obstacles along the path of a surface duct will scatter and absorb signals. Surface ducts do however propagate signals well over large, calm bodies of water, and these types surface ducts are often responsible for very long distance tropospheric propagation at VHF frequencies, particularly in coastal regions.

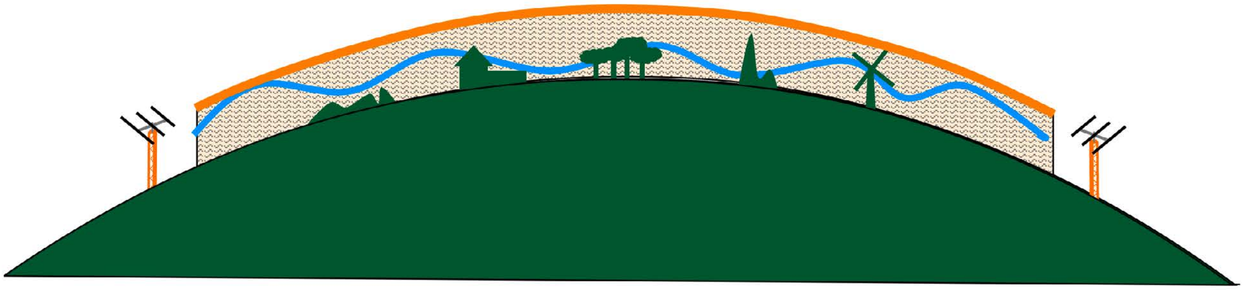

Figure 15: Surface duct

3.2.5.2 Elevated ducts

Elevated ducts are created by **two** discontinuities in the troposphere. The upper discontinuity refracts signals downwards and the lower discontinuity refracts signals upwards, with signals being propagated between these two discontinuities. Elevated ducts typically form at altitudes of a few hundred meters to a few kilometers. Since this is above many surface features, elevated ducts normally are able to propagate signals for longer distances over land compared to surface ducts.

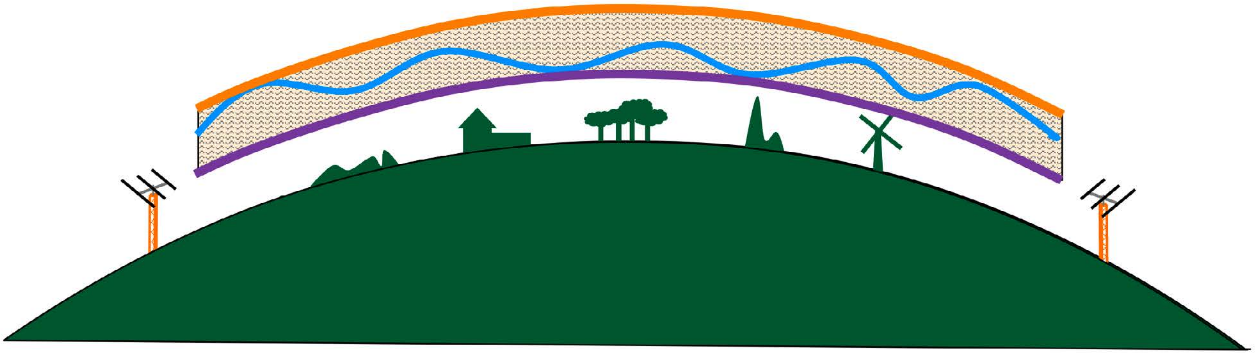

Figure 16: Elevated duct

3.2.6 Propagation along ducts

Regardless of the type of duct, optimal propagation conditions are observed between stations at or near opposite ends of the ducts. In many cases, stations that are along the path of an elevated duct may not be able to launch signals into or receive signals from the duct. Some ducts are however "leaky" and will allow signals to enter or exit the duct at various points along the path.

3.3 Sporadic E

3.3.1 About ionospheric propagation

Unlike tropospheric ducting, which occurs in the troposphere, Sporadic E, also called "E-skip" and "Es," is a form of ionospheric propagation. The ionosphere, a layer of charged particles surrounding the Earth, consists of several layers. One of these layers, the F layer, can refract or bend signals at HF frequencies back towards the Earth, enabling very long distance communications under the proper conditions. This is commonly called "skywave" propagation. However, at VHF and higher frequencies, signals reaching the ionosphere are generally not refracted back to Earth and simply pass through the ionosphere and continue into space.

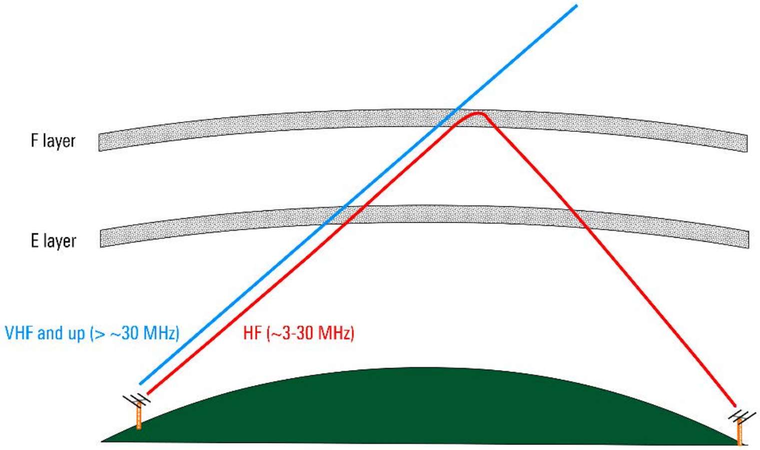

Figure 17: Normal ionospheric refraction

Below the F layer there is another layer of the ionosphere called the E layer, but under normal circumstances the E layer is not capable of refracting either HF or VHF signals back towards Earth. However, under special circumstances, patches or regions of increased ionization in the E layer can refract signals at lower VHF frequencies, enabling limited skywave propagation over longer distances. This is shown in Figure 18.

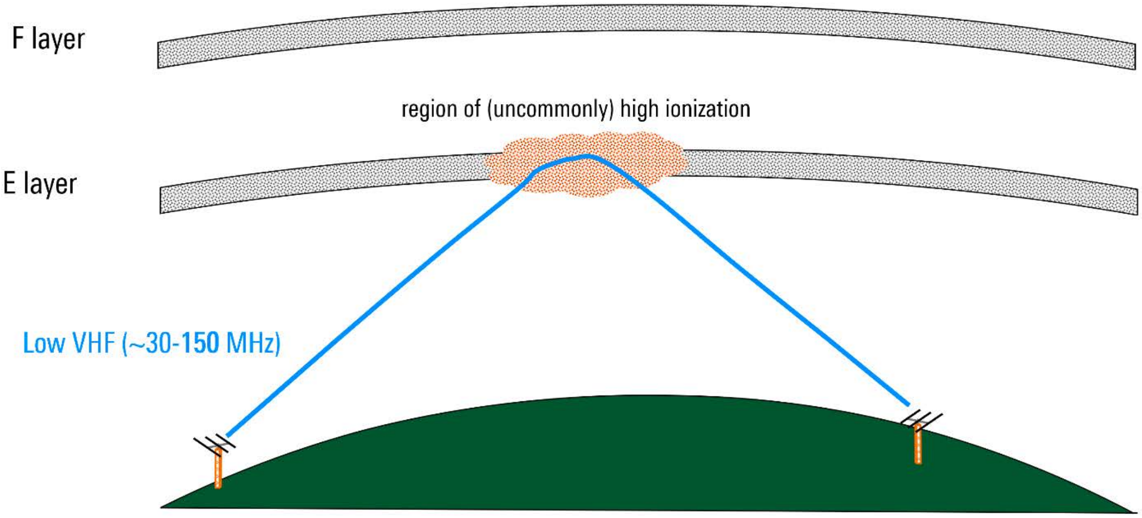

Figure 18: Principle of sporadic E

3.3.2 Principles of sporadic E

Sporadic E refers to propagation by means of these highly ionized regions or "clouds" in the E-layer of the ionosphere. This phenomenon takes place at altitudes of approximately 100 kilometers above the Earth's surface and can last from minutes to up to an hour or more. The signals propagated by sporadic E often have low path loss and therefore lead to high receive signal strengths at the receiver.

Sporadic E generally only propagates signals at lower VHF frequencies (< 150 MHz) but maximum propagation distances are typically in the range of 700 to 2500 kilometers. Because of the lower altitude of the E layer, these distances are somewhat lower than the distances achievable with F layer skywave propagation of HF signals.

This mode of propagation is called "sporadic" because it is difficult to predict, but it is still common enough to create problems. For example, early European TV broadcasters and American FM radio broadcasters moved up from their original frequencies in part to avoid issues caused by sporadic E.

3.3.3 Mapping sporadic E

The location and dimensions of sporadic E clouds can be mapped using reception reports between pairs of stations. If lines are drawn between transmitters and receivers, the intersection of these reports will often show the rough size and center position of the cloud (Figure 19).

Sporadic E clouds are however not stationary, and they tend to slowly move over the course of their appearance. In the Northern hemisphere, this motion is generally north or northwest and is caused by both winds in the upper atmosphere as well as the Earth's rotation.

Figure 19: Mapping sporadic E clouds

3.3.4 Causes of sporadic E and predicting sporadic E

There are many different theories about the origin of sporadic E, and as yet there is still no definitive, universally-accepted cause. Experiments have shown that sporadic E clouds contain high concentrations of metallic ions, and one of the more popular theories is that wind shear or other types of "violent" weather create thin layers of E-layer ionization. However, the lack of a clear, measurable cause makes sporadic E difficult to predict.

It is known that peaks in sporadic E activity occur between May and August in the Northern hemisphere, with some smaller peaks in December and January. And while there are studies that suggest that sporadic E may somehow be linked to meteor activity or solar activity, there is still no conclusive correlation between these phenomena and the appearance of sporadic E.

3.3.5 Sporadic E versus tropospheric ducting

Although they are very different modes of propagation, both tropospheric ducting and sporadic E can produce strong signals over large geographic areas. There are however ways to identify which of these two modes is responsible for extended range reception at VHF. As discussed above, sporadic E clouds can connect many different locations, whereas in tropospheric ducting, signals usually only propagate between endpoints or (sometimes) along the path between them. Another difference is that sporadic E tends to appear and disappear rather suddenly, whereas tropospheric ducts normally build up and fade out more slowly and also tend to last longer than sporadic E clouds.

3.4 Meteor burst

3.4.1 Overview of meteor burst

Meteor burst (also called meteor scatter) refers to a form of ionospheric propagation at VHF frequencies. Meteors leave highly ionized trails as they burn up in the Earth's atmosphere, although this increased ionization typically lasts only a few seconds. Meteor heating begins at an altitude of about 120 km and most meteors are completely burned up before they reach an altitude of 80 km – these heights correspond to the altitude of the E layer of the ionosphere. These ionization trails are roughly cylindrical, usually many kilometers long but only a few meters wide, and can be used to reflect VHF signals back towards Earth. In this way, meteor burst can enable long-distance, skywave communications at lower VHF frequencies.

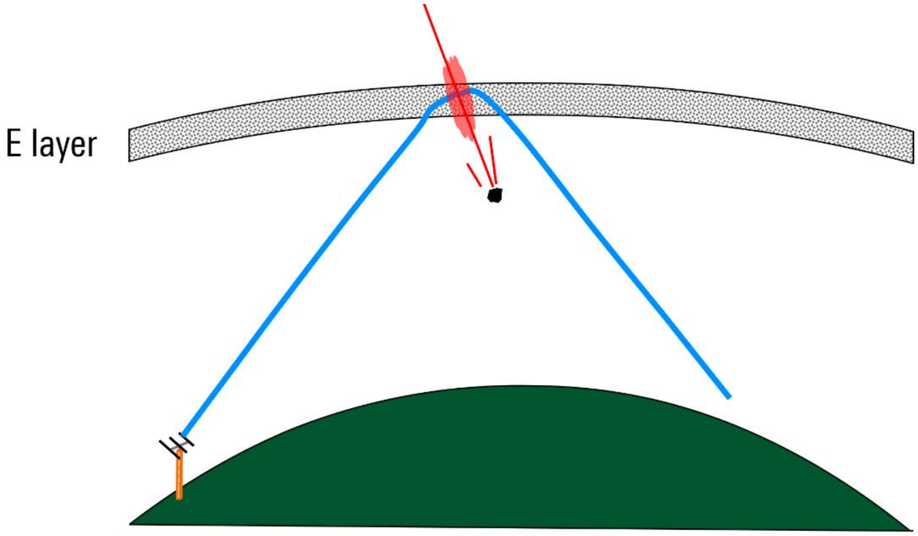

Figure 20: Principle of meteor burst

3.4.2 Meteor ionization as a function of size and velocity

Although not normally visible to human observers, many millions of meteors enter the Earth's atmosphere every day. Most of these meteors are very small – on the order of less than a millimeter to less than a centimeter in diameter. However, even small meteors are capable of creating ionization that can reflect signals at VHF. The ionization created by a meteor is function of both its velocity as well as its mass. Most meteors enter the atmosphere at speeds of 10 to 100 kilometers per second, and higher-speed meteors create greater ionization. Larger meteors burn for longer periods of time and thus create more intense, longer-duration ionization.

3.4.3 Types of meteors

Meteors can be grouped into two general categories. The first of these are meteors which occur as part of a meteor "shower" and the second are so-called sporadic meteors which occur year-round.

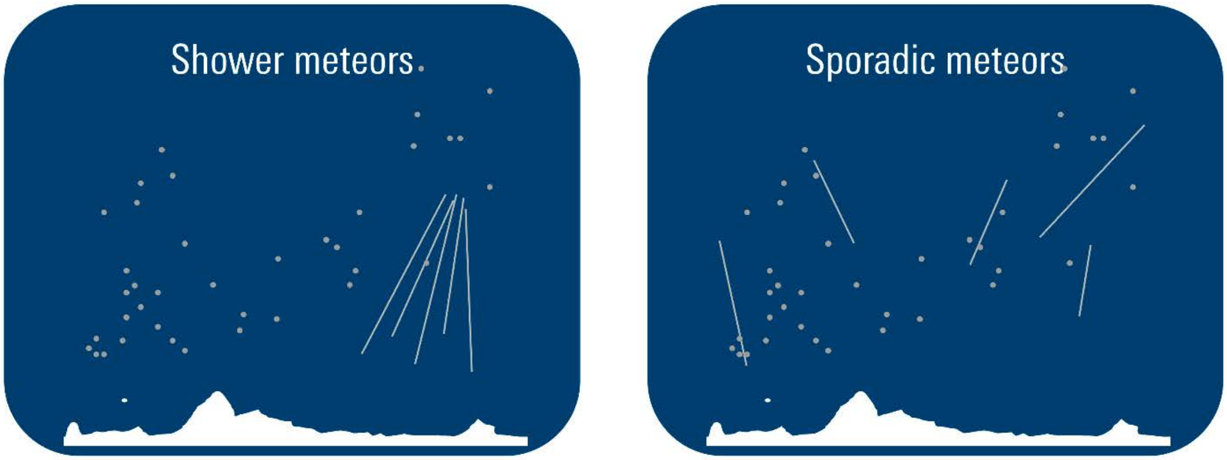

Figure 21: Two types of meteors

3.4.3.1 Shower meteors

Meteor showers are created when the Earth moves through fields of debris. It is generally believed that these debris fields are material left behind comets. These debris fields travel in known, fixed orbits around the sun, and thus the showers that they create occur periodically on predictable dates. One of the best known and largest meteor showers are the Perseids which occur every year in August.

Most meteor showers usually last for approximately one day, and during this time, the number of meteors entering the atmosphere increases by up to an order of magnitude. In fact, the larger showers often create large numbers of trails that are visible to the naked eye. However, since these showers are intermittent, they are less useful as a source of reliable propagation at VHF.

3.4.3.2 Sporadic meteors

The vast majority of meteors are sporadic. "Sporadic" means there is no way to predict precisely when or where these meteors will appear, and sporadic meteors also enter the atmosphere from random locations in the sky. The quantity of sporadic meteors does however vary in a somewhat predictable way during the course of a year. Generally, the greatest numbers of sporadic meteors enter during the months of June through August, and the least number enter the Earth's atmosphere during the months of February and March.

Time of day plays a very important role when it comes to sporadic meteors. As the Earth travels around the sun, it also rotates on its axis. This rotational velocity is added to or subtracted from the velocity of meteors coming in contact with the Earth. In the **morning**, the Earth's rotational velocity is **added** to the meteor's velocity. In the **evening**, the Earth's rotational velocity is **subtracted** from the meteor's velocity. This added or subtracted velocity can be up to 30 kilometers per second. Since higher speed means higher ionization, peak meteor-burst ionization normally occurs in the morning between 4 a.m. and 8 a.m. local time.

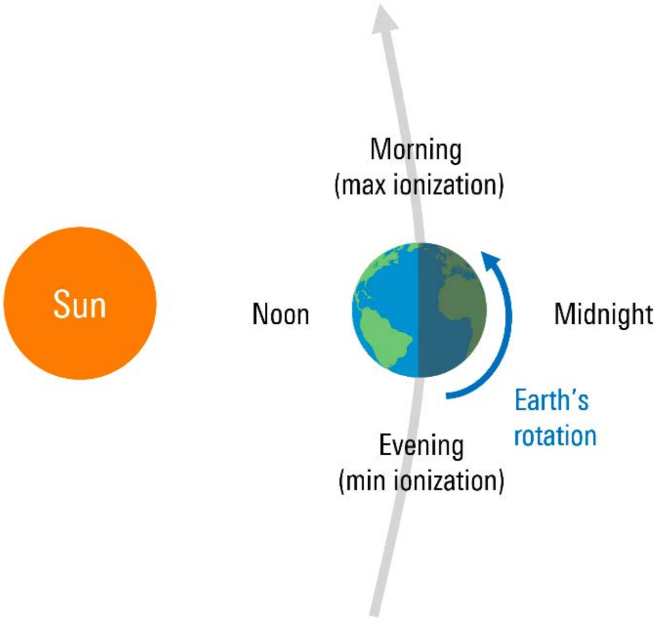

Figure 22: Time of day and meteor ionization

3.4.4 Applications of meteor burst

On average the ionized trails left by meteors only last several seconds, but can still be used for communications. Messages conveyed using meteor burst propagation must however be short and/or be spread across multiple transmissions. For this reason, meteor burst communication is most often used for non-realtime data collection, particularly in areas where cellular or other communications technologies may not be available.

An example of this is the United States Department of Agriculture's SNOTEL (snow telemetry) system, which has been in operation since the 1960s. SNOTEL collects snow and other weather related data from remote locations across the western United States and transmits this data using meteor burst technology. Sites are typically battery and solar powered and often operate for a year or more without maintenance. The system wide polling response rate in SNOTEL is greater than 95%, which demonstrates that meteor burst can provide reliable communications from locations where other technologies may be unavailable.

3.4.5 Distances and frequencies

The achievable distances and usable frequencies are also important considerations for meteor burst communications. Since meteor burst is a form of ionospheric E-layer propagation, the achievable distances are largely a function of the height of the E-layer. Maximum distances for meteor burst can be up to approximately 2000 kilometers, but there is also a minimum distance of about 500 kilometers – this "skip zone" is similar to that seen in HF skywave communications.

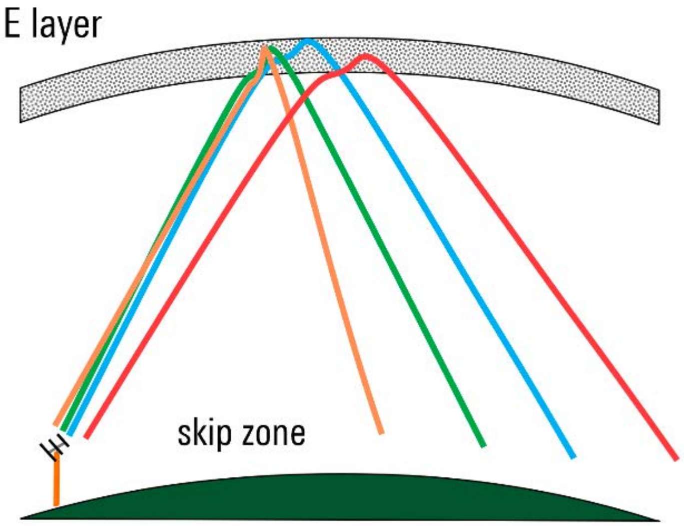

Figure 23: Skip zone in meteor burst communications

With regard to frequencies, the ionization created by meteor trails is usable for longer periods of time at lower frequencies. The maximum practical frequency for meteor burst communications is approximately 150 MHz. It should also be noted that ionized meteor trails expand due to the rapid and extreme heating during burn-up, and this signals reflected from meteor trails may therefore experience Doppler shift. The amount of shift is frequency dependent, but can be as high as 2 kHz at the upper end of frequency range used in meteor burst communications.

3.5 EME

3.5.1 The moon as a reflector

Section 2.3.1. discussed how natural terrestrial reflectors, such as mountains, can be used to extend the range of signals at VHF and higher frequencies. Under certain circumstances, this same principle can be applied to the Earth's moon. Using the moon to reflect radio signals can greatly increase maximum VHF communications range. This type of propagation is most often called EME or "Earth-Moon-Earth," although the older term "moonbounce" is also sometimes heard.

The first experiments into EME were made by the United States military in the 1940s, and by the 1950s and 1960s, EME was shown to be viable for use in both radar and communications. Although EME was never widely adopted for these applications, it was successfully used for many years in signals intelligence applications. For example, the Arecibo dish in Puerto Rico was used during the Cold War to monitor Soviet signals that were unintentionally reflected back to Earth by the moon.

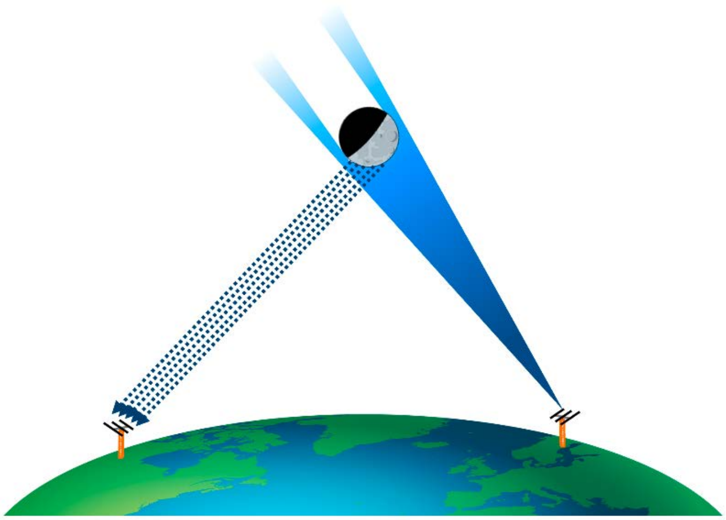

Figure 24: Principle of EME

3.5.2 Advantages of EME

The greatest advantage of EME is that it can provide reliable and predictable worldwide coverage at VHF and higher frequencies: this is not possible using any other VHF propagation mode. But as discussed below, the ability to use EME is strongly dependent on the position of the moon and the positions of both the transmit and the receive stations. However, once this condition is satisfied, EME is highly reliable when using proper equipment: although the path loss is very high, it is also well-known and relatively constant. Another advantage of EME is that, unlike most other HF or VHF propagation modes, it is not dependent on ionospheric or tropospheric propagation conditions. This in turns means that EME can be used as a backup or fallback communications mode when tropospheric or ionospheric conditions do not support using other propagation modes.

3.5.3 Challenges of EME

There are however significant challenges in using EME and these challenges can be grouped into two categories. The first is the very high path loss, which in turn requires high transmit powers, high gain antennas, and low-noise receivers. The second is that the moon itself is a challenging reflector. The moon is both a small target as well as a moving target, and the moon also has a very rough and irregular surface. These challenges will be discussed in more detail in the following sections.

Figure 25: EME challenges

3.5.3.1 EME path loss

Path loss is, by far, the greatest challenge when using EME. The two way path loss between Earth and its moon is often 250 dB or more, and this path loss increases with increasing frequency. Path loss is a function of many factors, one of which is the distance between the earth and moon, which changes due to the moon's elliptical orbit. Path loss can vary by about 2 dB between apogee, that is, when the moon is farthest away, and perigee, when the moon is closest to Earth. High transmit power is the primary method used to overcome the high path loss in EME.

3.5.3.2 EME antennas

In addition to high transmit powers, high gain antennas are another way of overcoming path loss. EME antennas are usually either large parabolic antennas or arrays of antennas. Ideally, antennas used for EME should have circular polarization or switchable polarization in order to deal with losses due to Faraday rotation (discussed in section 3.5.4). Regardless of antenna type, EME requires antennas that are adjustable in both azimuth and in elevation, since the moon is a moving target that must be tracked as it moves across the sky.

3.5.3.3 EME and noise

The high EME path loss also means that reducing received noise is critically important in EME. As with other forms of radio communication, noise in EME can be from external sources, either on the Earth or in space, or the noise may be internal generated from components and devices within the EME system or receiver itself.

Since the received signals can be very small, using sensitive receivers and low noise amplifiers is vital in EME. Noise figure is the most important figure of merit when building an EME system. Time of day can also play a role reducing noise, and nighttime operation is sometimes preferred since this can reduce the amounts of both man-made and solar noise. In addition, the position of the moon in the sky can also affect the amount of received noise.

3.5.3.4 Position of the moon

In order to use the moon as a reflector, it must be above the radio horizon for both stations. Atmospheric refraction, discussed in section 2.2.2, does however mean that the moon can be used as a reflector even when it is slightly below the geographic horizon.

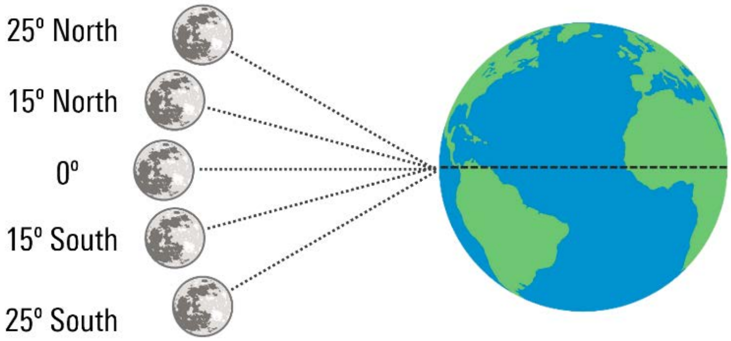

Figure 26: Declination of the moon

The position of the moon in the sky also influences the amount of received noise. Various celestial bodies, such as planets, generate radio frequency noise. Another way of saying this is that at any given time, some parts of the sky are more "quiet" than others. In particular, the sun and the moon should not be close together in the sky when attempting communications via EME. Although there are tools available for estimating the best operating times for a pair of geographical locations, the declination of the moon can often offer some guidance. Declination is the elevation of the moon relative to the equator: the moon moves through a declination range of approximately plus to minus 25 degrees over the course of a month, and generally speaking, the higher the declination, the lower the received noise.

3.5.3.5 Motion of the moon

Since the moon is a moving target, both EME stations must track and point their antennas at the moon as it moves across the sky. As seen from Earth, the moon moves through a 2-5° degree arc approximately every 10 minutes, so antennas must be periodically re-pointed to follow the moon, typically every 5 to 10 minutes. The antenna repointing frequency or interval – that is, how often the antenna must be re-positioned – is also a function of the antenna beamwidth: an antenna with a narrower main beam will have higher gain, but will need to be re-pointed more often than an antenna with a wider beamwidth.

The relative motion between the moon and the Earth also means that signals reflected from the moon will be shifted in frequency. When the moon is rising or moving towards the observer, received signals will be shifted up in frequency, and when the moon is setting, or moving away from the observer, frequencies will be shifted downwards. Like all other Doppler shifted signals, the amount of shift depends on frequency, with greater Doppler shift occurring for higher frequency signals.

3.5.3.6 Surface of the moon

The surface of the moon also plays a role in EME communications. As discussed in section 2.5, an effective radio frequency reflector should be large relative to signal wavelength and flat or smooth. Although the moon clearly meets the size requirement, it is not a particularly good reflector due to its rough and uneven surface. The moon's surface therefore will scatter rather than reflect most of the signals reaching it, and only about 6-7% of the signal received by the moon will be returned in the direction of the Earth.

This situation is exacerbated by the fact that the moon "wobbles" slightly on its axis, and the loss due to this wobbling is called libration fading. Libration fading causes fluctuation in received signal power, with the variation in loss usually in the range several dB. This in turn sometimes causes choppiness or fluttering in demodulated EME signals.

3.5.4 EME and the ionosphere

The ionosphere also plays a role in EME. In HF, and sometimes in VHF, refraction or "bending back" of signals by the ionosphere is desirable because this can increase the maximum communication range. However, EME requires that signals pass **through** the ionosphere. The appearance of phenomena such as sporadic-E (section 3.3) and meteor bust (section 3.4), can cause the ionosphere to return VHF signals to Earth and therefore prevent EME communications.

Another potential ionospheric issue is Faraday rotation. Faraday rotation refers to random changes in the polarization of a signal as it passes through the ionosphere. This rotation tends to be inversely related to frequency and is generally limited to signals under about 1 GHz. Faraday rotation can lead to so-called polarization loss, whereby signal strength is reduced due to a mismatch between the polarization of the transmit and receive antennas. Using circularly polarized antennas or rotating a linearly-polarized antenna are the two most common ways of reducing the effect of Faraday rotation in EME.

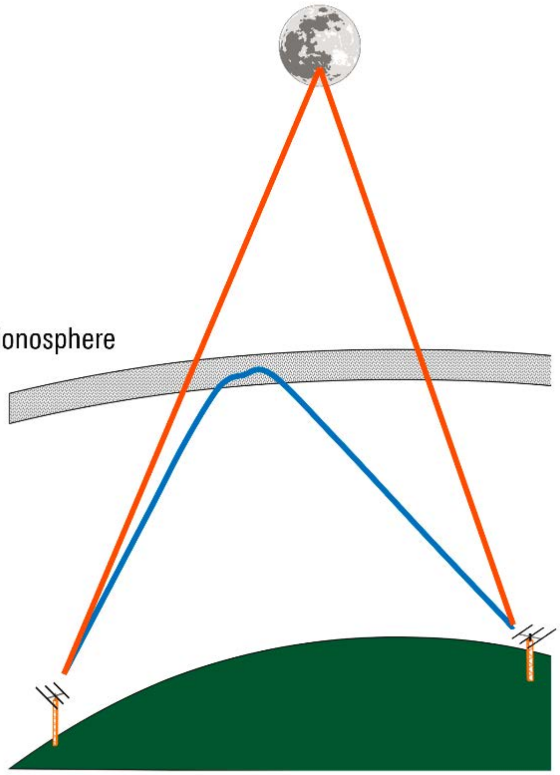

Figure 27: EME and the ionosphere

3.6 Summary of uncommon VHF propagation modes

Neither tropospheric ducting nor sporadic E are sufficiently predicable for use in reliable communications at VHF. Although "openings" do occur throughout the year, the number of openings between specific geographical endpoints is usually quite small, further reducing the effectiveness of these modes for VHF communications. These modes do however create very strong reception outside of their normal ranges, so the significance of tropospheric ducting and sporadic E is that they can create interference, sometimes for several hours or even days. Therefore, it is important to be aware of the possibility of receiving strong distant signals due to these modes.

Meteor burst can be used for reliable non-realtime communication. This is usually accomplished using the sporadic meteors that are constantly entering the Earth's atmosphere, although the appearance of meteor showers may further enhance performance. And while meteor burst does only provide very modest data rates, the station requirements are also very modest, with battery or solar power often being sufficient.

EME is capable of providing worldwide coverage at VHF under the proper circumstances. Although EME path loss is quite high, it is predictable and can be addressed using high power transmitters, high gain antennas, and low noise components.

3.7 Future of uncommon VHF propagation modes

An important reason for studying uncommon VHF propagation modes is that there is growing interest in alternative or backup modes for communications. For example, the vulnerability of satellites has increased interest in HF for worldwide communications coverage, since HF communications only requires the "natural" infrastructure of the ionosphere to accomplish this. Uncommon VHF propagation modes such as meteor burst and EME have numerous advantages when it comes to providing an alternative or backup to other forms of communications. First, they require no infrastructure between the stations other than natural features such as the troposphere, ionosphere, or the moon. These are also tested or proven technologies: both meteor burst and EME were first researched and used for communications over 50 years ago. They can also provide reliable, although somewhat low-throughput, communications, and under the right conditions they can provide coverage at the continent or global level. Finally, uncommon VHF propagation modes are relatively immune to solar weather, meaning that they are not disrupted by events such as solar flares, coronal mass ejections, etc. that can cause blackouts at HF.

4 SUMMARY

VHF is widely used in broadcasting, in voice and data communications, in avionics, and even in some types of radar. Although it is commonly believed that VHF propagation is mostly “line of sight,” true line of sight propagation is in fact relatively rare in terrestrial applications. Signals at VHF normally experience refraction, reflection, diffraction, and scattering, with these effects often increasing with distance.

In addition to these common propagation modes, there are also several uncommon modes at VHF. This educational note provided an introduction to the four most important of these modes: tropospheric ducting, sporadic E, meteor burst, and EME. Tropospheric ducting and sporadic E are not commonly used for communications due to their unpredictable appearance, but they are both sufficiently common that they can create issues with regard to interference, direction finding, and signals intelligence applications Other modes, such as meteor burst and EME, can however provide reliable long-distance communication at VHF, and thus represent potential backup communications methods at the regional or global level.

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