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Chapter 19
Propagation of Radio Signals

Radio waves are what amateur radio is all about, so it's very important for amateurs to understand how they *propagate*, or travel, from point to point. In addition, we need to understand how events ranging from local weather to solar activity affect radio wave propagation. Learning about these things makes us more effective operators and station builders.

This chapter has been comprehensively updated from previous editions by Carl Luetzelschwab, K9LA, with additional input from Frank Donovan, W3LPL, Ward Silver, NØAX, Ethan Miller, K8GU, and Hermann Schumacher, DF2DR. The material provides a basic understanding of the principles of electromagnetic radiation, the structure of the Earth's atmosphere, and solar-terrestrial interactions necessary for a working knowledge of radio propagation. The section on VHF/UHF mobile propagation was contributed by Alan Bloom, N1AL. More detailed discussions and the underlying mathematics of radio propagation physics can be found in the references listed at the end of this chapter.

19.1 Fundamentals of Radio Wave Propagation

Radio belongs to a family of electromagnetic radiation that includes infrared (radiation heat), visible light, ultraviolet, X-rays, and the even shorter-wavelength gamma and cosmic rays. Radio has the longest wavelength of this group and thus the lowest frequency frequency (see **Table 19.1**).

Electromagnetic radio waves are composed of an interrelated electric and magnetic field. The electric and magnetic components are oriented at right angles to each other and are also perpendicular to the direction of travel. The polarization of a radio wave is usually designated the same as the orientation of its electric field. This relationship can be visualized in **Figure 19.1**. Unlike sound waves or ocean waves, electromagnetic waves need no propagating medium, such as air or water. This property enables electromagnetic waves to travel through the vacuum of space.

A radio wave far enough from its source to appear flat is called a *plane wave*. From here on, we will be discussing plane waves. The path taken by a plane wave is called a *ray*. Traced from its source to any point on a spherical surface, such as the Earth, the ray will follow a straight line on an *azimuth-equidistant* map projection with the source at its center. (See the sidebar Azimuth-Equidistant Maps.)

19.1.1 Velocity

Radio waves, like all forms of electromagnetic radiation, travel nearly 300,000 kilometers (186,400 miles) per second in a vacuum. The speed of a radio wave is always the product of wavelength and frequency, whatever the medium. That relationship can be stated simply as:

$$c = f\,\lambda$$

where

c = speed in meters/second,
f = frequency in Hz, and
λ = wavelength in meters.

The wavelength (λ) of any radio frequency can be determined from this simple formula by rearranging the above equation to $\lambda = c/f$. For example, in free space the wavelength of a

Table 19.1
The Electromagnetic Spectrum

Radiation	*Frequency*	*Wavelength*
Radio	10 kHz – 300 GHz	30 km – 1 mm
Infrared	300 GHz – 428.6 THz	1 mm – 700 nm
Visible light	428.6 THz – 750 THz	700 nm – 400 nm
Ultraviolet	750 THz – 3×10^3 THz	400 nm – 100 nm
Extreme Ultraviolet	3×10^3 THz – 3×10^4 THz	100 nm – 10 nm
"Soft" X-ray	3×10^4 THz – 3×10^5 THz	10 nm – 1 nm
"Hard" X-ray	3×10^5 THz – 3×10^6 THz	1 nm – 0.1 nm

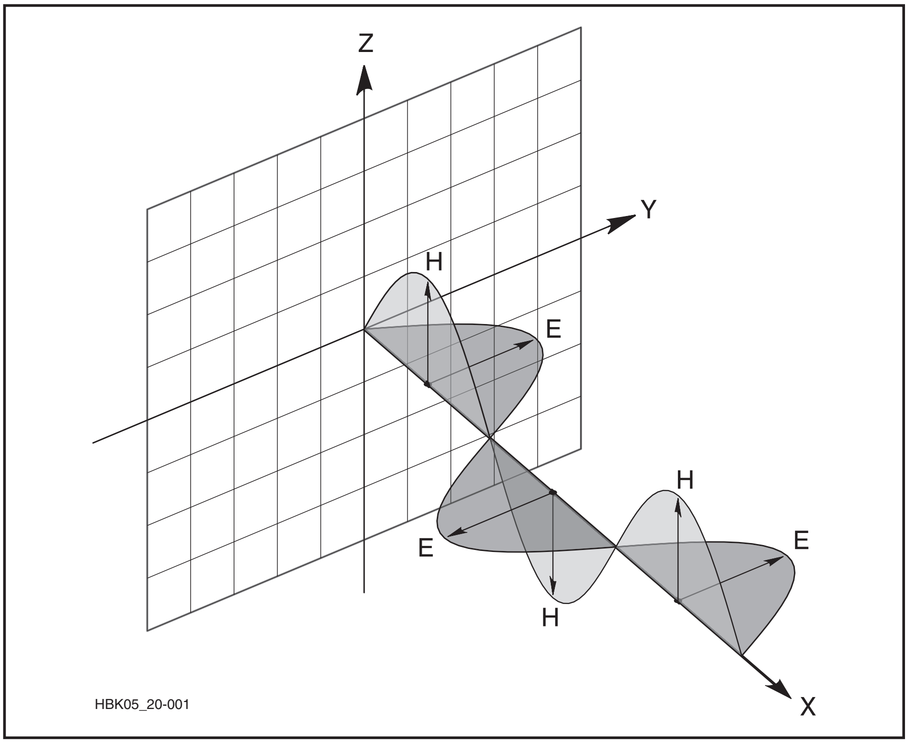

Figure 19.1 — Electric and magnetic field components of the electromagnetic wave. The polarization of a radio wave is the same direction as the plane of its electric field.

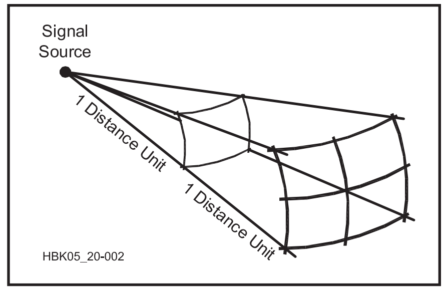

Figure 19.2 — Radio energy disperses as the square of the distance from its source. For the change of one distance unit shown the signal's power per unit of area is only one quarter as strong. Each spherical section has the same surface area.

30 MHz radio signal is thus 10 meters. A simplified equation in metric units is λ in meters = 300 divided by the frequency in MHz. Alternately, λ in feet = 984 divided by the frequency in MHz. Wavelength decreases in other media because the propagating speed is slower.

Radio waves travel more slowly through any other medium than the vacuum of free space. The decrease in speed through the atmosphere is so slight that it is usually ignored, but sometimes even this small difference is significant. The speed of a radio wave in a piece of wire, by contrast, is about 95% of that in free space, and the speed can be even slower in other media.

The reduction of velocity is expressed as the *velocity factor* (VF), which is a value between 0 and 1 representing the medium's fraction of free-space velocity. For example, if the wave travels in RG-213 coaxial cable at 66% of the free-space velocity, the VF for RG-213 is 0.66. Velocity factor must be taken into consideration in antenna designs, in transmission line designs, and in other applications.

19.1.2 Free-Space Attenuation

Free-space attenuation results from the spherical spreading of radio energy as it travels from its source (see **Figure 19.2**). Attenuation grows rapidly with distance because signal strength decreases with the square of the distance from the source. (The signal's field strength in V/m decreases linearly with distance, and its power density in W/m^2 decreases with the square of the distance.) In free space, if the distance between transmitter and receiver is increased from 1 kilometer to 10 kilometers (0.6 to 6 miles), the signal power will be reduced by a factor of 100 (20 dB). Attenuation increases with frequency as well (for example, doubling the frequency results in 6 dB more free-space path loss). Free-space attenuation (path loss) is

$$L_{fs} = 32.45 + 20 \log d + 20 \log f$$

where

L_{fs} = free space path loss in dB,
d = distance in kilometers, and
f = frequency in MHz.

Enhancements (especially at VHF and above) can increase signal strength at the receiver due to multi-path and scattering. Thus, the L_{fs} equation above may not be valid for actual terrestrial conditions.

19.1.3 Losses of Propagation

Radio energy is also lost during refraction, scattering, reflection, and knife-edge diffraction — the very phenomena that can allow long-distance propagation. Indeed, any form of useful propagation is accompanied by attenuation. This may vary from the slight losses encountered by refraction from sporadic E clouds near the maximum usable frequency, to the more considerable losses involved with tropospheric forward scatter (not enough ionization for refraction or reflection, but enough to send weak electromagnetic waves off into varied directions) or D region absorption in the lower HF bands.

Free-space attenuation is a major factor governing signal strength, but radio signals undergo other losses. Energy is lost to *absorption* when radio waves travel through media other than a vacuum. Radio waves propagate through the ionosphere or solid material (like a wire) by exciting electrons, which then reradiate energy at the same frequency. The amount of radio energy lost depends on the characteristic of the medium and on the frequency. In many circumstances, total losses can become so great that radio signals become too weak for communication (they are below the sensitivity of a receiver or receiving system).

19.1.4 Refraction

Electromagnetic waves travel in straight lines until they are deflected by something. Radio waves are *refracted*, or bent, slightly when traveling from one medium to another. *Refraction* is the bending of a ray as it passes from one medium to another at an angle. The apparent bending of a pencil partially immersed in a glass of water demonstrates this principle quite dramatically. The mediums should extend much more than one wavelength around the region in which refraction takes place. Radio waves behave no differently from other familiar forms of electromagnetic radiation in this regard.

Refraction is caused by a change in the velocity of a wave when it crosses the boundary between one propagating medium and another. If this transition is made at an angle, one portion of the wavefront slows down (or

Azimuth-Equidistant Maps

We can better understand several aspects of long-distance propagation if you become accustomed to thinking of the Earth as a ball. This is easy if you use a globe frequently. A flat map of the world, of the *azimuthal-equidistant* projection type, is a useful substitute.

Also known as great circle maps, these are a projection of the Earth's surface that make all great circle paths straight lines from a given location, which is at the center of the map. The outer perimeter of the map is usually 20,000 kilometers (12,427 miles or halfway around the world), but some mapping programs allow other distances.

An azimuth-equidistant map centered on Newington, Connecticut, is shown in **Figure 19.A**. NS6T provides an online service at **ns6t.net/azimuth/azimuth.html** to generate these maps centered on any location. The ARRL World Map is an azimuth-equidistant map centered on Wichita, Kansas. The program *DX Atlas* by VE3NEA (**www.dxatlas.com**) also presents azimuth-equidistant maps, and it offers the option of adding the terminator (the gray line), the auroral oval, and ionospheric parameters.

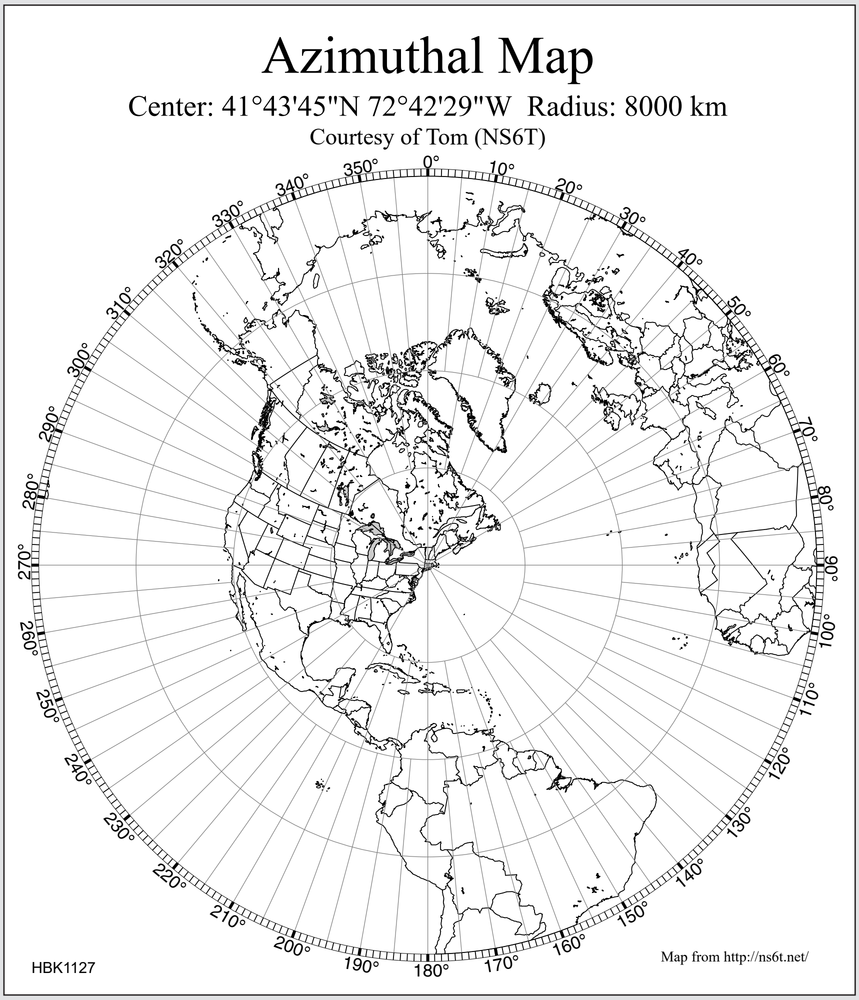

Figure 19.A — Azimuth-equidistant map centered on W1AW out to 8,000 kilometers. (Map provided by ns6t.net/azimuth/azimuth.html)

Optics and Radio Propagation

The four terms *reflection*, *refraction*, *scatter*, and *diffraction* were terms used in optics long before the radio age began. Radio propagation is nearly always a mix of these phenomena, and it may not be easy to identify or separate them while they are happening when we are on the air. This book tends to rely on the words *bending* (refraction) and *scattering* in its discussions, with appropriate modifiers as needed. The important thing to remember is that any alteration of the path taken by energy radiated from an antenna is almost certain to affect on-the-air results.

speeds up) before the other, thus bending the wave slightly. This is shown schematically in **Figure 19.3**.

The amount of bending increases with the ratio of the *refractive indexes* of the two media. The refractive index, n, is simply the velocity of a radio wave in free space divided by its velocity in the medium.

19.1.5 Reflection

Reflection occurs at any boundary between materials of differing dielectric constant when the extent of the materials is on the order of at least one wavelength at the frequency considered. (The surface should extend at least one wavelength from the point at which reflection takes place.) Familiar examples with light are reflections from water surfaces and window panes. Both water and glass are transparent for light, but their dielectric constants are very different from that of air. Light waves, being very short, seem to bounce off both surfaces. Radio waves, being much longer, are practically unaffected by glass, but will be at least partially reflected by a large body of conductive material such as soil or water.

The degree of bending of radio waves at boundaries between air masses which have different indexes of refraction increases with the radio frequency. When the ratio of the refractive indexes of two media is great enough, radio waves can be reflected, just like light waves striking a mirror.

At amateur frequencies above 30 MHz, reflections from a variety of large objects, such as water towers, buildings, airplanes, mountains, and the like, can provide a useful means of extending over-the-horizon paths several hundred kilometers. Two stations need only beam toward a common reflector, whether stationary or moving. A metal surface works well as a reflector if it is several wavelengths in diameter.

Maximum range is limited by the radio line-of-sight distance of both stations to the reflector and by reflector size and shape. The reflectors must be many wavelengths in size and ideally have flat surfaces. Large airplanes make fair reflectors and may provide the best opportunity for long-distance contacts. The calculated limit for airplane reflections is 900 kilometers (560 miles), assuming the largest jets fly no higher than 12,000 meters (40,000 ft), but actual airplane reflection contacts are likely to be considerably shorter.

Reflections from the ionosphere can occur when the plasma frequency (which is proportional to the square root of electron density) is much, much greater than the operating frequency. A good example is sporadic E propagation, since it occurs from a very thin layer

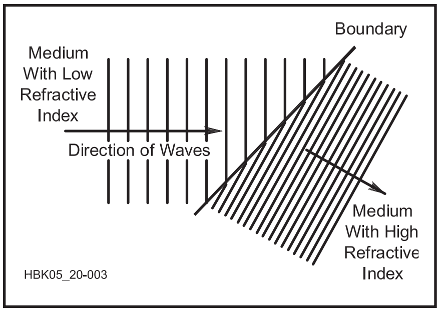

Figure 19.3 — Radio waves are refracted as they pass at an angle between dissimilar media. The lines represent the crests of a moving wave front and the distance between them is the wavelength. The direction of the wave changes because one end of the wave slows down before the other as it crosses the boundary between the two media. The wavelength is simultaneously shortened, but the wave frequency (number of crests that pass a certain point in a given unit of time) remains constant.

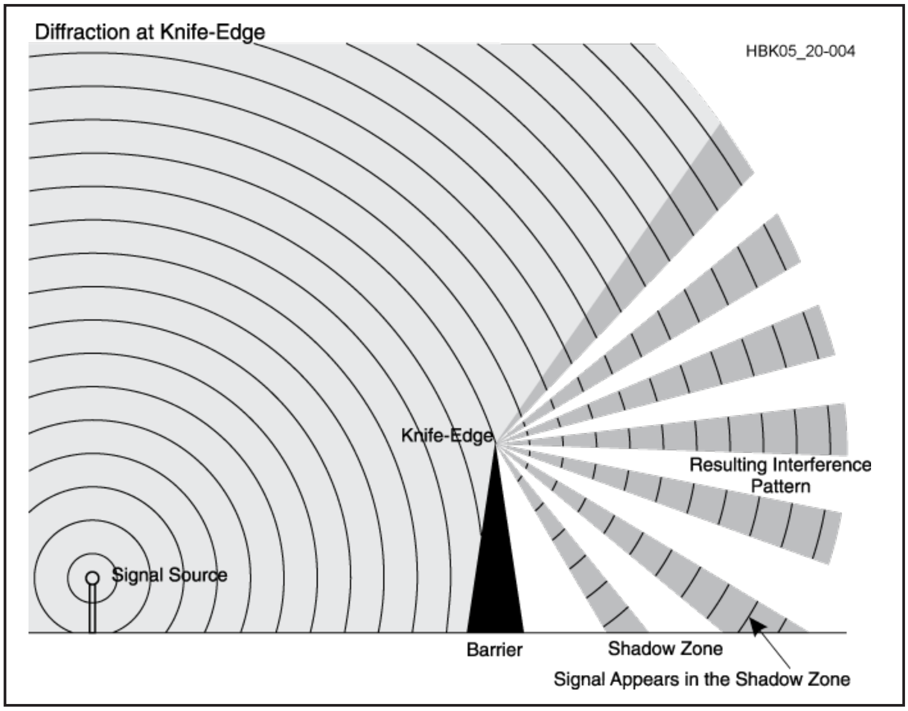

Figure 19.4 — VHF and UHF radio waves, light, and other waves are diffracted around the sharp edge of a solid object that is large in terms of wavelengths. Diffraction results from interference between waves right at the knife-edge and those that are passing above it. Some signals appear behind the knife-edge as a consequence of the interference pattern. Hills or mountains can serve as natural knife-edges at radio frequencies.

(a couple kilometers) that isn't thick enough to return signals to Earth via refraction.

In material of a given electrical conductivity, long waves penetrate deeper than short ones, and so require a thicker conductive region for good reflection. Thin metal, which is highly conductive, is a good reflector of even long-wavelength radio waves. The Earth is a rather lossy reflector of radio signals. With poorer conductors, such as the Earth's crust, long waves may penetrate quite a few feet below the surface. Soil conductivity ranging from poor (sand and rock) to high (wet, rich soil) affects reflection. Water will also reflect radio waves depending on its conductivity. Distilled water is an insulator but salt- and brackish water have high conductivity. The polarization of the reflected wave also affects reflection losses.

19.1.6 Scattering

The direction of radio waves can also be altered through *scattering*. Scatter is the redirection of an electromagnetic wave in many directions from a medium when the volume of material from which the scattering takes place is much smaller than one wavelength at the frequency being considered. Scatter inherently results in loss.

The effect seen by a beam of light attempting to penetrate fog is a good example of light-wave scattering. Even on a clear night, a highly directional searchlight is visible due to a small amount of atmospheric scattering perpendicular to the beam. Radio waves are similarly scattered when they encounter randomly arranged objects of wavelength size or smaller, such as masses of electrons or water droplets. When the density of scattering objects becomes great enough, they behave more like a propagating medium with a characteristic refractive index.

19.1.7 Knife-Edge Diffraction

Radio waves can also pass behind solid objects with sharp edges, such as a mountain range, by *knife-edge diffraction*. This is a common natural phenomenon that affects light, sound, radio, and other coherent waves, but it is difficult to comprehend. **Figure 19.4** depicts radio signals approaching an idealized knife-edge. The portion of the radio waves that strike the base of the knife-edge is entirely blocked, while that portion passing several wavelengths above the edge travel on relatively unaffected. It might seem at first glance that a knife-edge as large as a mountain, for example, would completely prevent radio signals from appearing on the other side but that is not quite true. Something quite unexpected happens to radio signals that pass just over a knife-edge.

Normally, radio signals along a wave front interfere with each other continuously as they propagate through unobstructed space, but the overall result is a uniformly expanding wave. When a portion of the wave front is blocked by a knife-edge, the resulting interference pattern is no longer uniform. This can be understood by visualizing the radio signals right at the knife-edge as if they constituted a new and separate transmitting point, but in-phase with the source wave at that point. The signals adjacent to the knife-edge still interact with signals passing above the edge, but they cannot interact with signals that have been obstructed below the edge. The resulting *interference pattern* no longer creates a uniformly expanding wave front, but rather appears as a pattern of alternating strong and weak bands of waves that spread in a nearly 180° arc behind the knife-edge.

The crest of a range of hills or mountains 50 to 100 wavelengths long can produce knife-edge diffraction at UHF and microwave frequencies. Hillcrests that are clearly defined and free of trees, buildings, and other clutter make the best knife-edges, but even rounded hills may serve as a diffracting edge. Alternating bands of strong and weak signals, corresponding to the interference pattern, will appear on the surface of the Earth behind the mountain, known as the *shadow zone*. The phenomenon is generally reciprocal, so that two-way communication can be established under optimal conditions. Knife-edge diffraction can make it possible to complete paths of 100 kilometers or more that might otherwise be entirely obstructed by mountains or seemingly impossible terrain.

19.1.8 Surface Wave

In general, an electromagnetic *surface wave* travels along an interface between two media with different dielectric constants or refractive indexes. At HF and lower frequencies, the most common type of surface wave travels along the surface of the Earth and is one aspect of what amateurs refer to as "ground wave" as discussed in the next section.

Surface waves can also travel along an interface between media with two different dielectric constants such as layers of air with different temperatures and humidity or insulating layers with different dielectric constants. At microwave frequencies, surface waves travel along the interface between a dielectric (such as air or plastic) and a conducting surface, usually metal.

A radio wave could be traveling in contact with the ground as a surface wave. As the frequency is raised, the distance over which surface waves can travel without excessive energy loss becomes smaller and smaller. The surface wave can provide coverage up to about 100 miles in the standard AM broadcast band during the daytime, but attenuation is high.

Power from a surface wave is typically not transferred to either medium. The wave's E and H fields become weaker exponentially with perpendicular distance from the interface. This property is called *evanescence*. If one or both of the mediums are lossy or leaky, some power can be transferred from the surface wave, and it will become weaker with increasing distance traveled along the interface.

19.1.9 Ground Wave

Ground wave propagation includes two types of radio wave propagation. One type is surface waves (as discussed above) that travel along the Earth's surface. The second is diffracted waves that are bent around the curvature of the Earth by a special form of diffraction that primarily affects longer-wavelength, vertically polarized radio waves.

Ground wave propagation is most apparent in the 3.5 MHz (80 meter), 1.8 MHz (160 meter), 475 kHz (630 meter), and 137 kHz (2200 meter) amateur bands, where practical ground-wave distances may extend beyond 200 kilometers (120 miles). It is also the primary mechanism used by AM broadcast stations in the medium-wave bands. The term ground wave is often mistakenly applied to any short-distance communication, but the actual mechanism is unique to the longer-wave bands.

Ground wave is most useful during the day at 1.8 and 3.5 MHz, when D region absorption makes skywave propagation more difficult. Vertically polarized antennas with excellent ground systems provide the best results. Ground-wave losses are reduced considerably over saltwater and are highest over dry and rocky land. As can be seen from **Figure 19.5**, the range increases with decreasing frequency. The results in this figure are for a typical 100-watt station using a vertical over average ground in a rural noise environment. Your results will vary depending on your power level, antenna, ground conditions, and local noise level.

19.1.10 The Space or Direct Wave

Propagation between two antennas situated within line of sight of each other is shown in **Figure 19.6**. Energy traveling directly between the antennas is attenuated to about the same degree as in free space. Unless the antennas are very high or quite close together, an appreciable portion of the energy is reflected from the ground. This reflected wave combines with direct radiation to affect the actual signal received.

In most communication between two stations on the ground, the angle at which the wave strikes the ground will be small. For a horizontally polarized signal, such a reflection reverses the phase of the wave. If the distances traveled by both parts of the wave were the same, the two parts would arrive out of phase, and would therefore cancel each other. The ground-reflected ray in Figure 19.6 must travel a little farther, so the phase difference between the two depends on the lengths of the paths, measured in wavelengths. The wavelength in use is important in determining the useful signal strength in this type of communication. Let's analyze an example of why the wavelength in use is important.

If the difference in path length is 3 meters, the phase difference with 160 meter waves would be only $360° \times 3/160 = 6.8°$. This is a negligible difference from the 180° shift caused by the reflection, so the effective signal strength over the path would still be very small because of cancellation of the two waves. But with 6 meter radio waves the phase length would be $360° \times 3/6 = 180°$. With the additional 180° shift on reflection, the two rays would add. Thus, the space wave is a negligible factor at low frequencies, but it can be increasingly useful as the frequency is raised. It is a dominant factor in local amateur communication at 50 MHz and higher.

Interaction between the direct and reflected waves is the principal cause of *mobile flutter* observed in local VHF communication between fixed and mobile stations. The flutter effect decreases once the stations are separated enough so that the reflected ray becomes inconsequential. The reflected energy can also confuse the results of field-strength measurements during tests on VHF antennas.

As with most propagation explanations, the space-wave picture presented here is simplified, and practical considerations dictate modifications. There is always some energy loss when the wave is reflected from the ground. Further, the phase of the ground-reflected wave is not shifted exactly 180°, so the waves never

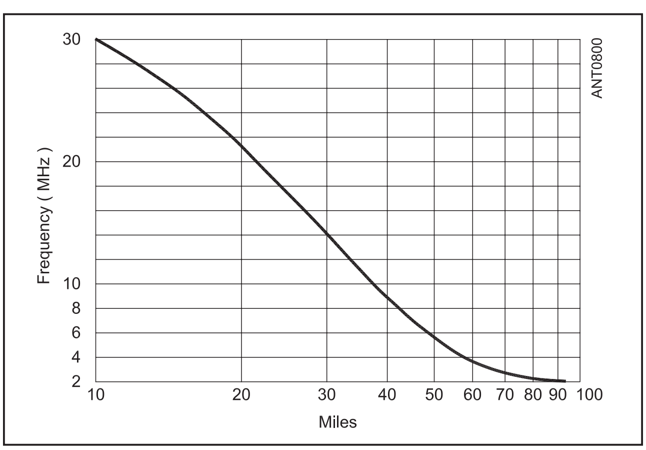

Figure 19.5 — Typical HF ground-wave range as a function of frequency.

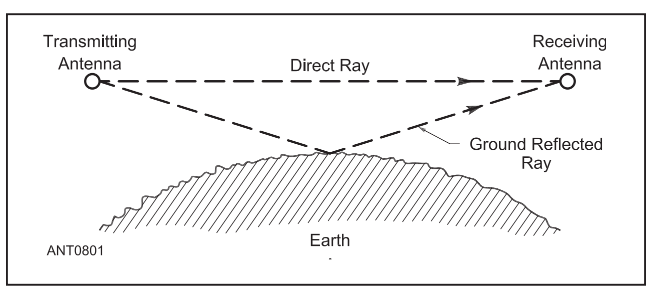

Figure 19.6 — The ray traveling directly from the transmitting antenna to the receiving antenna (direct wave) combines with a ray reflected from the ground (ground reflected ray) to form the space wave. For a horizontally polarized signal, a reflection as shown here reverses the phase of the ground-reflected ray.

cancel completely. At UHF, ground-reflection losses can be greatly reduced or eliminated by using highly directive antennas. By confining the antenna pattern to something approaching a flashlight beam, nearly all the energy is in the direct wave. The resulting energy loss is low enough that microwave relays, for example, can operate with moderate power levels over many miles. Thus, we see that, while the space wave is inconsequential below about 20 MHz, it can be a prime asset in the VHF realm and higher.

19.1.11 Polarization

ANTENNA POLARIZATION SELECTION

If effective communication over long distances were the only consideration, we might be concerned mainly with radiation of energy at the lowest possible angle above the horizon. As an example, our 1.8 and 3.5-MHz bands are well-suited for short-distance communication because they serve that purpose with antennas that are not difficult or expensive to put up. Out to a few hundred miles, simple wire antennas for these bands do well, even though their radiation is mostly at high angles above the horizon. (See the section on NVIS Communication.) Vertical antenna systems are generally better for long-distance use on these frequencies, although they require extensive ground systems for good performance.

Horizontal antennas that radiate well at low angles are most easily erected for 7 MHz and higher frequencies — horizontal wires and arrays are almost standard practice for work on 7 through 29.7 MHz. Vertical antennas, such as a single omnidirectional antenna of multiband design, are also used in this frequency range. An antenna of this type may be a good solution to the space problem for a city dweller on a small lot, or even for the resident of an apartment building.

High-gain antennas are almost always used at 50 MHz and higher frequencies, and most of them are horizontal. The principal exception is mobile communication with FM through repeaters. The height question is answered easily for VHF enthusiasts — the higher the better.

The theoretical and practical effects of height above ground at HF are treated in detail in the *ARRL Antenna Book* chapter **Effects of Ground**. Note that it is the electrical height in *wavelengths* that is important — a good reason to think in the metric system, rather than in feet and inches, since our bands are generally referred to in terms of meters.

In working locally on any amateur frequency band, best results will be obtained with the same polarization at both stations, except on rare occasions when polarization rotation is caused by terrain obstructions or reflections from buildings. Where such a shift is observed, mostly above 100 MHz or so, horizontal polarization tends to work better than vertical. This condition is found primarily on short paths, so it is not too important.

19.2 The Sun and Solar Activity

The Sun is important for amateur radio in two major ways:

1) The Sun emits electromagnetic radiation at appropriate wavelengths to ionize the Earth's atmosphere. This gives us long distance contacts via the ionosphere. Without this energy, we would be limited to line-of-sight propagation and ground wave propagation.
2) The Sun can be quiet or stormy. When the Sun is quiet, it doesn't disrupt the ionosphere. When the Sun becomes stormy, it can disrupt the ionosphere to a level that degrades propagation.

The goal of this section is not to make you a solar scientist. The goal is to give you a basic understanding of the Sun and how it affects propagation. For those who want to learn more about the Sun itself, here is a website that gives much more detail: **www.nasa.gov/mission_pages/sunearth/science/solar-anatomy.html**. Conditions related to solar phenomena that affect radio propagation are measured and reported by the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC: **www.swpc.noaa.gov**). The SWPC is an excellent resource for learning more about how solar behavior affects amateur radio.

Observing Solar Activity

The online content includes articles about observing solar phenomena, including a *QST* article by Mark Spencer, WA8SME, on building your own radio telescope. Numerous online sources such as **solar-center.stanford.edu/observe** explain how to view the Sun for yourself. When observing the Sun, be sure to follow safe viewing practices as described in the online *Sky and Telescope* article "Safe Solar Observing" by Jeff Medkeff (**skyandtelescope.org/observing/celestial-objects-to-watch/safe-solar-observing/**).

19.2.1 The "Quiet" Sun

In this section we describe the activity of the so-called quiet Sun, meaning those times when the Sun is not doing anything more spectacular than acting like a "normal" thermonuclear ball of fusing matter. However, activity on the surface of the Sun is changing continually. The Sun and its effects on earthly propagation can be described in statistical terms — that's what the 11-year solar cycle does as described below.

Because of the continual changes in solar activity, there are continual changes in the state of the Earth's ionosphere and resulting changes in propagation conditions. A short-term burst of solar activity may trigger unusual propagation conditions here on Earth lasting for less than an hour. In more active conditions, described below, activity may result in changes to conditions that last for days at a time. However, on any particular day and time, you are likely to experience very different conditions compared to what a long-term average would suggest.

There are also daily and seasonal variations in the Earth's ionized regions resulting from changes in the amount of ultraviolet and X-ray radiation received from the Sun. The 11-year solar cycle affects propagation conditions because there is a direct correlation between sunspot activity and ionization.

THE SOLAR WIND

The Sun is constantly ejecting material from its surface in all directions into space, making up the *solar wind*. Under relatively quiet solar conditions the solar wind blows around 250 miles per second (400 kilometers per second) — 900,000 miles per hour. Although the velocity is high, the density of the material in the solar wind is very small by the time it has been spread out into interplanetary space. Scientists calculate that the density of the particles in the solar wind is less than that of the best vacuum they've ever achieved on Earth. From **www.swpc.noaa.gov/phenomena/solar-wind**, we see that the solar wind continuously flows outward from the Sun and consists mainly of protons and electrons in a state known as a *plasma*. The solar magnetic field is embedded in the plasma and flows outward with the solar wind.

Different regions on the Sun produce solar wind of different speeds and densities. Coronal holes produce solar wind of high speed, ranging from 500 to 800 kilometers per second. The north and south poles of the Sun have large, persistent coronal holes, so high latitudes are filled with fast solar wind. In the equatorial plane, where the Earth and the other planets orbit, the most common state of the solar wind is the slow speed wind, with speeds of about 400 kilometers per second. This portion of the solar wind forms the equatorial current sheet. Coronal mass ejections (discussed later) can increase the solar wind speed to 3,000 kilometers per second.

The location of the Earth with respect to the current sheet is important because space weather impacts are highly dependent on the solar wind speed, the solar wind density, and the direction of the magnetic field embedded in the solar wind.

Each of the elements mentioned above play a role in space weather. High speed winds bring geomagnetic storms (described below), while slow speed winds bring calm space weather. Corotating interaction regions and to a lesser extent current sheet crossings can also cause geomagnetic disturbances.

THE INTERPLANETARY MAGNETIC FIELD (IMF)

The Sun's magnetic field isn't confined to the immediate vicinity of our star. The solar wind carries it throughout the solar system. Out among the planets we call the Sun's magnetic field the *interplanetary magnetic field* (IMF). Visit **www.spaceweatherlive.com/en/help/the-interplanetary-magnetic-field-imf.html** for more information.

During solar minimum, the magnetic field of the Sun looks similar to Earth's magnetic field. It looks a bit like an ordinary bar magnet with closed lines close to the equator and open field lines near the poles. Scientist call this orientation of a magnetic field a dipole. The dipole field of the Sun is about as strong as a magnet on a refrigerator (around 50 gauss). The magnetic field of the Earth is about 100 times weaker.

Around solar maximum, when the Sun reaches maximum activity, many sunspots are visible on the visible solar disk. Sunspots are the location of intense magnetic fields which cause ionized material to move along field lines. These fields are often hundreds of times stronger than the surrounding dipole field. This causes the magnetic field around the Sun to be very complex, with many disturbed field lines.

THE EARTH'S GEOMAGNETIC FIELD (GMF)

The Earth's magnetic field, called the *geomagnetic field* (GMF), forms a bubble around our planet called the *magnetosphere*, which deflects solar wind gusts. (Mars, which does not have a protective magnetosphere, has lost much of its atmosphere as a result of solar wind erosion.) Earth's magnetic field and the interplanetary magnetic field come into contact at the *magnetopause*: a place where the magnetosphere meets the solar wind.

Geomagnetic activity is monitored by devices known as *magnetometers*. These may be as simple as a magnetic compass rigged to record its movements. A worldwide network of magnetometers constantly monitors the Earth's magnetic field, because it varies with location. Small variations in the geomagnetic field are scaled to two measures known as the K- and A- indexes, which are described below.

A *geomagnetic storm* is a major disturbance of Earth's magnetosphere that occurs when there is a very efficient exchange of energy from the solar wind into the space environment surrounding Earth. These storms result from variations in the solar wind that produce major changes in the currents, plasmas, and fields in Earth's magnetosphere (from **www.swpc.noaa.gov/phenomena/geomagnetic-storms**).

K-INDEX

The *K-index* provides an indication of geomagnetic activity on a finite logarithmic scale of 0-9, updated every 3 hours. Very quiet conditions are reported as 0 or 1, while geomagnetic storm levels begin at 5 as described later. The K-index reflects readings of the Earth's geomagnetic field at, for example, Boulder, Colorado, over the 3 hours just preceding the data publication. It is the nearest thing to current data on radio propagation available. With new data every 3 hours, the K-index trend is important. For HF propagation, rising is bad news; falling is good, especially related to propagation on paths involving latitudes above 30° north. Because this is a single-location reading of geomagnetic activity, it may not correlate closely with conditions in other areas.

The K-index is also a timely clue to aurora possibilities. Values of 4, and rising, warn that conditions associated with auroras and degraded HF propagation are present in the Boulder area at the time of the bulletin's preparation.

The *planetary K-index,* K_p, is a preliminary value that is updated every minute by the NOAA SWPC with an estimate of the measured K_p of the past 3 hours based on eight ground-based magnetometers at sub-auroral and upper mid-latitude locations. Like the K-index, the estimated 3-hour planetary K_p-index ranges from 0 to 9. It is important to understand that this K_p-index isn't a forecast or an indicator of the current conditions, it always shows the K_p-value that was observed during a certain period.

A-INDEX

Daily geomagnetic conditions are also summarized by the open-ended linear *A-index*, which corresponds roughly to the cumulative K-index values (it's the daily average of the eight K-indexes after converting the K-indexes to a linear scale). See the table at **www.swpc.noaa.gov/products/station-k-and-indices** to translate the logarithmic K-indexes to the linear a-index. Remember the small case 'a' is the linear equivalent of the 3-hour K-index. The capital 'A'-index is the average of the eight 3-hour K-indexes.

The A-index is a daily figure for the state of activity of the Earth's magnetic field. The A-index tells you mainly how yesterday was, but it is very revealing when charted regularly because geomagnetic disturbances nearly always recur at approximately four-week intervals (see the section on 27-Day Recurrence). The A-index commonly varies between 0 and 30 during quiet to active conditions, and up to 100 or higher (the maximum is defined as 400) during geomagnetic storms.

Earth's magnetic field points north at the magnetopause. If the IMF points south — a condition scientists call "southward Bz" (a negative value for Bz) — then the IMF can partially cancel Earth's magnetic field at the point of contact and couple disruptive energy into the Earth's magnetic field. (Material in this section is excerpted from **spaceweather.com/glossary/imf.html**.)

For a geomagnetic storm to develop it is vital that the direction of the interplanetary magnetic field (Bz) turn southward. Persistent values of –10nT and lower (more negative) are good indicators that a geomagnetic storm could develop, but the lower this value goes, the better it is for auroral activity. Only during extreme events with high solar-wind speeds is it possible for a geomagnetic storm (K_p of 5 or higher) to develop with a northward Bz.

SOLAR ULTRAVIOLET RADIATION (UV)

Solar ultraviolet (UV) radiation creates small concentrations of ozone (O_3) molecules between 10 and 50 kilometers (6 and 30 miles) above the Earth's surface. Most UV radiation is absorbed by this process and never reaches the Earth. At even higher altitudes, *ionizing EUV* (Extreme UV with wavelengths of 10 to 100 nanometers or nm) and X-ray radiation partially ionize atmospheric gases. Electrons freed from gas atoms eventually recombine with positive ions to recreate neutral gas atoms, but this process of *recombination* takes some time. In the low-pressure environment at the highest altitudes, atoms are spaced far apart, and the gases may remain ionized for many hours. At lower altitudes, recombination happens rather quickly, and only constant radiation can keep any appreciable portion of the gas ionized.

SOLAR FLUX

Another method of gauging solar activity is the *solar flux*, which is a measure of the intensity of 2800 MHz (10.7 cm) radio noise coming from the Sun. Solar flux is a measure of energy received per unit time, per unit area, per unit frequency interval. (10^{-22} W m^{-2} Hz^{-1}). One solar flux unit equals 10^{-22} joules per second per square meter per hertz.

Values of solar flux at 10.7 cm are measured daily at The Dominion Radio Astrophysical Observatory, Penticton, British Columbia. Data have been collected in Penticton since 1991. (Prior to June 1991, the Algonquin Radio Observatory, Ontario, made the measurements.) Measurements are also made at other observatories around the world, at several frequencies. With some variation, the daily measured flux values increase with increasing frequency of measurement, to at least 15.4 GHz.

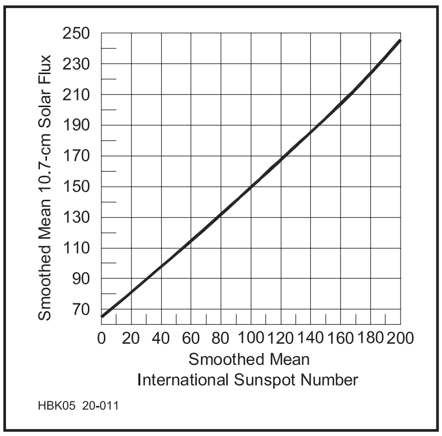

Figure 19.7 — Approximate conversion between solar flux and sunspot number. Note that this is for smoothed values of Solar Flux and Sunspot Numbers.

The daily 2800 MHz Penticton value is sent to the NIST in Boulder, Colorado, where it is incorporated into WWV propagation bulletins. Solar flux, just like a sunspot number, is a proxy (substitute) for the true ionizing radiation at much shorter wavelengths, as solar flux at 2800 MHz does not have enough energy to ionize any atmospheric constituent. The relationship between solar flux and sunspots numbers is discussed later in this section.

The smoothed 2800 MHz radio flux is an indication of the intensity of ionizing UV and X-ray radiation and provides a convenient alternative to sunspot numbers. Solar flux values commonly vary on a scale of 60 – 300 and can be related to sunspot numbers, as shown in **Figure 19.7** (note that this is only valid for converting between smoothed values). The Penticton observatory measures the 2800 MHz solar flux three times a day (centered on local noon). (A supplemental article, "The Penticton Solar Flux Receiver" from February 2013 *QST* is part of this book's online content.) NIST radio station WWV broadcasts the latest solar-flux index at 18 minutes after each hour; WWVH does the same at 45 minutes after the hour. The information is updated every three hours.

19.2.2 The 11-Year Solar Cycle

The density of ionospheric regions depends on the amount of solar radiation reaching the Earth, but solar radiation is not constant. Variations result from daily and seasonal motions of the Earth, the Sun's own 27-day recurrence, and the 11-year cycle of solar activity as described in the following sections. The solar cycle generally has four phases: the solar minimum phase, rising phase, solar maximum phase, and declining phase.

One visual indicator of both the Sun's recurrence and the solar cycle is the periodic appearance of sunspots, which have been observed continuously since the mid-18th century. (The terms "solar cycle" and "sunspot cycle" are often used interchangeably, although the former is more general and so is used in this chapter.)

Until the advent of satellites, solar UV and X-ray radiation could not be measured directly, because they were almost entirely absorbed in the upper atmosphere during the process of ionization. The sunspot number provided the most convenient approximation of general solar activity.

The sunspot number is not a simple count of the number of visual spots, but rather the result of a somewhat complicated formula that takes into consideration size, number, and grouping. (See the following sections on sunspot numbers.) On average, the number of sunspots reaches a maximum every 11 years, but the period has varied between 7 and 17 years. Cycle 19 peaked in 1958, with a smoothed sunspot number of 201, the highest recorded to date. **Figure 19.8** shows the smoothed sunspot numbers (these values are the new Version 2.0 sunspot data) for the past six cycles.

During the peak of the 11-year solar cycle, average solar radiation increases along with the number of flares and sunspots. The ionosphere becomes more intensely ionized consequently, resulting in higher critical frequencies, particularly in the F_2 region. The possibilities for long-distance communications are considerably improved during solar maximum phase, especially in the higher-frequency bands.

TRENDS IN SOLAR CYCLES

If one looks at all 24 recorded solar cycles, three characteristics stand out (see **Figure 19.9**). First, there is a cyclic nature to the maximum smoothed sunspot numbers. Second, there have been three high cycle periods of 50 years or so (consisting of several solar cycles) and two low cycle periods of 50 years or so (again, consisting of several solar cycles — the Dalton minimum and the Gleissberg minimum), and the Earth appears to be headed into a third low cycle period. Third, the Earth recently experienced a period of unusually high solar activity known as the Modern Maximum, which ended in 2002. This has allowed excellent worldwide propagation on the higher frequency bands and provided great enjoyment for radio amateurs.

If one looks at solar cycles prior to recorded history through various proxies for solar activity (for example, carbon-14 in trees and beryl-

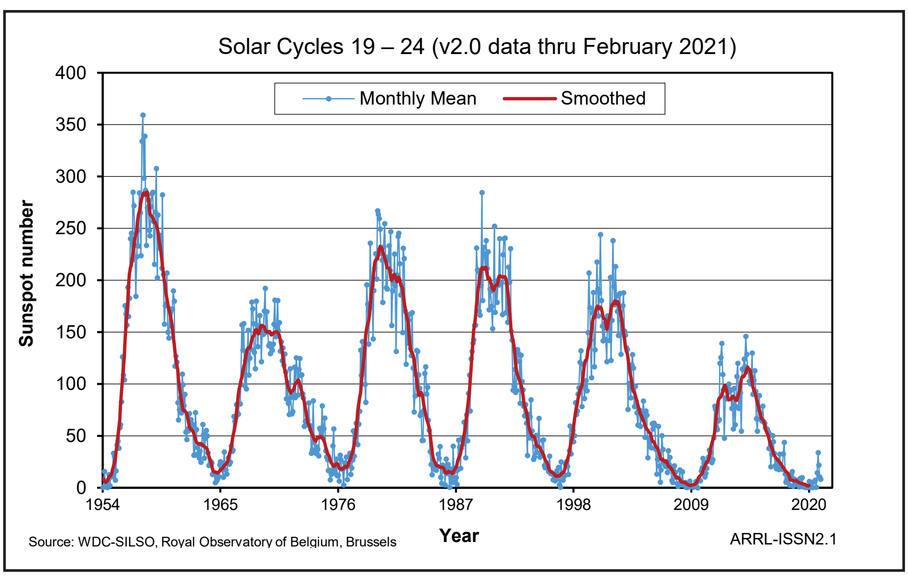

Figure 19.8 — Smoothed sunspot numbers (SSN) through February 2021 for solar cycles 19 to 25.

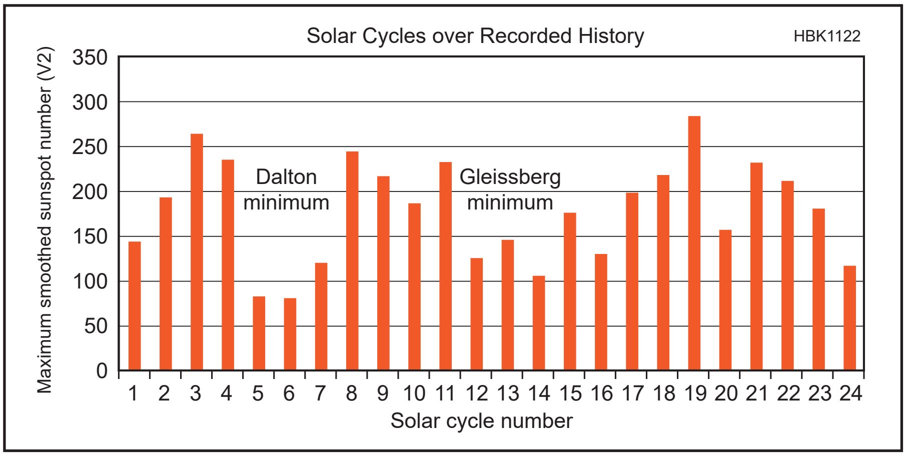

Figure 19.9 — Solar cycles historically

lium-10 in ice cores), one sees extended periods of very low solar activity referred to as Grand Minima (see **Figure 19.10**). The Maunder Minimum between 1645 and 1715 AD is one of the best known. When the Sun is at solar minimum, the Sun's magnetic field is weak, and this lets in galactic cosmic rays that result in more carbon-14 deposits in tree rings and more beryllium-10 deposits in ice cores. It's likely that we'll again enter one of these extended periods, but trying to predict when this will happen is, at best, a wild guess.

With respect to solar minimum periods between solar cycles, historical data shows great variation. The average length of solar minimum, for example defined as the number of months in which the smoothed sunspot number is below 20, is around 37 months. Using this definition, the shortest minimum was 17 months (between Cycles 1 and 2) and the longest minimum was 96 months (between Cycles 5 and 6). The minimum period between Cycle 23 and Cycle 24 turned out to be 56 months. Interestingly, up until the minimum between Cycle 23 and Cycle 24, in living memory, the Earth has experienced minimum periods of approximately 24 months — much shorter than the average. This may lead one to believe this recent solar minimum period was unusual. But historical data, with its great variation, says otherwise. (There is evidence that we may have missed a small solar cycle way back in the 1790 time frame. See **k9la.us/Did_We_Lose_a_Solar_Cycle.pdf**.)

19.2.3 Sunspots

Sunspots are cooler areas on the Sun's surface associated with high magnetic activity. Active regions adjacent to sunspot groups, called *plages* (French for 'beach'), can produce great flares and sustained bursts of electromagnetic radiation in the radio through X-ray spectrum. The white plages are where copious amounts of EUV radiation are emitted, which ionizes the F_2 region of the ionosphere. Since 1948 it has been well known that radio propagation phenomena vary with the number and size of sunspots, and with the position of sunspots on the surface of the Sun. (See the Reference entry for Phillips.)

Individual sunspots may vary in size, appearance, and duration — and may even disappear totally — within a single day. In general, larger active areas persist through several rotations of the Sun. Some active areas have been identified over periods of about a year.

SMOOTHED SUNSPOT NUMBERS

Sunspot data are averaged or smoothed to remove the effects of short-term changes. For example, if a solar cycle is plotted in terms of the daily sunspot number or the monthly mean sunspot number, the resulting curve would be very spiky. Thus, it would be somewhat difficult to ascertain when the solar cycle started, whether it had one or two peaks, and when it ended. Additionally, the sunspot values that should be used for correlating propagation conditions are *Smoothed Sunspot Numbers* (also known as R_{12}), often called 12-month running average values. Data for 13 consecutive months are required to determine a smoothed sunspot number. Sometimes you'll see SSN used as the abbreviation for Smoothed Sunspot Number. Historically SSN has simply meant Sun Spot Number — not a smoothed value. It is best to use R_{12} as the abbreviation for the smoothed sunspot number.

Long-time users have found that the upper HF bands are reliably open for propagation only when the average number of sunspots is above certain minimum levels. For example, between mid-1988 to mid-1992 during Cycle 22, the SSN stayed higher than 100. The 10 meter band was open then almost all day, every day, to some part of the world. However, by mid-1996, few if any sunspots showed up on the Sun and the 10 meter band consequently was rarely open. Even 15 meters, normally a workhorse DX band when solar activity is high, was closed most of the time during the low point in Cycle 22. This behavior is typical for solar cycles and was repeated for Cycles 23 and 24. So far as propagation on the upper HF bands is concerned, the higher the sunspot number, the better the conditions.

Each smoothed number is an average of 13 monthly means, centered on the month of concern. The 1st and 13th months are given a weight of 0.5. A monthly mean is simply the sum of the daily values of the International Sunspot Number (ISN) for a calendar month, divided by the number of days in that month. We would commonly call this value a monthly average.

This may all sound very complicated, but an example should clarify the procedure. Suppose we wished to calculate the smoothed sunspot number for June 1986. We would require monthly mean values for six months prior and six months after this month, or from December 1985 through December 1986. The

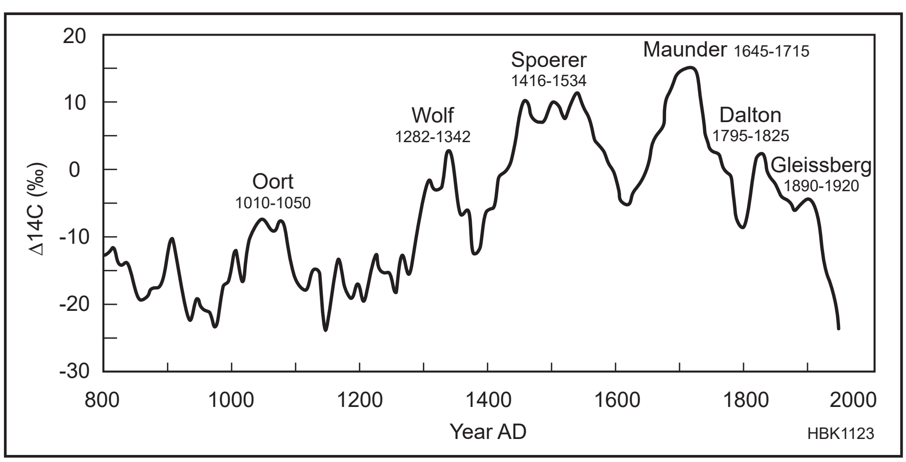

Figure 19.10 — Solar activity and carbon-14 levels from tree rings and other sources of data.

Cycle 25 Status

(This information was prepared in March 2022 by Carl Luetzelschwab, K9LA)

In December 2019, the smoothed sunspot number numerically minimized. This has been heralded as the end of Cycle 24 and the start of Cycle 25. But we have to remember that solar cycles overlap. In other words, we simultaneously see sunspots from the old cycle and the new cycle for a period of time.

Figure 19.B is the latest data for the new Cycle 25. It uses the latest monthly mean sunspot number from February 2022. The smoothed sunspot value is more heavily averaged than the monthly mean value to take out the spikiness of the monthly mean data. The smoothed calculation uses six months of data before and after the target month — thus the latest smoothed sunspot number is six months behind the latest monthly mean sunspot number. (The latest smoothed sunspot number in this graph is from August 2021.)

What's obvious so far is that Cycle 25 appears to be tracking the small Cycle 24, and not the average Cycle 23 nor the moderately big Cycle 21 that resulted in excellent 6-meter propagation. The next six to twelve months will likely give us a better indication of where Cycle 25 is headed. Regardless of where it heads, we should have good worldwide HF propagation for about five years through at least 2026. A good source of forecasting data and predictions for the solar cycle is the Solar Cycle Progression and Forecast at the Marshall Space Flight Center (**www.nasa.gov/msfcsolar**).

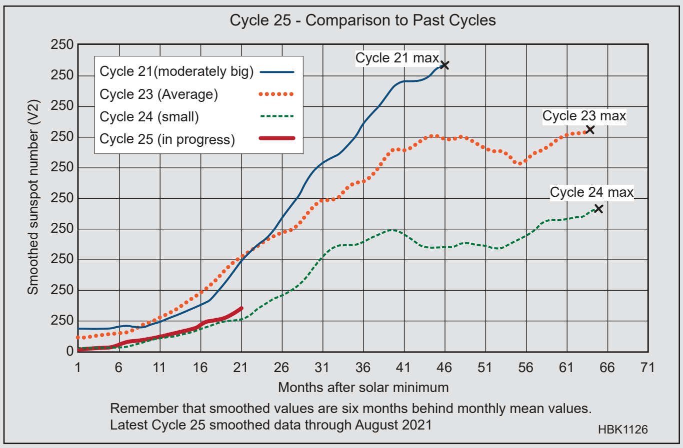

Figure 19.B — Smoothed sunspot numbers for Cycle 25 compared to three other cycles.

monthly mean ISN values for these months (again, these are Version 1.0 values) are:

Dec	85	17.3	Jul	86	18.1
Jan	86	2.5	Aug	86	7.4
Feb	86	23.2	Sep	86	3.8
Mar	86	15.1	Oct	86	35.4
Apr	86	18.5	Nov	86	15.2
May	86	13.7	Dec	86	6.8
Jun	86	1.1			

First, we find the sum of the values, but using only one-half the amounts indicated for the 1st and 13th months in the listing. This value is 166.05. Then we determine the smoothed value by dividing the sum by 12: 166.05/12 = 13.8. (Values beyond the first decimal place are not warranted.) Thus, 13.8 is the smoothed sunspot number for June 1986. From this example, you can see that the smoothed sunspot number for a particular month cannot be determined until six months afterwards.

Generally, the plots we see of sunspot numbers are averaged data. As already mentioned, smoothed numbers make it easier to observe trends and see patterns, but sometimes this data can be misleading. The plots tend to imply that solar activity varies smoothly, indicating, for example, that at the onset of a new cycle the activity just gradually increases. But this is definitely not so. On any given day, significant changes in solar activity can take place within hours, causing sudden band openings at frequencies well above the MUF values predicted from smoothed sunspot number curves. The durations of such openings may be brief, or they may recur for several days running, depending on the nature of the solar activity.

Smoothed numbers are also used in our propagation predictions. When the model of the ionosphere was developed for propagation predictions, scientists determined that the best (acceptable) correlation between what the Sun was doing and what the ionosphere was doing is to use smoothed sunspot numbers and monthly median ionospheric parameters. Median implies a 50% probability and thus our predictions are statistical in nature — we do not have daily predictions.

THE NEW SUNSPOT NUMBERS

Beginning in September 2011, there have been four Sunspot Number Workshops (sponsored by the US National Solar Observatory, the Royal Observatory of Belgium, and the US Air Force Research Laboratory) discussing the quality of the sunspot data. The last workshop reviewed the corrected time series of sunspot numbers from 1610 to the present, and the participants reached an agreement to publish the new data. The old data is designated Version 1.0 (V1.0), while the new data is designated Version 2.0 (V2.0). For more details on this effort, an explanation is provided by K9LA on his website (**k9la.us/Apr16_NEW_Sunspot_Numbers.pdf**). This paper also shows V1.0 vs V2.0 smoothed data (Figure 3 in the paper) from 1950 through 2015, and shows the difference in recent years. V2.0 smoothed values are on average 1.4 times the V1.0 smoothed values for this period.

Going forward, all sunspot numbers are V1.0 values unless otherwise noted as V2.0 data. A discussion of the impact of the new sunspot numbers with respect to propagation predictions will be addressed later.

19.2.4 27-Day Recurrence

Sunspot observations also reveal that the Sun rotates about its own axis. The Sun is composed of extremely hot gases and does not turn uniformly (it is essentially a fluid). At the equator, the period is just over 25 days, but it approaches 35 days at the poles. Sunspots and active regions that affect the Earth's ionosphere, which appear almost entirely within 35° of the Sun's equator, take about 26 days to return to the same position on the solar disk where they affect the Earth. After accounting for the Earth's movement around the Sun, it takes about 27 days for the apparent recurrence of solar activity.

Active regions must face the Earth in the proper orientation to have an impact on the ionosphere. This orientation is referred to as *geo-effective*. They may face the Earth only once before rotating out of view, but the larger active regions often persist for several solar rotations. The net effect is that solar activity from the larger active regions often recurs in 27-day cycles, even though the active regions themselves may last for several solar rotations.

19.2.5 The "Active" Sun

This section describes some of the ways in which strong disruptions to normal solar activity can affect radio wave propagation here on Earth. As far as amateur HF skywave propagation is concerned, the results of these disturbances on the active Sun are not generally beneficial. The most important solar disturbances affecting HF propagation are solar flares, coronal holes, and coronal mass ejections. (See the later section Propagation in Disturbed Conditions.) The occurrence of these conditions and the resulting changes to propagation are monitored and reported on the NIST broadcast stations WWV and WWVH.

NOAA CLASSIFICATION SCALES

In March 2002, NOAA changed the format of the WWV alert (at 18 minutes past the hour) to better align it to the current understanding of disturbances to propagation. NOAA assigns disturbances to propagation into three categories: Radio Blackouts (abbreviated R), Solar Radiation Storms (abbreviated S), and Geomagnetic Storms (abbreviated G). All the details are at **www.swpc.noaa.gov/noaa-scales-explanation**.

NOAA reports all three categories of propagation disturbance on a scale of 1 to 5, with 1 being a minor disturbance and 5 being an extreme disturbance. Although this chapter's discussion of geomagnetic storms, solar radiation storms, and radio blackouts gives you the fundamentals, reviewing the subject matter at the following website will give you a much deeper understanding of the level of impact of each and how and what they impact: See pages 8 – 10 of **www.swpc.noaa.gov/sites/default/files/images/u33/swx_booklet.pdf**.

SOLAR FLARES

Solar flares are large eruptions of electromagnetic radiation from the Sun lasting from minutes to hours. Their intensity and frequency of occurrence follow the 11-year solar cycle. The sudden outburst of electromagnetic energy travels at the speed of light, therefore any effect upon the sunlit side of Earth's exposed outer atmosphere occurs at the same time the event is observed. The increased level of X-ray and extreme ultraviolet (EUV) radiation results in ionization in the regions of the ionosphere on the sunlit side of Earth. (Material in this section is excerpted from **www.swpc.noaa.gov/phenomena/solar-flares-radio-blackouts**.)

Under normal conditions, high frequency (HF) radio waves support communication over long distances by refraction via the upper regions of the ionosphere. When a strong enough solar flare occurs, detrimental ionization is produced in the lower, more dense regions of the ionosphere (the D region), and radio waves that interact with electrons in that region lose energy due to the more frequent collisions that occur in the higher density environment of the D region.

This can cause HF radio signals propagating through the ionosphere on the daylight side of the Earth to become degraded or completely absorbed on the daylight side of Earth. This results in a radio blackout — the absence of HF communication, primarily impacting the 3 to 30 MHz band. This is the Radio Blackout disturbance categorized by NOAA

Very strong solar flares can also eject very high energy protons that cause increased D-region absorption of radio signals propagating through polar regions. This is the Solar Radiation Storm disturbance categorized by NOAA.

Solar flares usually take place in active regions, which are areas on the Sun marked by the presence of strong magnetic fields — typically associated with sunspot groups. As these magnetic fields evolve, they can reach a point of instability and release energy in a variety of forms. These include electromagnetic radiation, which is observed as solar flares.

Solar flare intensities cover a large range and are classified in terms of peak emission in the 0.1 – 0.8 nm spectral band (hard x-rays) of the NOAA/GOES XRS (X-ray Sensor). The X-ray flux levels start with the "A" level (nominally starting at 10^{-8} W/m^2). The next level, ten times higher, is the "B" level ($\geq 10^{-7}$ W/m^2); followed by "C" flares (10^{-6} W/m^2), "M" flares (10^{-5} W/m^2), and finally "X" flares (10^{-4} W/m^2).

Radio Blackouts and Solar Radiation Storms are classified using a five-level NOAA Space Weather Scale, directly related to the flare's max peak in hard X-rays reached or expected. The NOAA Space Weather Prediction Center (SWPC) currently forecasts the probability of C, M, and X-class flares and the probability of an R1 to R3 or greater event as part of the NOAA three-day forecast. Only M- and X-class flares affect HF propagation to a meaningful degree; the weaker M-class flares cause brief blackouts that are of little significance and usually aren't even noticed. The effects of C-class flares are difficult to detect.

CORONAL HOLES

Coronal holes appear as dark areas in the solar corona in extreme ultraviolet (EUV) and soft x-ray solar images. They appear dark because they are cooler, less dense regions than the surrounding plasma and are regions of open, unipolar magnetic fields. This open, magnetic field line structure allows the solar wind to escape more readily into space, resulting in streams of relatively fast solar wind, and is often referred to as a high-speed stream in the context of analysis of structures in interplanetary space. (Material in this section is excerpted from **www.swpc.noaa.gov/phenomena/coronal-holes**.)

Coronal holes can develop at any time and location on the Sun but are most common and persistent during the solar minimum phase. The more persistent coronal holes can sometimes last through several solar rotations (see the preceding section on 27-Day Recurrence). Coronal holes are most prevalent and stable at the solar north and south poles, but these polar holes can grow and expand to lower, more geo-effective, solar latitudes. It is also possible for coronal holes to develop in isolation from the polar holes, or for an extension of a polar hole to split off and become an isolated structure. Persistent coronal holes are long-lasting sources of high-speed solar wind streams.

CORONAL MASS EJECTIONS (CME)

Coronal Mass Ejections (CMEs) are large expulsions of plasma and magnetic field from the Sun's corona. Their intensity and frequency of occurrence tends to follow the solar cycle, although some of the most extremely intense CMEs have occurred outside the solar maximum phase of the solar cycle.

A CME can eject billions of tons of coronal material and carry an embedded magnetic field (frozen in flux) that is stronger than the background solar wind interplanetary magnetic field (IMF) strength. CMEs travel outward from the Sun at speeds ranging from slower than 250 kilometers per second (km/s) to as fast as nearly 3,000 km/s. Most CMEs take 24 to 36 hours to reach Earth, but the fastest take as little as 15 – 18 hours. Slower CMEs can take several days to arrive, or they may not escape the gravity of the Sun at all. They expand in size as they propagate away from the Sun, and larger CMEs can reach a size comprising nearly a quarter of the space between Earth and the Sun by the time they reach our planet. (Material in this section is excerpted from **www.swpc.noaa.gov/phenomena/coronal-mass-ejections**.)

CMEs are often associated with the sudden release of electromagnetic energy in the form of a solar flare, which typically accompanies the explosive acceleration of plasma away from the Sun — the CME. These types of CMEs usually take place from areas of the Sun with localized fields of strong and stressed magnetic flux, such as active regions associated with sunspot groups. CMEs travelling faster than the background solar wind speed can generate a shock wave. These shock waves can accelerate charged particles ahead of them, causing increased radiation storm potential or intensity.

19.3 Sky-Wave or Ionospheric Propagation

The Earth's atmosphere, which reaches to more than 600 kilometers (370 miles) altitude, is usually divided into a number of regions based on a transitioning characteristic of the atmosphere, such as temperature. For propagation purposes, the important regions are shown in **Figure 19.11**. The weather-producing *troposphere* lies between the surface and an average altitude of 10 kilometers (6 miles). Between 10 and 50 kilometers (6 and 30 miles) are the *stratosphere* and the embedded *ozonosphere*, where ultraviolet-absorbing ozone reaches its highest concentrations. About 99% of atmospheric gases are contained within these two lowest regions.

Above 50 kilometers to about 600 kilometers (370 miles) is the *ionosphere*, notable for its effects on radio propagation. At these altitudes, atomic oxygen, molecular oxygen, molecular nitrogen, and nitric oxide predominate under very low pressure and are the important species to consider for propagation. High-energy solar EUV and X-ray radiation ionize these constituents, creating a broad region where ions are created in relative abundance. The ionosphere is subdivided into distinctive D, E, and F regions.

19.3.1 Structure of the Geomagnetic Field

The north and south *magnetic poles* are the points on the surface of Earth at which the planet's magnetic field points vertically downward for the north pole and vertically upward for the south pole. In other words, if a magnetic compass needle is allowed to rotate in three dimensions, it will point straight down at the north magnetic pole and straight up at the south magnetic pole. There is only one location in each hemisphere where this occurs, near (but distinct from) the *geographic* north and south poles.

Related to the magnetic poles are the *geomagnetic poles*. These are the poles of an ideal dipole model of the Earth's magnetic field that most closely fits the Earth's actual magnetic field. The geomagnetic poles are the centers of the auroral ovals. **Figure 19.12** shows the location of the north magnetic pole and how it has drifted much more than the geomagnetic north pole over the years. The figure also shows how the location of the north geomagnetic pole has drifted very little during the same period.

GEOMAGNETIC EQUATOR

The geomagnetic equator is the great circle of the Earth whose plane is perpendicular to the axis of the geomagnetic field. **Figure 19.13** shows the geomagnetic equator (the dashed line) on a Mercator projection of Earth as of 1990. The geomagnetic equator is important for trans-equatorial propagation (TEP) and will be discussed later. This is also called the *magnetic dip equator.*

19.3.2 The Ionosphere

The ionosphere plays a basic role in long-distance communications in all the amateur bands from 1.8 MHz to 50 MHz. The effects of the ionosphere are less apparent at the very high frequencies (30 – 300 MHz), but they persist for terrestrial communications at least through 432 MHz. The basic physics of ionospheric propagation was largely worked out by the 1930s, yet both amateur and professional experimenters made further discoveries throughout the 1930s, 1940s, and 1950s, and continue to make important new discoveries to this day. Sporadic E (the term "layer" is appropriate here as the concentration of electrons is very thin — only a couple kilometers), aurora, trans-equatorial, meteor scatter, and several types of field-aligned scattering were among many additional ionospheric phenomena that required explanation and are still not fully understood.

REGION VERSUS LAYER

The commonly used term "layer" could lead to the erroneous assumption that the ionosphere consists of distinct thin sheets separated by emptiness in between. This is not so. The ionosphere's electronic density versus altitude varies continously with definite peaks and inflection points that define the D, E, F_1, and F_2 regions. (F_1 and F_2 are often labeled F1 and F2 — this chapter will use the subscripted version). These notations are equivalent and refer to the same region. Studies have shown that the height of the various regions may also vary by latitude. On-going ionospheric physics research seeks to better understand the geographic and day-to-day variability of the ionosphere.

IONIZATION PROCESSES

Extreme Ultraviolet (EUV) radiation (wavelengths of 10 to 100 nanometers or nm) from the Sun is the primary cause of ionization in the highest region of the ionosphere (the F_2 region), the region most important for long

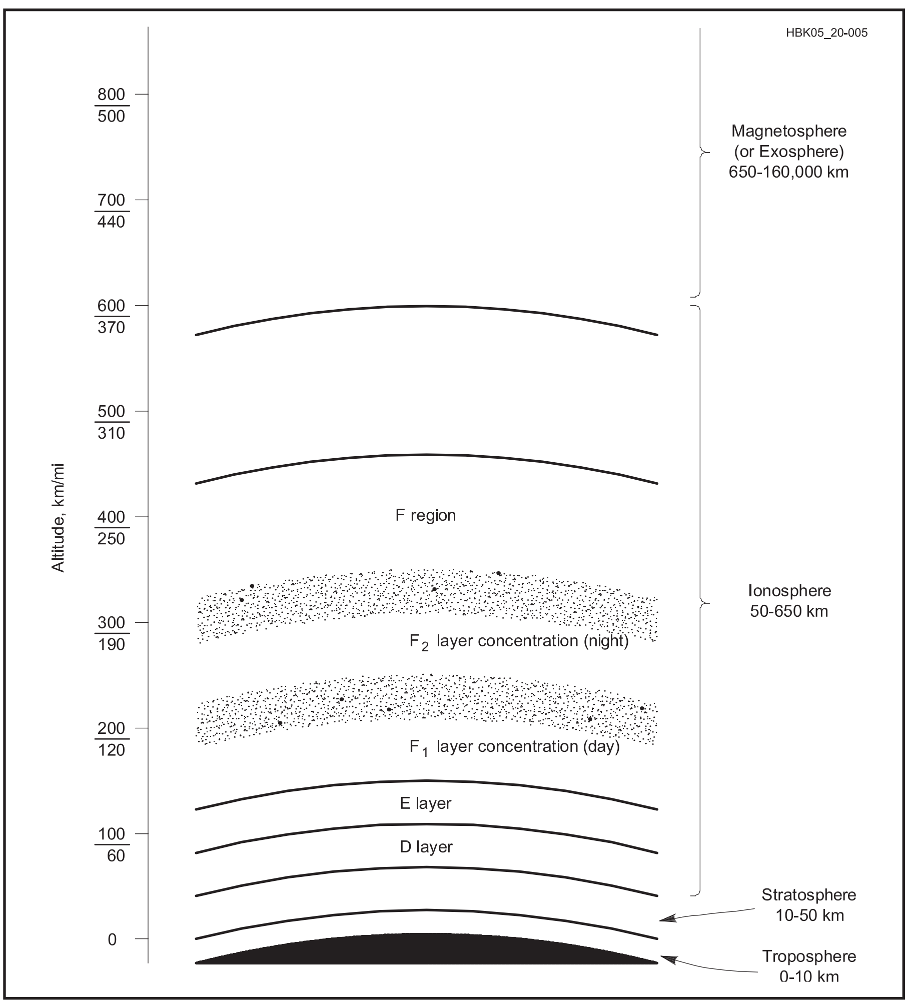

Figure 19.11 — Regions of the lower atmosphere and the ionosphere.

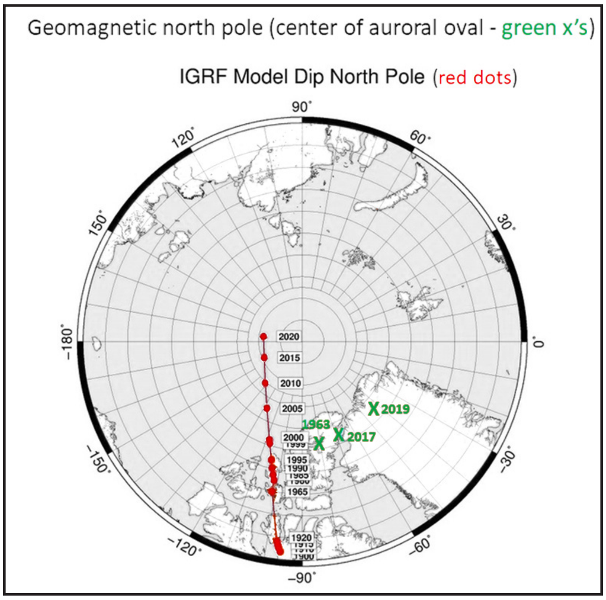

Figure 19.12 — Geomagnetic poles. The location of the north magnetic pole is shown as dots. The geomagnetic north pole locations are labeled with an X.

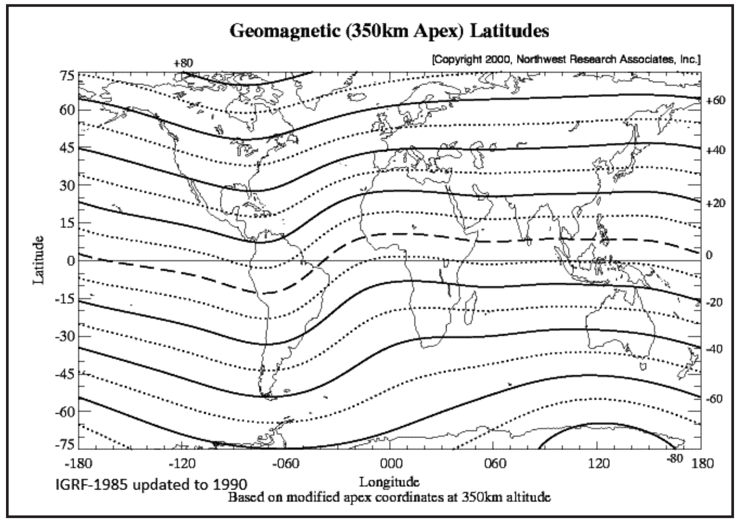

Figure 19.13 — Geomagnetic equator (the dashed line) on a Mercator projection of Earth as of 1990 (thanks Northwest Research Associates).

distance HF propagation. However, there are many other wavelengths of solar radiation as well, including both hard and soft x-rays (0.1 to 1 nm and 1 to 10 nm that contribute to the E region and the D region, respectively), gamma rays, and cosmic rays. The radiated energy breaks up or *photoionizes* atoms and molecules of atmospheric gases into free electrons and positively charged ions. The degree of ionization does not increase uniformly with distance from the Earth's surface. Instead, there are relatively dense regions of ionization, each quite thick and more or less parallel to the Earth's surface, at fairly well-defined intervals outward from about 60 to 400 kilometers (100 to 650 miles). These distinct regions are formed due to complex photochemical reactions of the various types of solar radiation with oxygen, ozone, nitrogen, and nitrous oxide in the rarefied upper atmosphere.

Ionization is not constant within each region. In the E and F_2 region, it tapers off gradually on either side of the maximum. In the D and F_1 regions ionization for all intents and purposes consists of inflection points in the level of ionization with altitude as shown in **Figure 19.14**. The total ionizing energy from the Sun reaching a given point, at a given time, is never constant, so the height and intensity of the ionization in the various regions will also vary. Thus, the practical effect on long-distance communication is an almost continuous variation in signal level, related to the time of day, the season of the year, the distance between the Earth and the Sun, and both short-term and long-term variations in solar activity. It is possible to plan antenna designs, particularly the choosing of antenna heights, to exploit known propagation characteristics.

19.3.3 Ionospheric Refraction

The degree of bending (refraction) of a wave path in an ionized region depends on the density of the ionization and the length of the wave (inversely related to the square of its frequency). The bending at any given frequency or wavelength will increase with increased ionization density and will bend away from the region of most-intense ionization. For a given ionization density, bending increases with longer wavelengths (that is, bending decreases with higher frequencies).

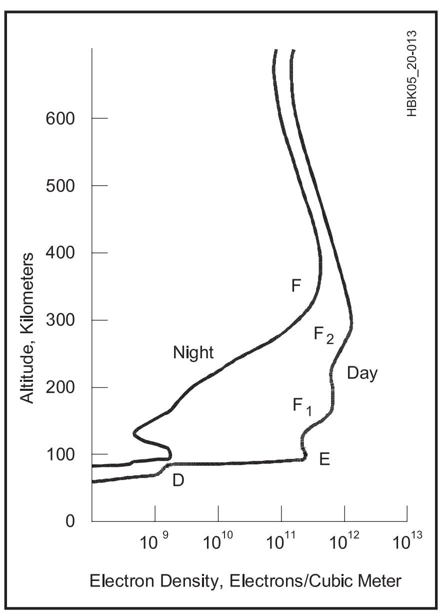

Figure 19.14 — Typical electron densities for the various ionospheric regions.

VIRTUAL HEIGHT

Although refraction is the primary mechanism of ionospheric propagation, it is usually more convenient to think of the process as a reflection. The *virtual height* of an ionospheric region is the equivalent altitude of a reflection that would produce the same effect as the actual refraction. The virtual height of any ionospheric region can be determined using an ionospheric sounder, or *ionosonde*, a sort of vertically oriented radar. The ionosonde sends pulses that sweep over a wide frequency range, generally from 2 MHz to 20 MHz or higher, straight up into the ionosphere. The frequencies of any echoes are recorded against time and then plotted as distance on an *ionogram*. **Figure 19.15** depicts a simple vertical incidence ionogram. (Ionospheric sounding is described in the following sections.)

CRITICAL FREQUENCY

The highest frequency that returns signals from the E and F regions at vertical incidence is known as the *vertical incidence* or *critical frequency*. When the frequency of a vertically incident signal is raised above the critical frequency of an ionospheric region, that portion of the ionosphere is unable to refract the signal back to Earth.

The critical frequency is a function of ion density. The higher the ionization at a particular altitude, the higher becomes the critical frequency. Strictly speaking, the critical frequency is the term applicable to the peak electron density of a region. Physicists relate any electron density in any part of the ionosphere to a plasma frequency, because technically gases in the ionosphere are in a plasma, or partially ionized state. F region critical frequencies commonly range from about 1 MHz and to occasionally as high as 15 MHz during periods of intense ionization.

19.3.4 Real-Time Sounding of the Ionosphere

For many years scientists have *sounded* the ionosphere to determine its communication potential at various elevation angles and frequencies. The word "sound" stems from an old idea — one that has nothing to do with the audio waves that we can hear as "sounds." Long ago, sailors sounded the depths beneath their boats by dropping weighted ropes, calibrated in fathoms, into the water. In a similar fashion, the instrument used to probe the height of the ionosphere is called an *ionosonde*, or ionospheric sounder. It measures distances to various regions by launching an electromagnetic wave directly up into the ionosphere.

VERTICAL-INCIDENCE SOUNDERS

Most ionosondes are *vertical-incidence sounders*, bouncing their signals perpendicularly off the various ionized regions above it by launching signals straight up into the ionosphere. The ionosonde frequency is swept upwards until echoes from the various ionospheric regions disappear, meaning that the critical frequencies for those regions have been exceeded, causing the waves to disappear into space.

Figure 19.15 shows the results of this refraction in a highly simplified ionogram for a typical vertical-incidence sounder. The vertical axis is the virtual height, not the true height attained by the echoes. That's because the virtual height assumes the ray always travels at the speed of light and is simply calculated from the up-down time of flight of the echo. In the real world, though, the ray slows down as it encounters a higher electron density (the group velocity decreases). To determine the electron density profile versus true height, the virtual height traces are used in software such as *POLAN* (POLynomial Analysis) or *ARTIST* (Automatic Real-Time Ionogram Scaler with True height).

Figure 19.16 shows an example of an actual ionogram from the vertical incidence Lowell Digisonde at Millstone Hill in Massachusetts, owned and operated by the Massachusetts Institute of Technology. This ionogram was made on June 18, 2000, and shows the conditions during a period of very high solar activity. The black-and-white rendition in Figure 19.16 of the actual color ionogram unfortunately loses some information. However, you can still see that a real ionogram is a lot more complicated looking than the simple simulated one in Figure 19.15. A map of active ionosonde stations is available at **www.digisonde.com/**

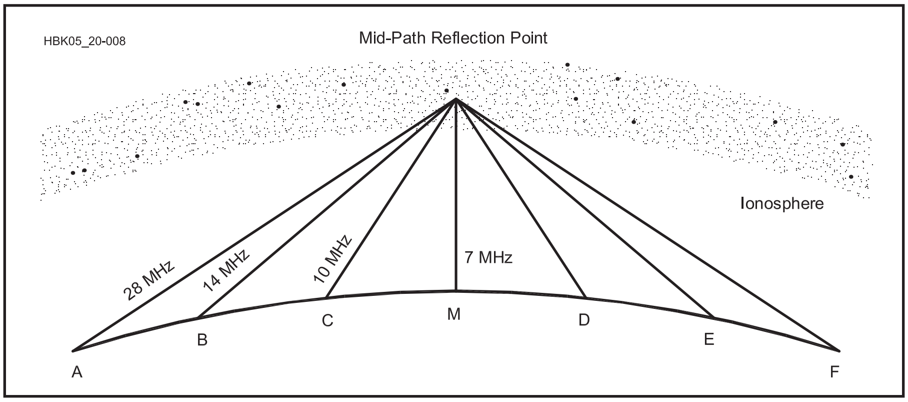

Figure 19.17 — The relationships between critical frequency, maximum usable frequency (MUF), and skip zone can be visualized in this simplified, hypothetical case. The critical frequency is 7 MHz, allowing frequencies below this to be used for short-distance ionospheric communication by stations in the vicinity of point M. These stations cannot communicate by the ionosphere at 14 MHz. Stations at points B and E (and beyond) can communicate because signals at this frequency are refracted back to Earth when they encounter the ionosphere at an oblique angle of incidence. At greater distances, higher frequencies can be used because the MUF is higher at the larger angles of incidence (low launch angles). In this figure, the MUF for the path between points A and F, with a small launch angle, is shown to be 28 MHz. Each pair of stations can communicate at frequencies at or below the MUF of the path between them, but not below the LUF — see text.

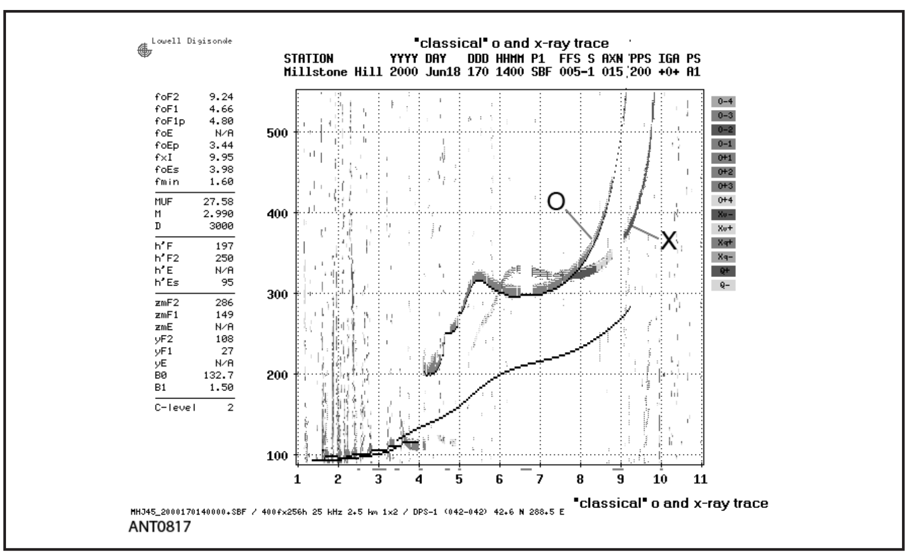

Figure 19.16 — Actual vertical-incidence ionogram from the Lowell Digisonde, owned and operated at Millstone Hill in Massachusetts by MIT (Massachusetts Institute of Technology). The ordinary (o) and extraordinary (x) traces are shown for heights greater than about 300 kilometers. At the upper left are listed the computer-determined ionospheric parameters, such as f_oF_2 at 9.24 MHz and f_oF_1 at 4.66 MHz.

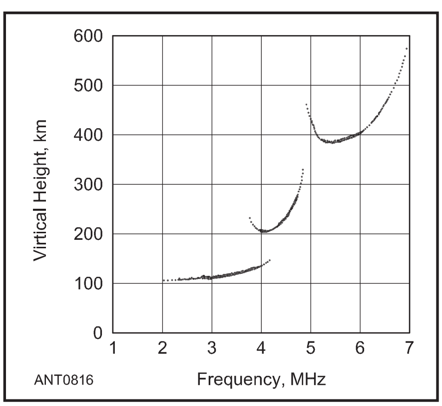

Figure 19.15 — Very simplified ionogram from a vertical-incidence sounder. The lowest trace is for the E region, the middle trace for the F_1 region, and the upper trace for the F_2 region.

index.html#stationmap-section. Real-time ionograms can be found online at the Digital Ionogram Database, sponsored by the University of Massachusetts Lowell (**giro.uml.edu/DIDBase/**).

The effects of noise and interference from other stations are shown by the many speckled dots appearing in the ionogram. The critical frequencies for various ionospheric regions are listed numerically at the left-hand side of the plot, and the signal amplitudes are color-coded by the color bars at the right-hand side of the plot. The X-axis is the frequency, ranging from 1 to 11 MHz.

19.3.5 Maximum and Lowest Usable Frequencies

A signal entering an ionospheric region above its critical frequency will not be reflected and may be lost to space. However, a signal above the critical frequency may be returned to Earth if it enters the region at an *oblique angle*, rather than at vertical incidence. This is fortunate because it permits two widely separated stations to communicate on significantly higher frequencies than the critical frequency (see **Figure 19.17**). This creates *skip propagation* in which the signal travels from the Earth, into the ionosphere, and back to the Earth where it can be received.

Lower frequency signals can be returned to Earth at higher incident angles, whereas a higher frequency signal at the same angle will not. The higher frequency signal will need to enter the ionosphere at a lower angle if it is to be returned to Earth. The lower angle also means it will be returned to Earth at a more distant point. The combination of ionization, angle of incidence, and fixed station locations creates ranges of frequencies for which communication is possible. This is discussed in the following sections.

MAXIMUM USABLE FREQUENCY (MUF)

The highest frequency supported by the ionosphere for reliable communications between two stations is the *maximum usable frequency* (MUF) for that path. If the separation between the stations is increased, a still higher frequency can be supported at lower launch angles. The MUF for this longer path is higher than the MUF for the shorter path because more refraction can occur for radio waves that encounter the ionosphere at more oblique angles. When the distance is increased to the maximum one-hop distance, the launch angle of the signals between the two stations is zero (that is, the ray path is tangential to the Earth at the two stations) and the MUF for this path is the highest that can be supported by that region of the ionosphere at that location, although antennas producing adequate radiation at very low angles may not be feasible at many locations. This maximum distance is about 4,000 kilometers (2500 miles) for the F_2 region and about 2,000 kilometers (1,250 miles) for the E region (see **Figure 19.18**). This is illustrated more completely in **Figure 19.19**, which gives maximum single-hop distances for E and F region propagation at various wave angles.

The MUF is a function of path, time of day, season, location, solar UV and X-ray radiation levels, and ionospheric disturbances. For vertically incident waves, the MUF is the same as the critical frequency. The seasonal variation of the MUF is due to the ratio of atomic oxygen to molecular nitrogen (O/N_2) in the atmosphere. Atomic oxygen is critical for electron production, whereas molecular nitrogen is critical for recombination. During the winter months in the northern hemisphere, the ratio of O/N_2 is higher, resulting

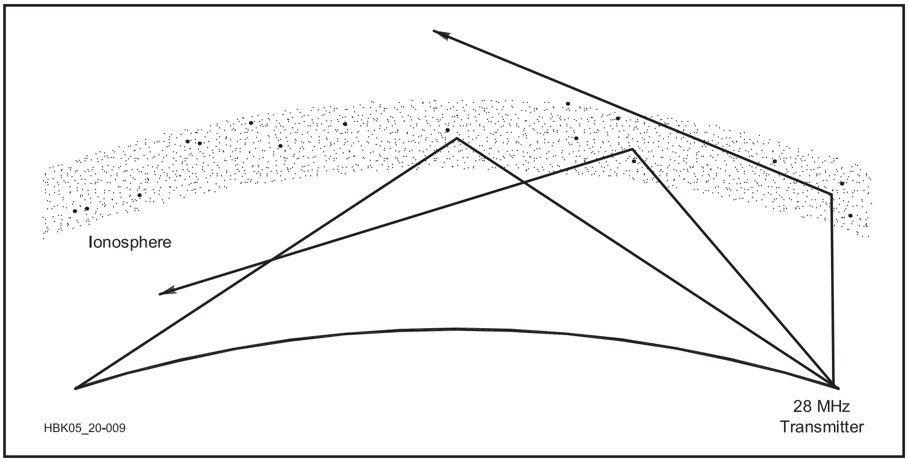

Figure 19.18 — Signals at the MUF propagated at a low angle to the horizon provide the longest possible one-hop distances. In this example, 28 MHz signals entering the ionosphere at higher angles are not refracted enough to bring them back to Earth.

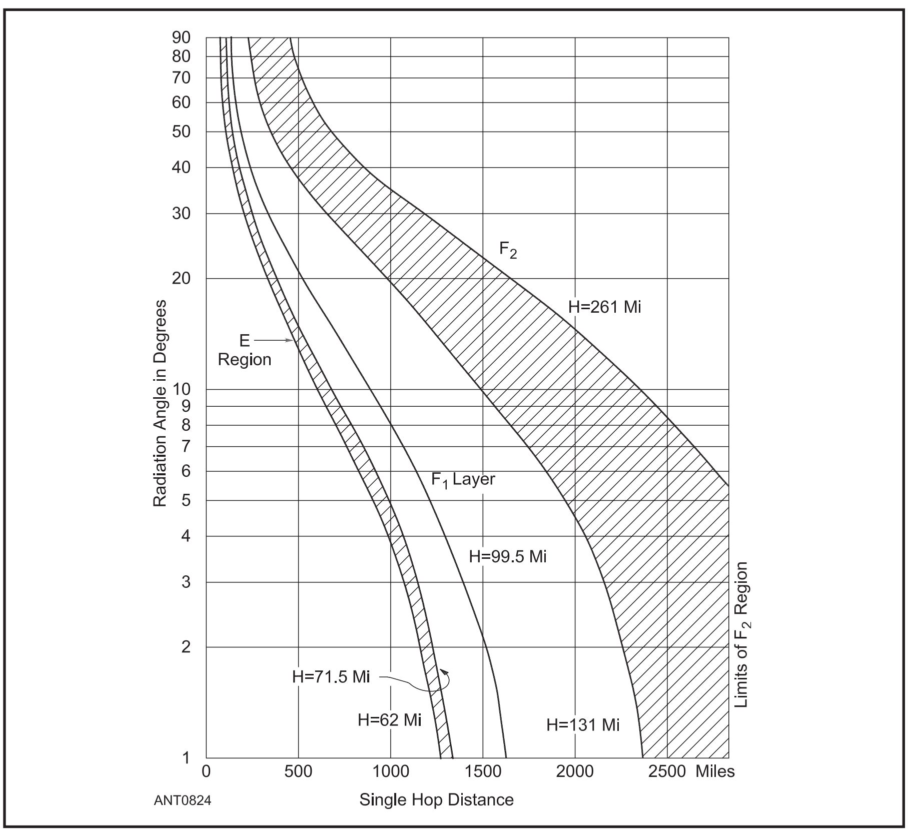

Figure 19.19 — Distance plotted against wave angle (one-hop transmission) for the nominal range of heights for the E, F_1, and F_2 regions.

in higher daytime MUFs.

Precisely speaking, a maximum usable frequency or MUF is defined for communication between two specific points on the Earth's surface, for the conditions existing at the time, including the minimum elevation angle that the station can launch at the frequency in use. (This practical form of MUF is sometimes called the *operational MUF*). At the same time and for the same conditions, the MUF from either of these two points to a third point may be different.

LOWEST USEABLE FREQUENCY (LUF)

The MUF at any time on a particular path is just that — the *maximum* usable frequency. Frequencies below the MUF will also propagate along the path, but ionospheric absorption and noise at the receiving location (due to man-made noise and/or noise from local or distant thunderstorms) may make the received signal-to-noise ratio too low to be usable. This happens because signal absorption increases proportionally to the square of the decrease in frequency. In this case, the frequency is said to be below the *lowest usable frequency* (LUF). The frequency nearest the point where reception became unusable would be the LUF. This occurs most frequently below 10 MHz, where atmospheric and man-made noises are most troublesome.

The LUF can be lowered somewhat by the use of high power and directive antennas, or through the use of communication modes that permit reduced receiver bandwidth or are less demanding of SNR — CW or PSK31 instead of SSB, for example. Digital modes such as JT65 and FT8 that use coding techniques to reject noise can also extend the LUF below what is available to analog modes. This is not true of the MUF, which is limited by the physics of ionospheric refraction, no matter how high your transmitter power or how narrow your receiver bandwidth.

The LUF can be higher than the MUF. When the LUF is higher than the MUF, there is no frequency that supports communication on the particular path at that time.

For example, when solar activity is very high at the peak of a solar cycle, the LUF often rises higher than 14 MHz on the morning Eastern US-to-Europe path on 20 meters. Just before sunrise in the US, the 20 meter band will be first to open to Europe, followed shortly by 15 meters, and then 10 meters as the Sun rises further. By mid-morning, however, when 10 and 15 meters are both wide open, 20 meters will become very marginal to Europe, even when both sides are running maximum legal power levels. By contrast, stations on 10 meters can be worked readily with a transmitter power of only 1 or 2 W, indicating the wide range between the LUF and the MUF.

19.3.6 Skip Zone and Skip Distance

Figure 19.20 shows we can communicate with the point on the Earth labeled "A" (where Wave #3 arrives), but not any closer to our transmitter site. When the critical angle is less than 90° (that is, directly overhead) there will always be a region around the transmitting site where an ionospherically propagated signal cannot be heard, or is heard weakly.

The area between the outer limit of the ground-wave range and the inner edge of signals returning from the ionosphere is the *skip zone*. The outer edge of the skip zone is the distance between the originating site and the beginning of the ionospheric return and is called the *skip distance*. This terminology should not be confused with ham jargon such as "skip is in," referring to the fact that a band is open for skywave propagation. Since both skip distance and maximum ground-wave distance change with frequency, the size of the skip zone also changes with frequency.

The size of the skip zone is closely related to MUF. When two stations are unable to communicate with each other on a particular frequency because the ionosphere is unable to refract the signal enough from one to the other through the required angle — that is, the operating frequency is above the MUF — the stations are in the skip zone for that frequency. Stations within the skip zone may be able to work each other on a lower frequency, or by ground wave, or by other mechanisms if they are close enough. There is no skip zone at frequencies below the MUF for those paths.

19.3.7 Multi-Hop Propagation

As mentioned previously in the discussion about Figure 19.20, the Earth itself can act as a reflector for radio waves, resulting in multiple hops. Thus, a radio signal can be reflected from the reception point on the Earth back into the ionosphere, reaching the Earth a second time at a still more-distant point. This effect is illustrated in **Figure 19.21**, where a single ionospheric region is depicted, although this time we show both the region and the Earth beneath it as curved rather than flat. The wave identified as "Critical Angle" travels from the transmitter via the ionosphere to point A, in the center of the drawing, where it is reflected upwards and travels through the ionosphere to point B, at the right. This shows a two-hop signal.

As in the simplified case in Figure 19.20, the distance at which a ray eventually reaches

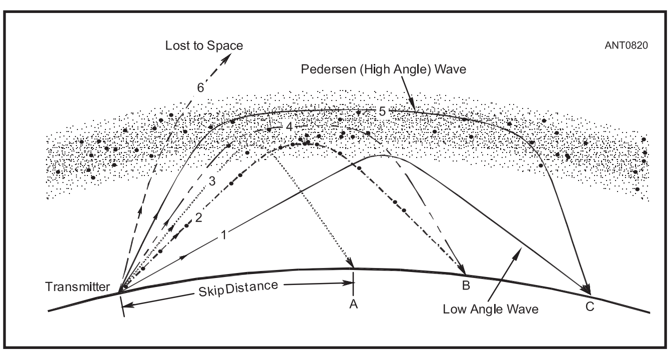

Figure 19.20 — Very simplified smooth-Earth/ionosphere diagram showing how the ground range from transmitter to receiver can vary as the elevation angle is gradually raised. The Pedersen wave, launched at a relatively high angle, has the same ground range as the low-angle wave #1. It may be slightly weaker and less stable, having traveled for a long distance in the ionosphere.

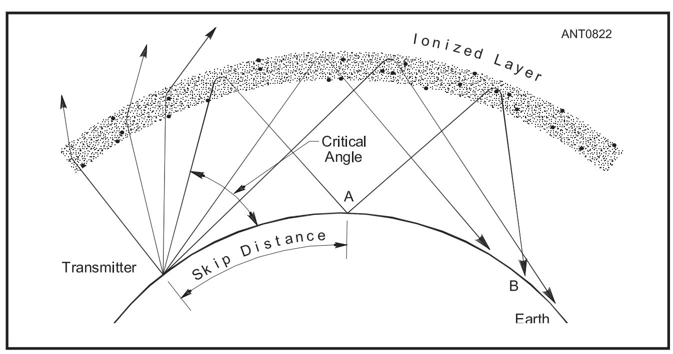

Figure 19.21 — Behavior of waves encountering a simple curved ionospheric region over a curved Earth. Rays entering the ionized region at angles above the critical angle are not bent enough to be returned to Earth and are lost to space. Waves entering at angles below the critical angle reach the Earth at increasingly greater distances as the launch angle approaches the horizontal. The maximum distance that may normally be covered in a single hop is 4,000 kilometers for low elevation angle signals at the upper end of HF. Greater distances are covered with multiple hops. Lower frequencies have shorter maximum hop distances due to more bending in the ionosphere.

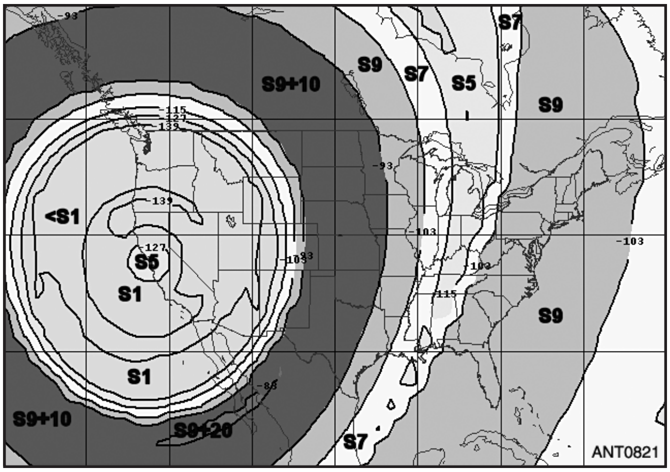

Figure 19.22 — Modified *VOAAREA* plot for 21.2 MHz from San Francisco to the rest of the US, annotated with signal levels in S units, as well as signal contours in dBW (dB below a watt). Antennas are assumed to be 3-element Yagis at 55 feet above flat ground; the transmitter power is 1,500 W; the month is November with SSN=50, a moderate level of solar activity, at 22 UTC. The most obvious feature is the large "skip zone" centered on the transmitter in San Francisco, extending almost one third of the distance across the US.

the Earth depends on the launch elevation angle at which it left the transmitting antenna.

The information in Figure 19.21 is greatly simplified. On actual communication paths the picture is complicated by many factors. One is that the transmitted energy spreads over a considerable area after it leaves the antenna. Even with an antenna array having the sharpest practical beam pattern, there is what might be described as a *cone of radiation* centered on the wave lines (rays) shown in the drawing. The reflection/refraction in the ionosphere is also highly variable and is the cause of considerable spreading and scattering.

Under some conditions it is possible for as many as four or five signal hops to occur over a radio path, as illustrated by the oblique ionogram in Figure 19.19. But no more than two or three hops is the norm. In this way, HF communication can be conducted over many thousands of miles.

An important point should be recognized with regard to signal hopping. A significant loss of signal occurs with each hop — especially at lower HF frequencies. The D and E regions of the ionosphere absorb energy from signals as they pass through, and the ionosphere tends to spread and scatter the radio energy in various directions, rather than confining it in a tight bundle. The roughness of the Earth's surface also scatters the energy at the Earth reflection point.

Assuming that both waves do reach point B in Figure 19.21, the low-angle wave will contain more energy at point B. This wave passes through the lower regions just twice, compared to the higher-angle route, which must pass through these regions four times, plus encountering an Earth reflection. Measurements indicate that although there can be great variation in the relative strengths of the two signals — the one-hop signal will generally be from 7 to 10 dB stronger, although many amateurs may not be capable of transmitting at these low angles. The nature of the terrain at the mid-path reflection point for the two-hop wave, the angle at which the wave is reflected from the Earth, and the condition of the ionosphere in the vicinity of all the refraction points are the primary factors in determining the signal-strength ratio.

The loss per hop becomes significant at greater distances. It is because of these losses that no more than four or five propagation hops are useful; the received signal becomes too weak to be usable over more hops. Although modes other than signal hopping also account for the propagation of radio waves over thousands of miles, backscatter studies of actual radio propagation have displayed signals with as many as five hops. So, the hopping mode is arguably the most prevalent method for long-distance communication.

Figure 19.22 shows another way of looking at propagation — at a *geographic area*. Figure 19.22 shows 15 meter signal levels across the US as they propagate from a transmitting station in San Francisco. This simulation of propagation conditions is for the month of November, with a medium level of solar activity (SSN = 50) at 22 UTC. Figure 19.22 was created using the *VOAAREA* software program, part of the *VOACAP* software suite. Transmitter power is assumed to be 1,500 W, with 3-element Yagis, 55 feet high, at the transmitter and at each receiving location.

From the transmitter out to about 50 miles, signals are moderate, at about S-5 on an S meter. Beyond that coverage area to almost ⅓ of the way across the country (to Colorado), there is a large and distinctive skip zone, where only very weak signals return to Earth (S-1 or less). Beyond Colorado, signals rapidly build up to S-9+10 dB across the middle of the US, falling to S-9 and then to S-7 in the vicinity of Chicago, Illinois. Beyond Chicago, the signals drop to S-5 in a swath from Michigan and part of Ohio down to Alabama. All along the US East Coast, signals come back strong at S-9.

The reason why the signals in Figure 19.22 drop down to S-5 in the Midwest is that the necessary elevation angles to cover this region in a single F_2 hop are extremely low even at a moderate level of solar activity. To achieve launch angles as low as 1 degree requires either very high antenna heights or a high mountaintop location. Beyond the Midwest, out to the US East Coast, two F_2 hops are required, with higher elevation angles and hence greater antenna gain for moderate antenna heights.

19.3.8 NVIS Propagation

The purpose of *near vertical incidence skywave* (*NVIS*) propagation is to bridge the gap between where ground wave is too weak and where the skip zone ends. Because NVIS communication operates with high angles of incidence to the ionosphere, signals return to Earth relatively close to the transmitter. By using frequencies close to and below the critical frequency and antennas that produce radiation at high elevation angles, NVIS operation exhibits no skip zone and communications can be maintained over these relatively short distances. (See the previous section on Ionospheric Refraction for an explanation of critical frequency.)

Frequency selection is important since absorption in the ionosphere increases as frequency decreases. By operating close to the critical frequency, absorption is minimized. This requires knowing the critical frequency, which is continually changing from day to day and hour to hour. Propagation modeling software can be used to predict the critical frequency for propagation between two locations. You can also use real-time ionosonde data as discussed previously if the data is representative of your location and the desired communication path. You should expect to change bands as conditions change to remain close to the critical frequency.

A desirable NVIS antenna radiation pattern is one in which most of the radiation is upward at elevation angles greater than 45 degrees. This is referred to as *NVIS directivity*, defined as the average directivity for elevation angles between 70° and 90°. To maximize NVIS directivity, the most common antenna is a $\lambda/2$

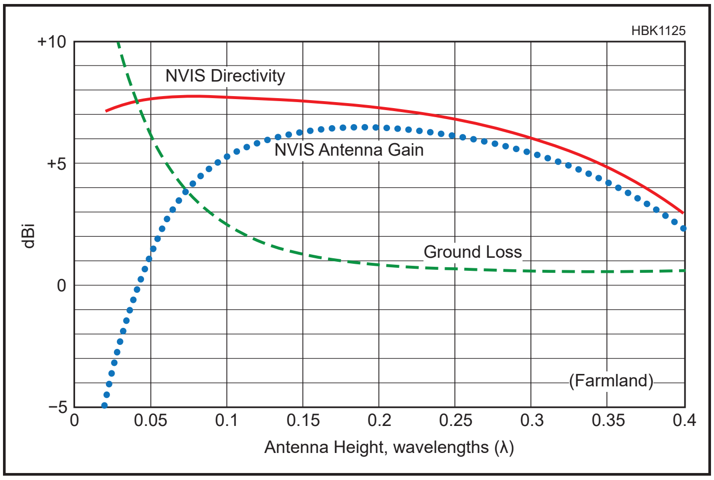

Figure 19.23 — The relationship between antenna height, ground loss, and NVIS directivity at 5.4 MHz. The same general relationship exists on the lower HF bands and for different types of soil. (Graph from Witvliet et al, see References.)

dipole mounted approximately 0.2 λ above the ground. Lower heights incur greater ground losses, and larger heights result in more low-angle radiation such that NVIS performance begins to suffer.

Figure 19.23 summarizes the relationship of antenna height, NVIS directivity, and ground loss at 5.4 MHz. NVIS directivity varies only slowly with height with an optimum at 0.09 λ, whereas the antenna gain has a distinct optimum at 0.19 λ, sharply decreasing at low heights due to excessive ground loss. The same general relationship exists for the other amateur bands below 10 MHz, leading to the overall recommendation for antenna heights of approximately 0.2 λ for best NVIS performance. (This paragraph and figure are from the referenced 2015 article by Witvliet and others — see below.) In the December 2005 issue of *QST*, Dean Straw, N6BV, used the *VOACAP* propagation prediction program to analyze a variety of NVIS paths centered on San Francisco. His analysis showed area coverage maps (signal strength contours versus distance from the transmitter) and elevation patterns of antennas at various heights. His analysis allowed him to formulate a very nice summary: *As a rule-of-thumb, for ham band NVIS, I would recommend that 40 meters be used during the day, 80 meters during the night.* Additionally, during a winter night near solar minimum, changing to 160 meters may be necessary.

Another way to summarize this would be to say that 40 meters (7 MHz) and 60 meters (5 MHz) are good for NVIS propagation out to a couple hundred miles during the day, with 40 meters better at solar maximum and 60 meters better at solar minimum. Likewise, 80 meters (4 MHz, aka 75 meters) and 160 meters (1.9 MHz) are good for NVIS propagation out to several hundred miles during the night, with 80 meters better at solar maximum and 160 meters better at solar minimum (especially during the winter months). This summary takes into account both the MUF and ionospheric absorption.

Along with N6BV's *QST* article, there are several excellent articles that apply to the amateur radio use of NVIS. Ed Farmer, AA6ZM, contributed an overview of NVIS techniques, including an analysis of antenna type and pattern with height, in January 1995 *QST*, which is also listed in the References section. Perhaps the most complete current article on NVIS is from 2015: "Near Vertical Incidence Skywave Propagation: Elevation Angles and Optimum Antenna Height for Horizontal Dipole Antennas" by Witvliet and others in the *IEEE Antennas and Propagation Magazine*. It presents a comprehensive discussion of propagation, coverage, and antenna systems. Tom Kamp, DF5JL, also studied NVIS on the 60 meter band in Germany. See the References entry for his article in *CQ DL*. NVIS antenna systems are also discussed extensively in the *ARRL Antenna Book* chapter on HF Antenna System Design.

19.3.9 Propagation in Disturbed Conditions

So far, we have discussed the Earth's ionosphere when conditions at the Sun are undisturbed. Unfortunately, events on the Sun can disrupt propagation on Earth, especially during the roughly eight to nine years removed from the solar minimum phase. These events cause three types of disturbances to propagation on Earth: radio blackouts, solar radiation storms, and geomagnetic storms. These three categories were defined by NOAA in early 2002 when they changed their format for solar disturbances to better align with the current understanding of these disturbances to propagation. These and related terms, along with the scales for reporting solar disturbances, were described earlier in the section "The Sun and Solar Activity."

GEOMAGNETIC STORMS

Geomagnetic storms are generally caused by coronal mass ejections (CME) and high-speed streams in the solar wind originating from coronal holes. It usually takes 24 to 36 hours for a CME or the effects of a coronal hole to reach and impact the Earth's ionosphere, so we generally have ample warning of the impending disturbance from satellite observations.

CMEs and coronal holes can result in increased geomagnetic field activity, which we see as higher A- and K-indexes. This can cause electrons that are trapped in the Earth's magnetosphere to precipitate into the auroral zones, resulting in increased D and E region ionization. Generally, a similar effect is seen in both auroral zones since the precipitating electrons come from within the Earth's magnetosphere (they don't come directly from the Sun). Thus, as the K-index goes to much higher levels (7 or above), check for auroral VHF propagation. Storm levels range from a K value of 5 (minor) all the way to 9 (extreme). Extreme storms only occur for a few days during a typical solar cycle. (Remember that the A-index reflects yesterday's geomagnetic activity.) See **Table 19.2** for the latest NOAA descriptions of geomagnetic storms.

An elevated K-index would also be a good time to check for skewed paths on the low bands — especially 160 meters — since the amount of refraction by a given electron density profile is inversely proportional to the square of the frequency (the lower the frequency, the more the bending).

Additionally, when the K-index is high, F_2 region ionization generally is depleted at middle and high latitudes, thus moving down in frequency may minimize the impact to propagation. F_2 region ionization can also be enhanced at the low latitudes during geomagnetic storms, so check for enhanced low latitude (equatorial) propagation.

SOLAR RADIATION STORMS AND RADIO BLACKOUTS

Solar radiation storms and radio blackouts are caused by X-class and strong M-class solar flares. When a large solar flare erupts from the Sun's surface, it can launch out into space a wide spectrum of electromagnetic energy. Since electromagnetic energy travels at the speed of light, the first indication of a solar

Table 19.2
Geomagnetic Storms

Scale	*Description*	*Effect on HF Radio*	*Physical measure*	*Average Frequency (1 cycle = 11 years)*
R 5	Extreme	Complete HF (high frequency) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector.	X20	Less than 1 per cycle
R 4	Severe	HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time.	X10	8 per cycle
R 3	Strong	Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth.	X1	175 per cycle
R 2	Moderate	Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes.	M5	350 per cycle
R 1	Minor	Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact.	M1	2000 per cycle

(Data from www.swpc.noaa.gov/noaa-scales-explanation)

flare reaches the Earth in about eight minutes. A large flare shows up as an increase in visible brightness near a sunspot group, accompanied by increases in UV and X-ray radiation and high levels of Sun noise in the VHF radio bands. It is the X-ray radiation that results in radio blackouts for signals propagating across the daytime side of the Earth due to increased D region absorption, and this is called a *sudden ionospheric disturbance* (SID) or a *radio blackout*. The lower frequencies are affected for the longest period. In extreme cases, nearly all background noise will be gone as well. SIDs may last from minutes to a few hours, after which ionospheric conditions return to their pre-blackout conditions.

A large solar flare can also release matter into space, mainly in the form of very energetic particles. These cause *solar radiation storms*, whereby increased absorption in the polar cap (that area inside the auroral oval) degrades over-the-pole propagation paths. This is called a *polar cap absorption* (PCA) event. A PCA event may last for days, dramatically affecting transpolar HF propagation. An interesting fact with respect to PCAs is that they do not necessarily affect the northern and southern polar regions similarly. Thus, if the short path between two points is degraded over one pole, the long path may still be available over the other pole.

19.3.10 E Region Propagation

The lowest portion of the ionosphere useful for long-distance communication by amateurs, the *E region* lies between 90 and 150 kilometers (60 and 90 miles) altitude, but a narrower region centered at 95 to 120 kilometers (60 to 70 miles) is more important for radio propagation. In the E region, nitric oxide and molecular oxygen are ionized by short-wavelength UV and long-wavelength X-ray radiation (so-called soft X-rays). Normally, the E region exists primarily during daylight hours, because, like the D region, it requires a constant source of ionizing radiation. Recombination is not as fast as in the denser D region and absorption is much less. The E region has a daytime critical frequency that varies between 3 and 4 MHz with the solar cycle. At night, the normal E region decays to a minimum critical frequency of 0.3 – 0.5 MHz, which is still enough to refract low elevation angle 1.8 MHz signals.

DAYTIME AND NIGHTTIME E REGION

In the E region, at intermediate atmospheric density, ionization varies with the Sun angle above the horizon (the solar zenith angle), but solar EUV radiation is not the sole ionizing agent. Solar X-rays, meteors, and meteoroids entering this portion of the Earth's atmosphere also play a part. Ionization increases rapidly after sunrise, reaches maximum around noon local time, and drops off quickly after sundown. The minimum is after midnight, local time. As with the D region, the E region absorbs wave energy in the lower-frequency amateur bands when the Sun angle is high,

The E region plays a small role in propagating HF signals but can be a major factor limiting propagation during daytime hours. Its usual critical frequency of 3 to 4 MHz, with an M-factor of about 5, suggests that single-hop E region skip might be useful between 5 and 20 MHz at distances up to 2,300 kilometers (1,400 miles). In practice this is not the case, because the potential for E region skip is severely limited by D region absorption. Signals radiated at low angles at 7 and 10 MHz, which might be useful for the longest-distance contacts, are largely absorbed by the D region. Only high-angle signals pass through the D region at these frequencies, but high-angle E region skip is typically limited to 1,200 kilometers (750 miles) or so. Signals at 14 MHz penetrate the D region at lower angles at the cost of some absorption, but the casual operator may not be able to distinguish between signals propagated by the E region or higher-angle F region propagation.

E REGION BLANKETING

On 20 meters during the summer, on 40 and 30 meters around mid-day, and on 160 meters mostly during the evening hours or well into the night in summer, the E region can block a signal from getting to the higher F region that offers longer hops. This is known as *E region blanketing*, in reference to the E region acting as a blanket that nothing can get through. This is often mistakenly considered to be ionospheric absorption from the D region.

E region blanketing is the primary reason why long-distance propagation is uncommon during midday on the 40- and 30 meter bands and during the summer on 20 meters. D region absorption — to a much lesser degree — also degrades midday long-distance propagation on 40 and 30 meters, mainly by absorbing most low angle, multi-hop, E region propagation.

AURORA

If the orientation of the magnetic field from a powerful CME is aligned southward (opposite to that of the Earth's magnetic field) and if the magnetic field strength is greater than about 5 nanoteslas and *if both conditions* persist for about two hours or more, the magnetic bubble can partially collapse and the particles normally trapped there can be deposited into the Earth's upper atmosphere. This produces a visible or radio *aurora*. An aurora is visible if the time of entry is after dark.

The visible aurora is an optical signature of the plasma curtain capable of refracting radio waves in the range of frequencies above about 20 MHz. D-region absorption increases between midnight and sunrise on lower frequencies during auroras. The exact frequency ranges depend on many factors: time, season, position with relation to the Earth's auroral regions, and the level of solar activity at the time, to name a few.

Radar signals as high as 3 GHz have been scattered by the *aurora borealis* or northern lights (*aurora australis* in the Southern Hemisphere), but amateur aurora contacts are common only from 28 through 432 MHz. By pointing directional antennas generally northward toward the center of aurora activity, oblique paths between stations up to 2,300 kilometers (1,400 miles) apart can be completed (see **Figure 19.24**). High power and large antennas are not necessary. Stations with small Yagis and as little as 10 W output have used auroras on frequencies as high as 432 MHz, but contacts at 902 MHz and higher are exceedingly rare. Auroral propagation works just as well in the Southern Hemisphere, in which case antennas must be pointed generally southward.

In addition to scattering radio signals, auroras have other effects on worldwide radio propagation. Communication below 20 MHz is disrupted in high latitudes, primarily by absorption, and is especially noticeable over polar and near-polar paths. Signals on the AM broadcast band through the 40-meter band late in the afternoon may become weak and watery. The 20-meter band may close down altogether. Satellite operators have also noticed that 144 MHz downlink signals are often weak and distorted when satellites pass near the polar regions. At the same time, the MUF in equatorial regions may temporarily rise dramatically, including an enhancement of transequatorial paths at frequencies as high as 50 MHz.

Auroras occur more often around the spring and fall equinoxes (March-April and September-October), but auroras may appear in any month. Aurora activity generally peaks about two years before and after solar cycle maximum (the "before" generally due to CMEs and the "after" generally due to coronal hole high-speed wind streams). There is a marked diurnal swing in the number of auroras. Favored times are late afternoon and early evening, late evening through early morning, and early afternoon, in about that order. Major auroras often start in early afternoon and carry through to early morning the next day

19.3.11 F Region Propagation

Most of our long-distance communication capability stems from the tenuous outer reaches of the Earth's atmosphere known as the F region. At heights above 100 miles, ions and electrons recombine more slowly, allowing the region to hold its ability to reflect wave energy back to Earth well into the night.

The F region, from 150 kilometers (90 miles) to over 400 kilometers (250 miles) altitude, is by far the most important for long-distance HF communications. F-region oxygen atoms are ionized primarily by ultraviolet radiation. During the day, ionization reaches maxima in two distinct regions, called F_1 and F_2. The F_1 region forms between 150 and 250 kilometers (90 and 160 miles), is most prevalent in the summer months, and disappears at night. The F_2 region extends above 250 kilometers (160 miles), with a peak of ionization around 300 kilometers (190 miles). At night, F-region ionization collapses into one broad region at 300 – 400 kilometers (190 – 250 miles) altitude. Ions recombine very slowly at these altitudes because atmospheric density is relatively low. Maximum ionization levels change significantly with time of day, season, and year of the solar cycle.

The region's height may be from 160 to more than 500 kilometers (100 to over 310 miles), depending on the season of the year, the latitudes, the time of day, and, most capricious of all, what the Sun has been doing in the last few minutes and in perhaps the last three days before the attempt is made. The MUF between Eastern US and Europe, for example, has been anything from 7 to 70 MHz, depending on the conditions mentioned above, plus the point in the long-term solar-activity cycle at which the check is made. The MUF between North America and Europe frequently drops below 7 MHz during the fall and winter during solar minimum years, mainly because of the electron depletion effects of the mid-latitude trough, which is discussed later.

During a summer day, the F region may split into two, the F_1 region and the F_2 region. The lower and weaker F_1 region, about 160 kilometers (100 miles) up, has only a minor role, often blanketing access to the F_2 region during summer daytime hours. At night the F_1 region disappears and the F_2 region height drops somewhat.

Propagation information tailored to amateur needs is published by the ARRL via propagation bulletins that are issued every Friday — they are archived at **arrl.org/w1aw-bulletins-archive-propagation**. Finally, solar and geomagnetic field data, transmitted hourly and updated eight times daily, are given in brief bulletins carried by the US Time Standard stations, WWV (18 minutes past the hour) and WWVH (45 minutes past the hour), and also on internet websites. More information on these services is provided later.

F_1 REGION

The daytime F_1 region is not very important to HF communication. In reality it is an inflection point in the electron density profile, not a peak. It exists only during daylight hours and is largely absent in winter. Radio signals below 10 MHz are not likely to reach the F_1 region, because they are either absorbed by the D region or refracted by the E region.

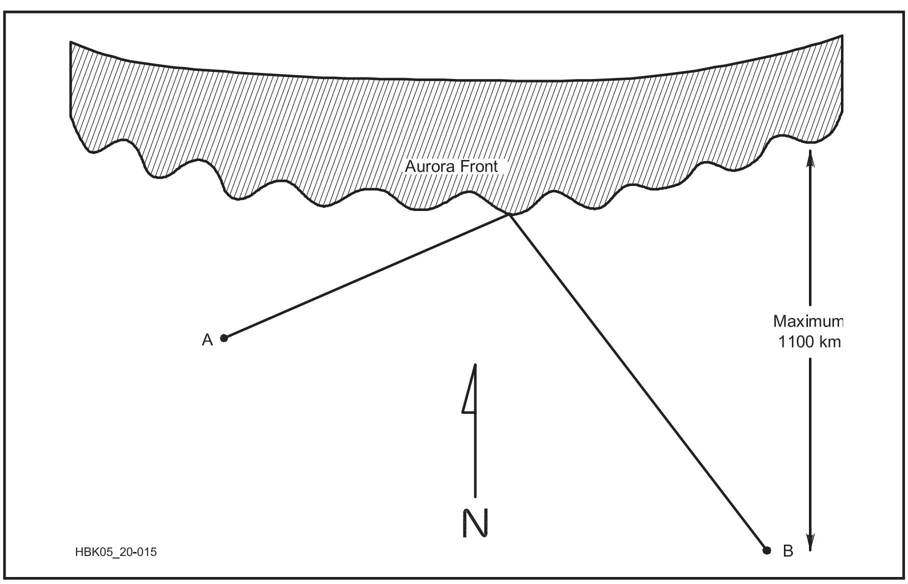

Figure 19.24 — Point antennas generally north to make oblique long-distance contacts on 28 through 432 MHz via aurora scattering. Optimal antenna headings may shift considerably to the east or west depending on the location of the aurora. This necessitates moving your antenna azimuth direction for best propagation and continuing to do so as the aurora progresses.

Signals higher than 20 MHz that pass through both of the lower ionospheric regions are likely to pass through the F_1 region as well, because the F_1 MUF rarely rises above 20 MHz. Absorption diminishes the strength of any signals that continue through to the F_2 region during the day. Some useful F_1 region refraction may take place between 10 and 20 MHz during summer days, yielding paths as long as 3,000 kilometers (1,900 miles), but these would be practically indistinguishable from F_2 skip. The F_1 region often blankets F_2 region daytime 20 meter propagation during the summer, preventing most mid-day long distance propagation. As with E region blanketing, this is often mistaken for absorption.

F_2 REGION

The F_2 region forms between 250 and 400 kilometers (160 and 250 miles) during the daytime and persists throughout the night as a single consolidated F region 50 kilometers (30 miles) higher in altitude. Typical ion densities are the highest of any ionospheric region, with the possible exception of some unusual E region phenomena. In contrast to the other ionospheric regions, F_2 ionization varies considerably with time of day, season, and position in the solar cycle, but it is never altogether absent. These two characteristics make the F_2 region the most important for long-distance HF communications.

The F_2 region MUF is nearly a direct function of ultraviolet (UV) solar radiation, which in turn closely follows the solar cycle. During the lowest years of the cycle, the daytime MUF may climb above 14 MHz for only a few hours a day. In contrast, the MUF may rise beyond 50 MHz during peak years of strong solar cycles and stay above 14 MHz throughout the night. The virtual height of the F_2 region averages 330 kilometers (210 miles) but varies between 200 and 400 kilometers (120 and 250 miles). Maximum one-hop distance is about 4,000 kilometers (2,500 miles). Near vertical incidence skywave propagation just below the critical frequency provides reliable coverage out to 200 – 300 kilometers (120 – 190 miles) with no skip zone. It is most often observed on 7 MHz during the day.

The extremely high-angle *Pedersen ray* can create effective single-hop paths of 5,000 to 12,000 kilometers under certain conditions, but most operators will not be able to distinguish Pedersen ray paths from normal F region propagation. A Pedersen ray path follows the contour of the Earth near the height of the maximum F_2 region electron density, and it requires a fairly stable ionosphere. Pedersen ray paths are most evident over high-latitude east-west paths at frequencies near the MUF. They appear most often about noon local time at mid-path when the geomagnetic field is very quiet. Pedersen ray propagation may be responsible for 50 MHz paths between the US Northeast and Western Europe, for example, when ordinary MUF analysis could not explain the 5,000-kilometer contacts (see part E in **Figure 19.25**).

At any given location on Earth, in general both F_2 region ionization and MUF at that point build rapidly at sunrise, usually reaching a maximum after local noon, and then decrease to a minimum at night prior to the next sunrise. Depending on the season, the MUF is generally highest on paths directed within 20 degrees of the Equator and lower toward the poles. For this reason, transequatorial paths may be open at a particular frequency when all other paths are closed, especially when TEP propagation is available during late afternoon and evening.

In contrast to all the other ionospheric regions, daytime ionization in the winter F_2 region averages four times the level of the summer at the same period in the solar cycle, doubling the MUF. This so-called *winter anomaly* is caused by a seasonal increase in the ratio of atoms to molecules at F_2 region heights (atoms are instrumental in the production of electrons, whereas molecules are instrumental in the loss of electrons). Winter daytime F_2 conditions are much superior to those in summer, because the MUF is much higher.

Propagation modes called *above-the-MUF* can also come into play. Normally we believe the MUF must be equal to or greater than the operating frequency for propagation to occur. This assumes pure refraction. But the MUF can be below the operating frequency — especially for chordal hop modes such as TEP — with additional loss incurred due to the scatter process. The *VOACAP* propagation prediction program includes this above-the-MUF mode, and it will be discussed later.

TRANSEQUATORIAL PROPAGATION

Discovered by amateur radio operators in 1947, *transequatorial propagation* (commonly abbreviated TE or TEP) supports propagation between 5,000 and 8,000 kilometers (3,100 and 5,000 miles) across the magnetic equator from 28 MHz to occasionally as high as 432 MHz. (See the Bibliography entry for *Beyond Line of Sight* by Pocock.) Stations attempting TE contacts must be nearly equidistant from the geomagnetic equator. Many contacts have been made at 50 and 144 MHz between Europe and South Africa, Japan and Australia, and the Caribbean region and South America. Fewer contacts have been made on the 222 MHz band, and TE signals have been heard at 432 MHz.

The ionosphere over equatorial regions — but not directly over the Equator — is higher, thicker, and denser than elsewhere. Because of its more constant exposure to solar radiation, the equatorial belt has high nighttime-MUF possibilities. The potential MUF varies with solar activity, but not to the extent that conventional F-region propagation does.

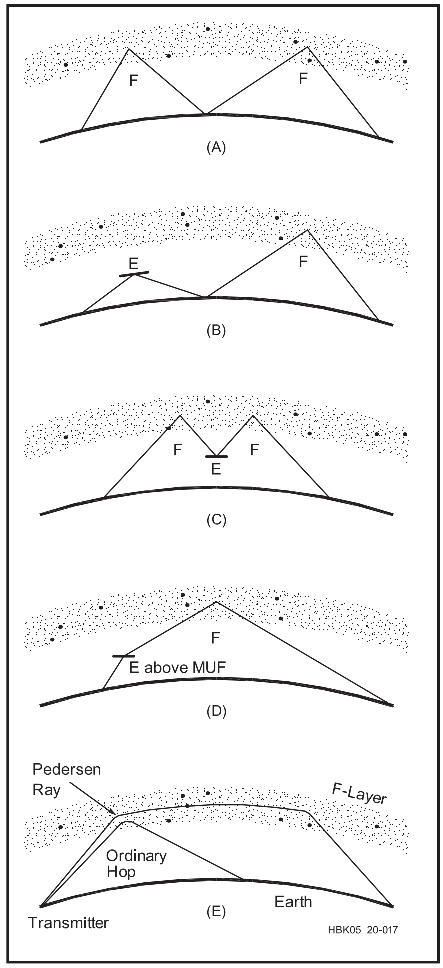

Figure 19.25 — Multihop paths can take many different configurations, including a mixture of E and F region hops. (A) Two F region hops. Five or more consecutive F region hops are possible. (B) An E region hookup to the F region. (C) A top-side E region reflection can shorten the distance of two F region hops. (D) Refraction in the E region above the MUF is insufficient to return the signal to Earth, but it can go on to be refracted in the F region. (E) The Pedersen ray, which originates from a signal launched at a relatively high angle above the horizon into the E or F region, may result in a single-hop path, 5,000 kilometers (3,100 miles) or more. This is considerably farther than the normal 4,000 kilometer (2,500 mile) maximum F-region single-hop distance, where the signal is launched at a very low takeoff angle. The Pedersen ray can easily be disrupted by any sort of ionospheric gradient or irregularity. Not shown in this figure is a chordal hop — since chordal hops are most prevalent in the equatorial ionosphere, refer to Figure 19.26.

TE propagation depends on bulges of intense F_2 region ionization on both sides of the geomagnetic equator. This field-aligned ionization forms shortly after sunset via a process known as the *fountain effect* in an area 100-200 kilometers (60 – 120 miles) north and south of the geomagnetic equator and 500 – 3,000 kilometers (310 – 1,900 miles) wide. It moves west with the setting Sun. The MUF may increase to twice its normal level 15 degrees on either side of the geomagnetic equator (see **Figure 19.26**). For an overview of trans quatorial propagation, read *F-Region Propagation and the Equatorial Ionosphere Anomaly* included with the supplemental content.

The TE range is usually within about 4,000 kilometers (2,500 miles) on either side of the geomagnetic equator. The Earth's magnetic axis is tilted with respect to the geographical axis, so the TE belt appears as a curving band on conventional flat maps of the world (see **Figure 19.27**). As a result, TE has a different latitude coverage in the Americas from that from Europe to Africa.

Unfortunately for most continental US stations, the *geomagnetic equator* dips south of the geographic equator in the Western Hemisphere, as shown in Figure 19.27. Primary northern TEP areas are the Virgin Island, Haiti, the Dominican Republic, Jamaica, Mexico, and much less frequently Florida south of Miami. TE contacts from the southeastern part of the country may be possible with Argentina and Chile.

Transequatorial propagation peaks between 5 p.m. and 10 p.m. during the spring and fall equinoxes, especially during the peak years of the solar cycle. The lowest probability is during the summer and winter solstices. Quiet geomagnetic conditions are required for TE to form. High power and large antennas are not required to work TE, as VHF stations with 100 W and single long Yagis have been successful.

Within its optimum regions of the world, the TE mode extends the usefulness of the 50-MHz band far beyond that of conventional F-region propagation, since the practical TE MUF can be up to 1.5 times that of normal F2 MUF based on analysis with ray tracing. During unusually high periods of F2 region ionization on both sides of the geomagnetic equator (high solar activity) and perhaps aided by geomagnetic field activity, TEP on 144 MHz and 432 MHZ has been observed around the equinoxes for several hours after sunset. Both its seasonal and diurnal characteristics are extensions of what is considered normal for 50-MHz propagation. In that part of the Americas south of about 20 degrees North latitude, the existence of TE affects the whole character of band usage, especially in years of high solar activity. More northerly stations frequently access 50 MHz TEP via an additional E_s hop as discussed in the section on sporadic E. TE propagation is also discussed in the paper "Trans-Equatorial Propagation" by Carl Luetzelschwab, K9LA, on his website, **k9la.us**.

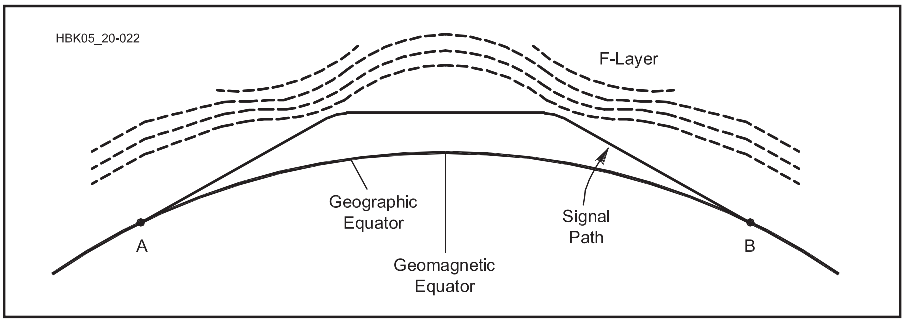

Figure 19.26 — Cross-section of a transequatorial signal path, showing the effects of ionospheric bulging and a double refraction or chordal hop above the normal MUF.

MULTI-HOP F REGION PROPAGATION

Most HF communication beyond 4,000 kilometers (2,500 miles) takes place via multiple ionospheric hops. Radio signals are reflected from the Earth back toward the ionosphere for additional ionospheric refractions. A series of ionospheric refractions and ter-

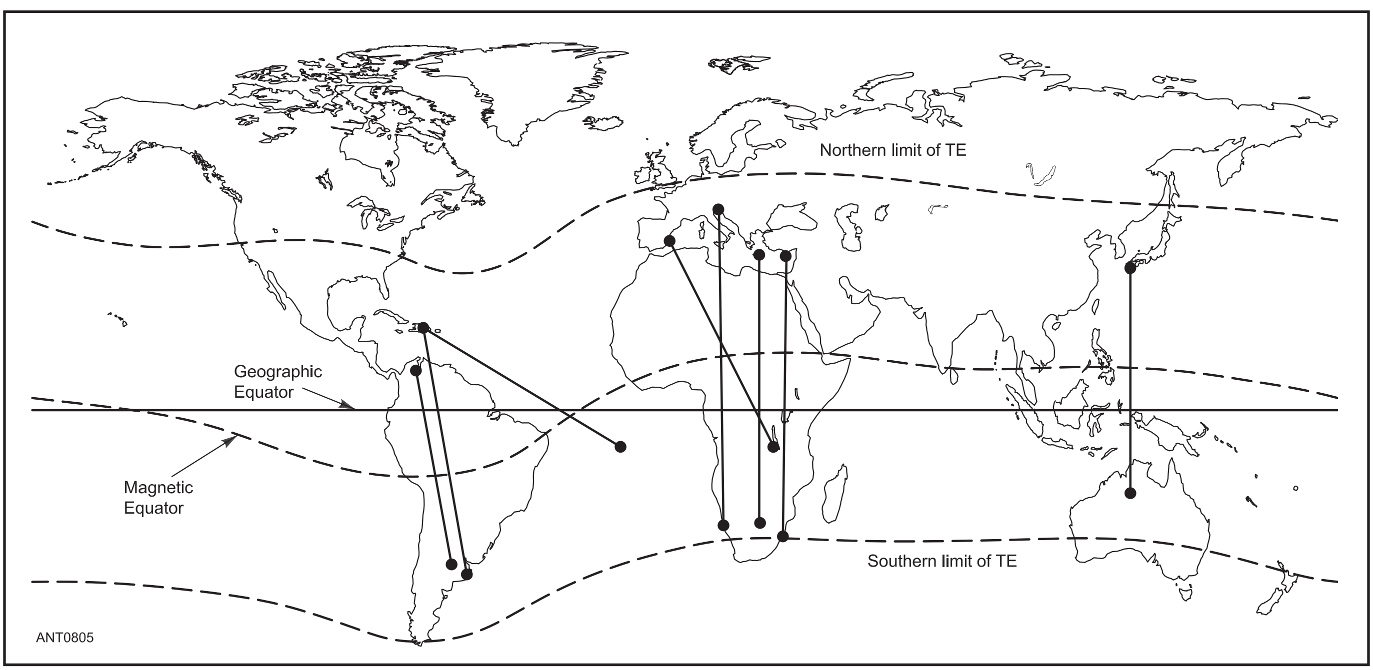

Figure 19.27 — Transequatorial propagation takes place between stations equidistant across the geomagnetic equator. Distances up to 8,000 kilometers (5,000 miles) are possible on 28 through 432 MHz. Note the geomagnetic equator is considerably south of the geographic equator in the Western Hemisphere.

restrial reflections commonly create paths halfway around the Earth. Each hop involves additional attenuation and absorption, so the longest-distance signals tend to be the weakest. Even so, it is possible for signals to be propagated completely around the world and arrive back at their originating point. Multiple reflections within the F region may at times bypass ground reflections altogether, creating what are known as *chordal hops* (see Figure 19.26), with lower total attenuation. It takes a radio signal about 0.14 seconds to make an around-the-world trip.

Multi-hop paths can take on many different configurations, as shown in the examples of Figure 19.25. E region (especially sporadic E) and F region hops may be mixed. In practice, multi-hop signals arrive via many different paths, which often increases the problems of fading. Analyzing multi-hop paths is complicated by the effects of D- and E-region absorption, possible reflections from the tops of sporadic E regions, disruptions in the auroral zone, and other phenomena.

In general, when a band is opening and closing as the MUF changes, extremely low elevation angles are dictated (less than 5 degrees). During the main part of the opening, the elevation angle is higher — generally in the range of 5 to 20 degrees. This is why stations with extremely high antennas (which have higher gain at lower takeoff angles) perform better at band openings and closings.

F-REGION LONG PATH

Most HF communication takes place along the shortest great-circle path between two stations. Short-path propagation is always less than 20,000 kilometers (12,000 miles) — halfway around the Earth. Nevertheless, it may be possible at times to make the same contact in exactly the opposite direction via the *long path*. The long-path distance will be 40,000 kilometers (25,000 miles) minus the short-path length. Signal strength via the long path is usually considerably less than the more direct short path. When both paths are open simultaneously, there may be a distinctive sort of echo on received signals. The time interval of the echo represents the difference between the short-path and long-path distances.

Sunlight is a required element in long-haul communication via the F region above about 10 MHz, but due to recombination being a slow process after sunset, propagation may be supported in the dark ionosphere for many hours after sunset. This fact tends to define long-path timing and antenna aiming. Both are essentially the reverse of the "normal" for a given circuit. We know also that salt-water paths work better than overland ones. This can be significant in long-path work.

There is sometimes a great advantage to using the long path when it is open because signals can be stronger and fading less troublesome, or because fewer interfering signals lie along the path between the stations. There are times when the short path may be closed or disrupted by E region blanketing (described earlier), D region absorption, or F region gaps, especially when operating just below the MUF. Long paths that predominantly cross the night side of the Earth, for example, are sometimes useful because they generally avoid blanketing and absorption problems. Daylight-side long paths may take advantage of higher F region MUFs that occur over the sunlit portions of the Earth. If there is knowledge of this potential at both ends of the circuit, long-path communication may work very well. Cooperation is almost essential, because both the aiming of directional antennas and the timing of the attempts must be right for any worthwhile result.

F-REGION GRAY-LINE

Gray-line paths can be considered a special form of long-path propagation that take into account the unusual ionospheric configuration along the twilight region between night and day. The gray line, as the twilight region is sometimes called, extends completely around the world. Astronomers call this the *terminator*. It is not precisely a line, for the distinction between daylight and darkness is a gradual transition due to atmospheric scattering. Notice that on one side of the Earth, the gray line is coming into daylight (sunrise), and on the other side it is coming into darkness (sunset). In addition, the upper regions of the ionosphere are illuminated longer than lower regions; they come into sunlight first and enter darkness last.

The ionosphere undergoes a significant transformation between night and day. As day begins, the highly absorbent D and E regions are recreated, while the F region MUF rises from its pre-dawn minimum. At the end of the day, the D and E regions quickly disappear, while the F region MUF continues its slow decline from late afternoon. For a brief period just along the gray-line transition, the D and E regions are not well formed, yet the F_2 MUF usually remains higher than 5 MHz. This would normally provide a special opportunity for stations at 1.8 and 3.5 MHz except that:

• ionospheric absorption is still high on these bands in this twilight region from an understanding of the physics of absorption, and

• the electron density gradient across the gray line (also known as the terminator) skews RF away from the day ionosphere into the night ionosphere (shown by ray tracing studies taking into account the Earth's magnetic field and the electron-neutral collision frequency).

What this means is that contrary to decades of popular belief, propagation along the terminator on the low bands is not efficient, and it is not possible for RF on these bands to even follow the terminator. This is supported by the fact that there has never been a report of enhanced propagation on these bands along a short path that is aligned with the gray line.

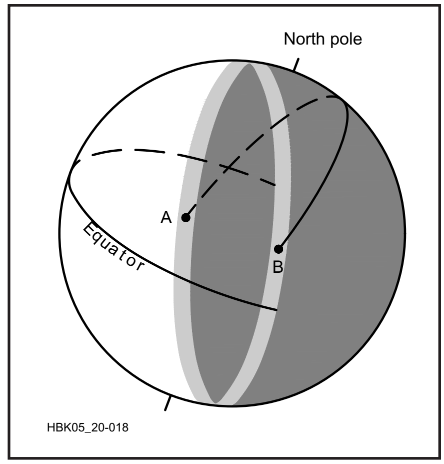

Figure 19.28 — The gray line encircles the Earth, but the tilt at the equator to the poles varies over 46 degrees with the seasons. Long-distance contacts on 1.8 MHz and 3.5 MHz at more than halfway around the Earth can be enabled by the gray line, putting both ends of the path near darkness and allowing RF to cut across the dark ionosphere with minimal absorption. The strength of the signals indicates that multiple Earth-ionosphere hops are not the likely mode of propagation, since losses in many such hops would be prohibitive. Ducting in the electron density valley above the E region peak in the dark ionosphere is the likely mechanism.

Thus, what's important about the gray line is that it puts both ends of the path very near darkness (see **Figure 19.28**). What really appears to be happening is that the RF is taking a shortcut across the dark ionosphere. This requires a skew point to join the two great circle paths in the dark ionosphere out of each end of the path, and the auroral zone is the likely area for the skew. An investigation of this phenomena is contained in N4II's article "Gray Line Propagation, or Florida to Cocos (Keeling) on 80m" at **www.arrl.org/files/file/QEX%20Binaries/2016/Callaway.pdf**.

To take advantage of these paths, you need to understand the mechanics of gray line. The gray line generally runs north-south, but it varies by 23 degrees either side of true north as measured at the equator over the course of the year. This variation is caused by the tilt in the Earth's axis. The gray line is exactly north-south through the poles at the equinoxes (March 21 and September 21) and is at its 23-degree extremes on June 21 and December 20. Over a one-year period, the gray line crosses a 46-degree sector of the Earth north and south of the equator, providing optimum paths to slightly different parts of the world each day. Many commonly available computer programs plot the gray line on a flat map or globe.

To an observer on the Earth, the direction of the terminator is always at right angles to the direction of the Sun at sunrise or sunset. It is important to note that, except at the equinoxes, the gray-line direction will be different at sunrise from that at sunset. This means you can work different areas of the world in the evening than you worked in the morning. Finally, it isn't necessary to be located inside the twilight zone in order to take advantage of gray-line propagation.

A number of web-based applications to calculate worldwide sunrise and sunset times are available online. The software package *DXATLAS* (**www.dxatlas.com/DxAtlas**) includes the gray line with an azimuthal-equidistant map and several logging software packages. For an online gray line map, visit **dx.qsl.net/propagation/greyline.html**.

ENHANCEMENTS NEAR SUNRISE AND SUNSET

There appear to be two mechanisms for signal enhancements around sunrise and sunset. When the path is approximately parallel to the terminator, a signal enhancement can occur when the eastern end is around sunrise or the western end is around sunset. When the path is approximately along the terminator, a signal enhancement can occur when one end of the path is at sunrise and the other end of the path is at sunset (or vice versa).

Propagation Summary, by Band

LOW FREQUENCY (LF) BANDS AND MEDIUM FREQUENCY (MF) BANDS

135.7 – 137.8 kHz (2200 meters) and 472-479 kHz (630 meters)

See the section Propagation Below 1.8 MHz.

1.8 – 2.0 MHz (160 meters)

160 meters suffers from daytime D region absorption. Daytime communication is limited to ground-wave coverage and a single E hop out to about 1,500 kilometers for well-equipped stations (running the full legal limit, quarter-wave verticals with a good ground system, and a low noise receiving environment). At night, the D region quickly disappears and worldwide 160-meter communication becomes possible via F_2 region propagation. Atmospheric and man-made noise limits propagation. Tropical and mid latitude thunderstorms cause high levels of static in summer, making winter evenings the best time to work DX at 1.8 MHz. A proper choice of receiving antenna (Beverage, 4-square, small loop) can often significantly reduce the amount of received noise to improve the signal-to-noise ratio.

HIGH FREQUENCY (HF) BANDS (3 – 30 MHz)

A wide variety of propagation modes are useful on the HF bands. The 80-meter band shares many daytime characteristics with 160 meters. The 60-meter band is better for daytime communications than the 160- and 80 meter bands and is much more similar to the 40 meter band. The transition between bands primarily useful at night or during the day appears around 10 MHz. Most long-distance contacts are made via F_2 region skip. Above 21 MHz, more exotic propagation, including TE, sporadic E, aurora, and meteor scatter, begins to be practical.

3.5 – 4.0 MHz (80 meters for the lower end, 75 meters for the higher end)

The lowest HF band is similar to 160 meters in many respects. Daytime absorption is significant, but not quite as extreme as at 1.8 MHz. At night, signals are often propagated halfway around the world. As at 1.8 MHz, atmospheric noise is a nuisance, especially during the summer, making winter the most attractive season for the 80/75 meter DXer.

5.3 – 5.4 MHz (60 meters)

The distance covered during daytime propagation is very similar to the 40-meter band. At night, worldwide propagation is possible in spite of the relatively low power limit. Signal strengths will typically be higher than on 80 meters but not as high as on 40 meters.

7.0 – 7.3 MHz (40 meters)

The popular 40-meter band supports daytime NVIS propagation and E region propagation out to about 500 miles during most daylight hours. D region absorption is much less severe than on the 160- and 80-meter bands except at low elevation angles, so short-distance skip via the E and F regions is possible. During the day, a typical station can cover a radius of approximately 800 kilometers (500 miles). At night, reliable worldwide communication via F_2 is common on the 40-meter band.

Atmospheric noise is much less troublesome than on 160 and 80 meters, and 40-meter DX signals are often of sufficient strength to override even high-level summer static. For these reasons, 40 meters is the lowest-frequency amateur band considered reliable for DX communication in all seasons. Even during the lowest point in the solar cycle, 40 meters is usually open for worldwide DX throughout the night.

10.1 – 10.15 MHz (30 meters)

The 30-meter band is unique because it shares characteristics of both daytime and nighttime bands. D region absorption is not a significant factor. Communication up to 3,000 kilometers (1,900 miles) is typical during the daytime, and this extends halfway around the world via all-darkness paths. The band is generally open via F_2 on a 24-hour basis, but during a solar minimum the MUF on many DX paths often drops below 10 MHz shortly after sunset. DX paths may drop below 10 MHz at night. Under these conditions, 30 meters adopts the characteristics of the daytime bands at 14 MHz and higher.

14.0 – 14.35 MHz (20 meters)

The 20-meter band is traditionally regarded as the amateurs' primary long-haul DX favorite. Regardless of the 11-year solar cycle, 20 meters can be depended on for at least a few hours of worldwide F_2 propagation during the day. During solar-maximum periods, 20 meters will often stay open to distant locations throughout the night. Skip distance is usually appreciable and is always present to some degree. Daytime E region and sporadic E propagation from sunrise through midnight propagation may be detected along very short paths. Atmospheric noise is not a serious consideration, even in the summer. Because of its popularity, 20 meters tends to be very congested during the daylight hours.

18.068 – 18.168 MHz (17 meters)

The 17-meter band is similar to the 20 meter band in many respects, but the effects of fluctuating solar activity on F_2 propagation are more pronounced. During the years of high solar activity, 17 meters is reliable for daytime and early-evening long-range communication, often lasting well after sunset. During moderate years, the band may open only during sunlight hours and close shortly after sunset. At solar minimum, 17 meters will open to middle and equatorial latitudes, but only for short periods during midday on north-south paths.

21.0 – 21.45 MHz (15 meters)

The 15-meter band has long been considered a prime DX band during solar cycle maxima, but it is sensitive to changing solar activity. During peak years, 15 meters is reliable for daytime F_2 region DXing and will often stay open well into the night. During periods of moderate solar activity, 15 meters is basically a daytime-only band, closing shortly after sunset. During solar minimum periods, 15 meters may not open at all except for infrequent north-south transequatorial circuits. Sporadic E is observed occasionally in early summer and mid-winter, although the effects are not as pronounced as on the higher frequencies.

24.89 – 24.99 MHz (12 meters)

This band offers propagation that combines the best of the 10- and 15-meter bands. Although 12 meters is primarily a daytime band during low and moderate sunspot years, it may stay open well after sunset during the solar maximum. During years of moderate solar activity, 12 meters opens to the low and middle latitudes during the daytime hours, but it seldom remains open after sunset. Periods of low solar activity seldom cause this band to go completely dead, except at higher latitudes. Occasional daytime openings, especially in the lower latitudes, are likely over north-south paths. The main sporadic E season on 24 MHz lasts from late spring through summer and short openings may be observed in mid-winter.

28.0 – 29.7 MHz (10 meters)

The 10-meter band is well known for extreme variations in characteristics and a variety of propagation modes. During solar maxima, long-distance F_2 propagation is so efficient that very low power can produce strong signals halfway around the globe. DX is abundant with modest equipment. Under these conditions, the band is usually open from sunrise to a few hours past sunset. During periods of moderate solar activity, 10 meters usually opens only to low and transequatorial latitudes around noon. During the solar minimum, there may be no F_2 propagation at any time during the day or night.

Sporadic E is fairly common on 10 m, especially May through August, although it may appear at any time. Short skip, as sporadic E is sometimes called on the HF bands, has little relation to the solar cycle and occurs regardless of F region conditions. It provides single-hop communication from 300 to 2,300 kilometers (190 to 1,400 miles) and multiple-hop opportunities of 4,500 kilometers (2,800 miles) and farther.

Ten meters is a transitional band in that it also shares some of the propagation modes more characteristic of VHF. Meteor scatter, aurora, and auroral E provide the means of making contacts out to 2,300 kilometers (1,400 miles), and TEP propagation often supports propagation to 5,000 miles and farther, but these modes often go unnoticed at 28 MHz. Techniques similar to those used at VHF can be very effective on 10 meters, as signals are usually stronger and more persistent. These exotic modes can be more fully exploited, especially during the solar minimum when F_2 DXing has waned.

VERY HIGH FREQUENCY (VHF) BANDS (30 – 300 MHz)

A wide variety of propagation modes are useful in the VHF range. F-region skip appears on 50 MHz during solar cycle peaks. Sporadic E and several other E-region phenomena are most effective in the VHF range. Still other forms of VHF ionospheric propagation, such as field-aligned irregularities (FAI) and transequatorial propagation (TE), are rarely observed at VHF. Tropospheric propagation, which is not a factor at HF, becomes increasingly important above 50 MHz.

50 – 54 MHz (6 meters)

The lowest amateur VHF band shares many of the characteristics of both lower and higher frequencies. In the absence of any favorable ionospheric propagation conditions, well-equipped 50 MHz stations work regularly over a radius of 300 kilometers (190 miles) via tropospheric scatter, depending on terrain, power, receiver capabilities, and antenna. Weak-signal troposcatter allows the best stations to make 500 kilometers (310 mile) contacts nearly any time. Weather effects may extend the normal range by a few hundred kilometers, especially during the summer months, but true tropospheric ducting is rare.

During the peak of the 11-year solar cycle (especially during the winter months), worldwide 50 MHz DX is possible via the F_2 region during daylight hours. F_2 backscatter provides an additional propagation mode for contacts as far as 4,000 kilometers (2,500 miles) when the MUF is just below 50 MHz. TE paths as long as 8,000 kilometers (5,000 miles) across the magnetic equator are common around the spring and fall equinoxes of peak solar cycle years.

Sporadic E is probably the most common and certainly the most popular form of propagation on the 6-meter band. Single-hop E-skip openings may last many hours for contacts from 600 to 2,300 kilometers (370 to 1,400 miles), primarily during the spring and early summer. Multiple-hop E_s provides transcontinental contacts mostly during June and July in the northern hemisphere at distances of 10,000 kilometers or more, and contacts between the US and South America, Europe and Japan via multiple-hop E-skip occur nearly every summer.

Other types of E region ionospheric propagation make 6 meters an exciting band. Maximum distances of about 2,300 kilometers (1,400 miles) are typical for all types of E-region modes. TEP propagation is frequent for stations within range of the geomagnetic equator and for stations farther away when sporadic E propagation couples to TEP. Propagation via FAI often provides additional hours of contacts immediately following sporadic E events. Auroral propagation often makes its appearance in late afternoon when the geomagnetic field is disturbed. Closely related auroral E propagation may extend the 6-meter range to 4,000 kilometers (2,500 miles) and sometimes farther across the northern states and Canada and Alaska and occasionally to Scandinavia, usually after midnight. Meteor scatter provides reliable contacts almost every day around sunrise and especially during one of the dozen or so prominent annual meteor showers.

144 – 148 MHz (2 meters)

Ionospheric effects are significantly reduced at 144 MHz, but they are far from absent. F-region propagation is unknown except for TE, which is responsible for the current 144 MHz terrestrial DX record of nearly 8,000 kilometers (5,000 miles). Sporadic E occurs as high as 144 MHz less than a tenth as often as at 50 MHz, but the usual maximum single-hop distance is the same, about 2,300 kilometers (1,400 miles). Multiple-hop sporadic E contacts greater than 3,000 kilometers (1,900 miles) have occurred from time to time across the continental US, as well as across Southern Europe.

Auroral propagation is quite similar to that found at 50 MHz, except that signals are weaker and more Doppler-distorted. Auroral E contacts are rare. Meteor-scatter contacts are limited primarily to the periods of the great annual meteor showers and require much patience and operating skill. Contacts have been made via FAI on 144 MHz, but its potential has not been fully explored.

(Continued on next page.)

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Tropospheric effects improve with increasing frequency, and 144 MHz is the lowest VHF band at which terrestrial weather plays an important propagation role. Weather-induced enhancements may extend the normal 300- to 600-kilometer (190- to 370-mile) range of well-equipped stations to 800 kilometers (500 miles) and more, especially during the summer and early fall. Tropospheric ducting extends this range to 2,000 kilometers (1,200 miles) and farther over the continent and at least to 4,000 kilometers (2,500 miles) over some well-known all-water paths, such as that between California and Hawaii.

222 – 225 MHz (135 cm)

The 135 cm band shares many characteristics with the 2-meter band. The normal working range of 222 MHz stations is nearly as far as comparably equipped 144 MHz stations. The 135 cm band is slightly more sensitive to tropospheric effects, but ionospheric modes are more difficult to use. Auroral and meteor-scatter signals are somewhat weaker than at 144 MHz, and sporadic E contacts on 222 MHz are extremely rare. FAI and TE may also be well within the possibilities of 222 MHz, but reports of these modes on the 135 cm band are uncommon. Increased activity on 222 MHz will eventually reveal the extent of the propagation modes on the highest of the amateur VHF bands.

ULTRA-HIGH FREQUENCY (UHF) BANDS (300 – 3000 MHz) AND HIGHER

Tropospheric propagation dominates the bands at UHF and higher, although some forms of E region propagation are still useful at 432 MHz. Above 10 GHz, atmospheric attenuation increasingly becomes the limiting factor over long-distance paths. Reflections from airplanes, mountains and other stationary objects may be useful adjuncts to propagation at 432 MHz and higher.

420 – 450 MHz (70 cm)

The lowest amateur UHF band marks the highest frequency on which ionospheric propagation is commonly observed. Auroral signals are weaker and more Doppler distorted; the range is usually less than at 144 or 222 MHz. Meteor scatter is much more difficult than on the lower bands, because bursts are significantly weaker and of much shorter duration. Although sporadic E and FAI are unknown as high as 432 MHz and probably impossible, TE may be possible.

Well-equipped 432 MHz stations can expect to work over a radius of at least 300 kilometers (190 miles) in the absence of any propagation enhancement. Tropospheric refraction is more pronounced at 432 MHz and provides the most frequent and useful means of extended-range contacts. Tropospheric ducting supports contacts of 1,500 kilometers (930 miles) and farther over land. The current 432 MHz terrestrial DX record of more than 4,000 kilometers (2,500 miles) was accomplished by ducting over water.

902 – 928 MHz (33 cm) and Higher

Ionospheric modes of propagation are nearly unknown in the bands above 902 MHz. Auroral scatter may be just within amateur capabilities at 902 MHz, but signal levels will be well below those at 432 MHz. Doppler shift and distortion will be considerable, and the signal bandwidth may be quite wide. No other ionospheric propagation modes are likely, although high-powered research radars have received echoes from auroras and meteors as high as 3 GHz.

Almost all extended-distance work in the UHF and microwave bands is accomplished with the aid of tropospheric enhancement. The frequencies above 902 MHz are very sensitive to changes in the weather. Tropospheric ducting occurs more frequently than in the VHF bands, and the potential range is similar. At 1296 MHz, 2,000-kilometer (1,200 mile) continental paths and 4,000-kilometer (2,500 mile) paths between California and Hawaii have been spanned many times. Contacts of 1,000 kilometers (620 miles) have been made on all bands through 10 GHz in the US and over 1,600 kilometers (1,000 miles) across the Mediterranean Sea. Well-equipped 903 and 1296 MHz stations can work reliably up to 300 kilometers (190 miles), but normal working ranges generally shorten with increasing frequency.

Other tropospheric effects become evident in the GHz bands. Evaporation inversions, which form over very warm bodies of water, are usable at 3.3 GHz and higher. It is also possible to complete paths by scattering from rain, snow, and hail in the lower GHz bands. Above 10 GHz, attenuation caused by atmospheric water vapor and oxygen becomes the most significant limiting factor in long-distance communication.

19.4 VHF/UHF Non-Ionospheric Propagation

All radio communication involves propagation through the troposphere for at least part of the signal path. Radio waves traveling through the lowest part of the atmosphere are subject to refraction, scattering, and other phenomena, much like ionospheric effects. Tropospheric conditions are rarely significant below 30 MHz, but they are very important at 50 MHz and higher. Much of the long-distance work on the VHF, UHF, and microwave bands depends on some form of tropospheric propagation. Instead of watching solar activity and geomagnetic indices, those who use tropospheric propagation are much more concerned about terrestrial weather as opposed to space weather. General characteristics of the amateur bands above 30 MHz are summarized in the previous sidebar **Propagation Summary — By Band**.

19.4.1 Line of Sight

At one time it was thought that communications in the VHF range and higher would be restricted to line-of-sight paths. Although this has not proven to be the case even in the microwave region, the concept of line of sight is still useful in understanding tropospheric propagation. In the vacuum of space or in a completely homogeneous medium, radio waves do travel essentially in straight lines, but these conditions are almost never met in terrestrial propagation.

Radio waves traveling through the troposphere are ordinarily refracted slightly earthward. The normal drop in temperature, pressure, and water-vapor content with increasing altitude changes the index of refraction of the atmosphere enough to cause refraction. Under average conditions, radio waves are refracted toward Earth enough to make the horizon appear 15 percent farther away than the visual horizon. Under unusual conditions, tropospheric refraction may extend this range significantly.

A simple formula can be used to estimate the distance to the radio horizon under average conditions:

$$d = \sqrt{2h}$$

where
d = distance to the radio horizon, miles, and
h = height above average terrain, ft.

and

$$d = \sqrt{17h}$$

where
d = distance to the radio horizon, kilometers, and
h = height above average terrain, m.

The distance to the radio horizon for an antenna 30 meters (98 feet) above average terrain is thus 22.6 kilometers (14 miles). A station on top of a 1,000-meter (3,280 foot) mountain has a radio horizon of 130 kilometers (80 miles).

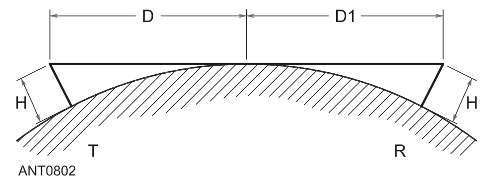


Figure 19.29 — The distance D to the horizon from an antenna of height H is given by equations in the text. The maximum line-of-sight distance between two elevated antennas is equal to the sum of their distances to the horizon as indicated here.

19.4.2 Beyond Line of Sight

From Figure 19.6 it appears that use of the space wave depends on direct line of sight between the antennas of the communicating stations. This is not literally true, although that belief was common in the early days of amateur communication on frequencies above 30 MHz. When equipment became available that operated more efficiently and after antenna techniques were improved, it soon became clear that VHF waves were actually being bent or scattered in several ways, permitting reliable communication beyond visual distances between the two stations. This was found true even with low power and simple antennas. The average communication range can be approximated by assuming the waves travel in straight lines, but with the Earth's radius increased by one-third. The distance to the *radio horizon* is then given as

$$D_{miles} = 1.415 \sqrt{H_{feet}}$$

or

$$D_{km} = 4.124 \sqrt{H_{meters}}$$

where H is the height of the transmitting antenna, as shown in **Figure 19.29**.

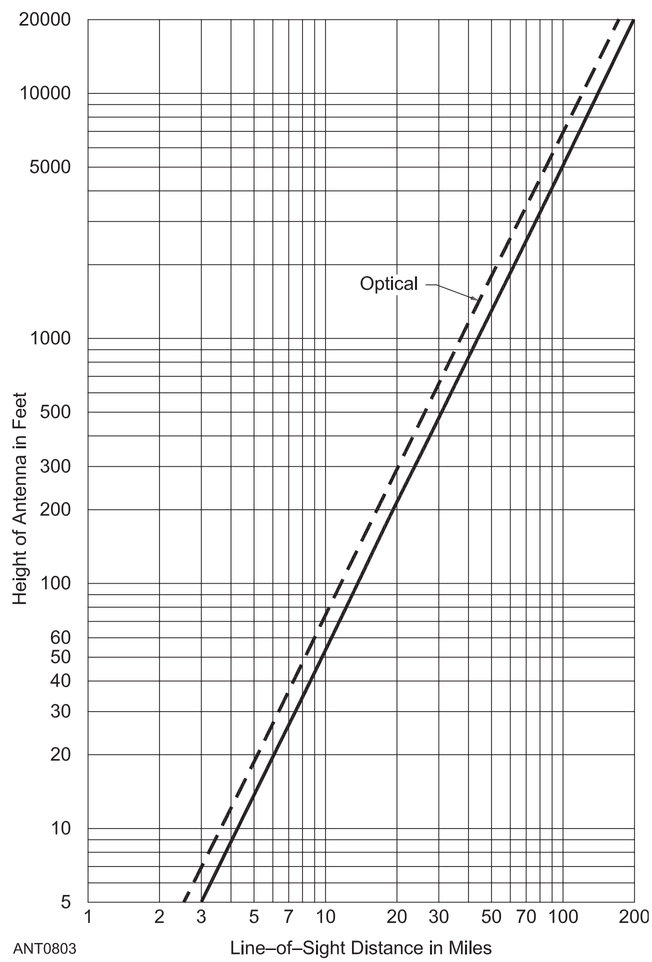


Figure 19.30 — Distance to the horizon from an antenna of given height. The solid curve includes the effect of atmospheric refraction. The optical line-of-sight distance is given by the broken curve.

The formula assumes that the Earth is smooth out to the horizon, so any obstructions along the path must be taken into consideration. For an elevated antenna, the communication distance is equal to D + D1, that is, the sum of the distances to the horizon of both antennas. Radio horizon distances are given in graphic form in **Figure 19.30**. Two stations on a flat plain, one with its antenna 60 feet above ground and the other 40 feet, could be up to about 20 miles apart for strong-signal line-of-sight communication (11 + 9 miles). The terrain is almost never completely flat, however, and variations along the way may add to or subtract from the distance for reliable communication. Remember that energy is absorbed, reflected, or scattered in many ways in nearly all communication situations. The formula or the chart will be a good guide for estimating the potential radius of coverage for a VHF FM repeater, assuming the users are mobile or portable with simple, omnidirectional antennas. Coverage with optimum equipment, high-gain directional arrays, and weak-signal analog or digital modes is quite a different matter. A much more detailed method for estimating coverage on frequencies above 50 MHz is given later in this chapter.

For maximum use of the ordinary space wave, it is important to have the antenna as high as possible above nearby buildings, trees, wires, and surrounding terrain. A hill that rises above the rest of the countryside is a good location for an amateur station of any kind,

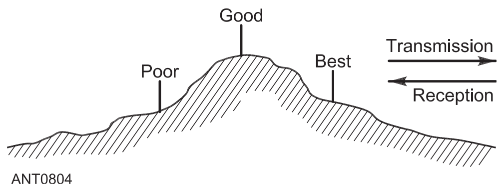


Figure 19.31 — Propagation conditions are generally best when the antenna is located near the top of a downslope facing the distant station. Communication is poor when there is a sharp rise immediately in front of the antenna in the direction of communication.

and particularly so for extensive coverage on the frequencies above 50 MHz. That highest point is not necessarily the best location for the antenna, though. In the example shown in **Figure 19.31**, the hilltop would be a good site in all directions. But if maximum performance to the right is the objective, a downslope in terrain results in more energy at lower elevation angles. This would involve a trade-off with reduced coverage in the opposite direction. Conversely, an antenna situated on the left side, lower down the hill, might do well to the left, but almost certainly would be inferior in performance to the right. For more information about the effect of terrain on ground reflections and elevation patterns, see the discussion of the Fresnel zone in the *ARRL Antenna Book* chapter on HF Antenna System Design.

19.4.3 Long-Distance Propagation

The wave energy of VHF stations does not simply disappear once it reaches the radio horizon. It is scattered, but it can be heard to some degree for hundreds of miles, well beyond line-of-sight range. Everything on Earth, and in the regions of space up to at least 100 miles, is a potential forward-scattering agent. Propagation via various phenomena in the troposphere is often referred to as simply "tropo."

WEATHER EFFECTS AT VHF/UHF

Varied weather patterns over most of the Earth's surface can give rise to boundaries between air masses of very different temperature and humidity characteristics. These boundaries can be anything from local anomalies to air-circulation patterns of continental proportions. The boundaries create opportunities for refraction due to the different indexes of refraction for the different regions.

There is a diurnal effect in temperate climates. At sunrise the air aloft is warmed more rapidly than that near the Earth's surface, and as the Sun lowers late in the day, the upper air is kept warm, while the ground cools. In fair, calm weather such as sunrise and sunset *temperature inversions* create boundaries in the atmosphere that improve signal strength over paths beyond line of sight as much as 20 dB over levels prevailing during the hours of high sun. Operating during hours when the diurnal inversion is present may also extend the operating range for a given strength by some 20 to 50 percent.

Under stable weather conditions, large air masses can retain their characteristics for hours or even days at a time (see **Figure 19.32**). Stratified warm dry air over cool moist air, flowing slowly across the Great Lakes region to the Atlantic Seaboard, can provide the medium for east-west communication on 144 MHz and higher amateur frequencies over as much as 1,200 miles. More common, however, are communication distances of 400 to 600 miles under such conditions.

A similar inversion along the Atlantic Seaboard as a result of a tropical storm air-circulation pattern may bring VHF and UHF openings extending from the Maritime Provinces of Canada to the Carolinas. Propagation across the Gulf of Mexico, sometimes with very high signal levels, enlivens the VHF

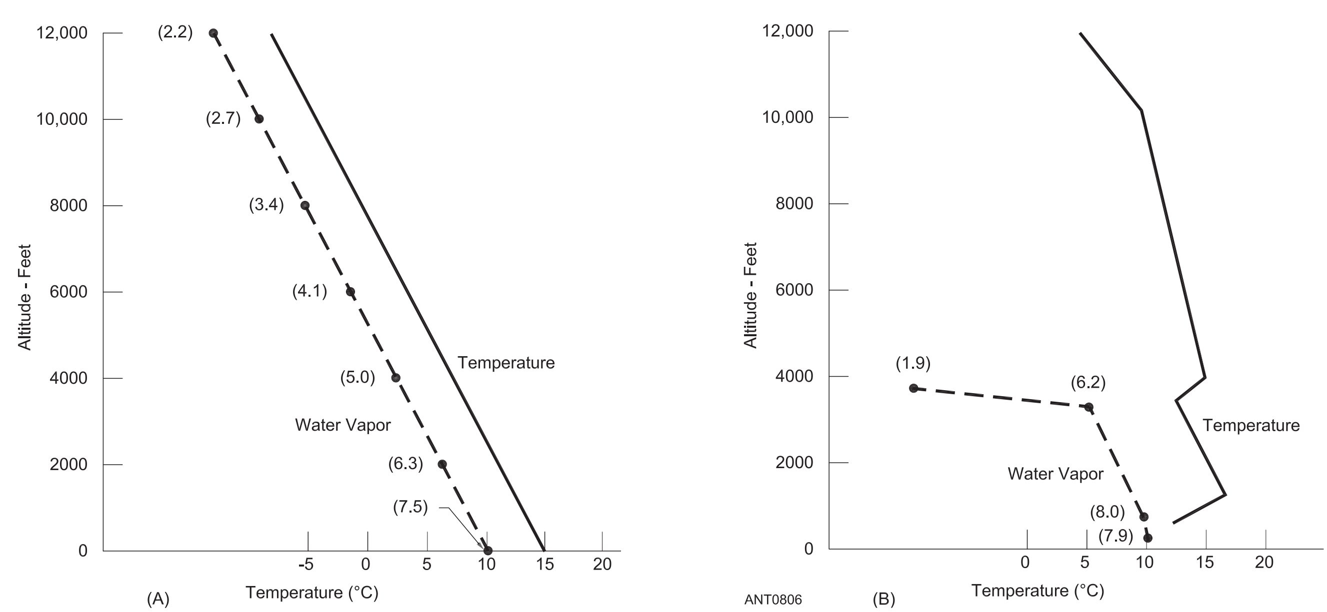


Figure 19.32 — Upper air conditions that produce extended-range communication on the VHF bands. At the left is shown the US Standard Atmosphere temperature curve. The humidity curve (dotted) is what would result if the relative humidity were 70%, from ground level to 12,000 feet elevation. There is only slight refraction under this standard condition. A sounding that is typical of marked refraction of VHF waves appears at the right. Figures in parentheses are the "mixing ratio" — grams of water vapor per kilogram of dry air. Note the sharp break in both curves at about 3,500 feet.

bands in coastal areas from Florida to Texas. The California coast, from below the San Francisco Bay Area to Mexico, experiences a similar propagation aid during the warmer months. Tropical storms moving west across the Pacific below the Hawaiian Islands may provide a transpacific long-distance VHF medium. Amateurs first exploited this on 144, 220, and 432 MHz in 1957. It has been used fairly often in the summer months since, although not yearly.

The examples of long-haul work cited above may occur infrequently, but lesser extensions of the minimum operating range are available almost daily. Under minimum conditions there may be little more than increased signal strength over paths that are workable at any time.

There are other short-range effects of local atmospheric and topographical conditions. Known as *subsidence*, the flow of cool air down into the bottom of a valley, leaving warm air aloft, is a familiar summer-evening pleasure. The daily inshore-offshore wind shift along a seacoast in summer sets up daily inversions that make coastal areas highly favored as VHF sites.

Tropospheric effects can show up at any time, in any season. Late spring and early fall are the most favored periods, although a winter warming trend can produce strong and stable inversions that work VHF magic almost equal to that of the more familiar spring and fall events.

Regions where the climate is influenced by large bodies of water enjoy the greatest degree of tropospheric bending. Hot, dry desert areas see little of it, at least in the forms described above.

TROPOSPHERIC DUCTING

Tropospheric propagation of VHF and UHF waves can influence signal levels at all distances from purely local to something beyond 4,000 kilometers (2,500 miles). The outer limits are not well known. At the risk of oversimplification, we will divide the modes into two classes — extended-local and long-distance. This concept must be modified depending on the frequency under consideration, but in the VHF range the extended-local effect gives way to a form of propagation much like that of microwaves in a waveguide, called *ducting*. The transition distance is ordinarily somewhere around 200 miles. The difference lies in whether the atmospheric condition producing the bending is localized or continental in scope. Remember, we're concerned here with frequencies in the VHF range, and perhaps up to 500 MHz. At 10 GHz, for example, the extent of the required atmospheric conditions producing ducting are smaller.

VHF propagation beyond a few hundred miles probably required more than one weather system. On long-distance paths over the ocean (two notable examples are California to Hawaii and Ascension Island to Brazil), propagation is likely to be between two atmospheric regions. On such circuits, the communicating station antennas must be in the duct, or capable of propagating strongly into it. Here again, we see that the positions and radiation angles of the antennas are important. As with microwaves in a waveguide, the low-frequency limit for the duct is critical. In long-distance ducting it is also very variable. Airborne equipment has shown that duct capability exists well down into the HF region in the stable atmosphere west of Ascension Island. Some contacts between Hawaii and Southern California on 50 MHz are believed to have been by way of tropospheric ducts. Probably all contact over these paths on 144 MHz and higher bands is because of duct propagation.

Long-distance communication using tropospheric modes is possible to some degree on all amateur frequencies from 50 MHz to at least 10 GHz. For forecasts of tropospheric ducting possibilities, visit **www.dxinfocentre.com/tropo.html**.

POLARIZATION FACTORS ABOVE 50 MHZ

Horizontal systems are popular, in part because they tend to reject man-made noise, much of which is vertically polarized. There is some evidence that vertical polarization shifts to horizontal in hilly terrain more readily than horizontal shifts to vertical. With large arrays, horizontal systems may be easier to erect, and they tend to give higher signal strengths over irregular terrain, if any difference is observed.

Practically all work with VHF mobiles is now handled with vertical systems. For use in a VHF repeater system, the vertical antenna can be designed to have gain without losing the desired omnidirectional quality. In the mobile station, a small vertical whip has obvious aesthetic advantages. Often, a telescoping whip used for broadcast reception can be pressed into service for 144 MHz FM. A car-top mount is preferable, but the broadcast whip is a practical compromise. Tests have shown that horizontal polarization can give a slightly larger service area, but mechanical advantages of vertical systems have made them the almost unanimous choice in VHF FM communication.

19.4.4 Reliable VHF Coverage

EFFECTS OF TERRAIN AT VHF/UHF

The coverage figures derived from the above procedure are for smooth terrain. What of stations in mountainous country? Although an open horizon is generally desirable for the VHF station site, mountain country should not be considered hopeless. Help for the valley dweller often lies in the optical phenomenon known as *knife-edge diffraction* as described earlier. A flashlight beam pointed at the edge of a partition does not cut off sharply at the partition edge, but is diffracted around it, partially illuminating the shadow area. A similar effect is observed with VHF waves passing over ridges; there is a shadow effect, but not a complete blackout. If the signal is strong where it strikes the mountain range, it will be heard well at the bottom of a valley on the far side. (See the *ARRL Antenna Book*'s chapter on **The Effects of Ground** for a more thorough discussion of the theory of diffraction.)

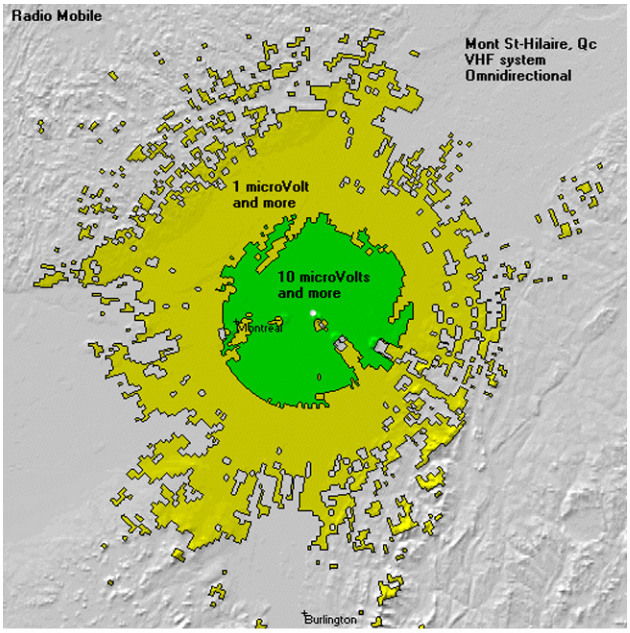
This is familiar to all users of VHF communications equipment who operate in hilly terrain. Where only one ridge lies in the way, signals on the far side may be almost as good as on the near side. Under ideal conditions (a very high and sharp-edged obstruction near the midpoint of a long-enough path so that signals would be weak over average terrain), knife-edge diffraction may yield signals even stronger than would be possible with an open path.

The obstruction must project into the radiated beam of the antennas used. Often mountains that look formidable to the viewer are not high enough to have an appreciable effect, one way or the other. Since the normal radiation pattern from a VHF array is several degrees above the horizontal, mountains that are less than about three degrees above the horizon, as seen from the antenna, are missed by the radiation from the array. Moving the mountains out of the way would have substantially no effect on VHF signal strength in such cases.

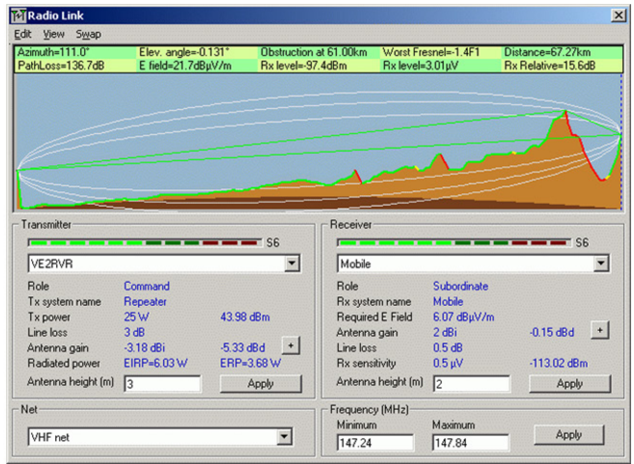
Rolling terrain, where obstructions are not sharp enough to produce knife-edge diffraction, still does not exhibit a complete shadow effect. There is no complete barrier to VHF propagation — only attenuation, which varies widely as the result of many factors. Thus, even valley locations are usable for VHF communication. Good antenna systems, preferably as high as possible, the best available equipment, and above all the willingness and ability to work with weak signals may make outstanding VHF work possible, even in sites that show little promise to casual inspection.

The availability of detailed terrain data for much of the world enables software to make good predictions about coverage of VHF, UHF, and microwave signals. The software is freely available to amateurs and can run online in a web browser without having to download and install software or large databases on a PC.

Radio Mobile Online is the online version of the popular RF propagation tool *Radio Mobile* by Roger Coudé, VE2DBE (**www.ve2dbe.com/rmonline.html**). It uses digital terrain information and a mathematical model to simulate coverage between two fixed sites (such as a radio link) or between a fixed site



HBK1128 (A)



(B)

Figure 19.33 — *Radio Mobile* signal-strength contour map (A) and a point-to-point link map (B). Both figures are from www.ve2dbe.com/rme.html.

and a mobile (such as for repeater coverage). The digital terrain information comprises two databases totaling 198 gigabytes: elevation and land cover. Its online model works with amateur bands from 30 MHz to 25 GHz. The information for both stations (whether fixed/fixed or fixed/mobile) is comprehensive. The model is based on the public-domain ITM model augmented with the author's decades of experience in the mobile communications field. To use the service, you must first create a personal account (free) and your calculations will be saved on the system's server for online access.

A tutorial on *Radio Mobile Online* is available from KØLWC — search **YouTube.com** for "Radio Mobile Tutorial — How To Predict Ham Radio Coverage." Two sample outputs from *Radio Mobile Online* are shown in **Figure 19.33**: a coverage signal-strength contour map (A) and a point-to-point link map (B). Both figures are from **www.ve2dbe.com/rme.html**.

The AREDN network (**www.arednmesh.org**) operates Ubiquiti microwave wireless networking equipment with customized firmware to support amateur radio operation. Nodes in the network are situated to offer coverage to individual stations, relay stations, and stations deployed in disaster response. To support network node setup and site selection, the Ubiquiti *AirLink* planning tool software is used (**link.ubnt.com**).

After creating a free account, the simplest way to get started is to enter your own address, zoom out on the map, and select a nearby location. The link profile will automatically be generated as shown in **Figure 19.34** which

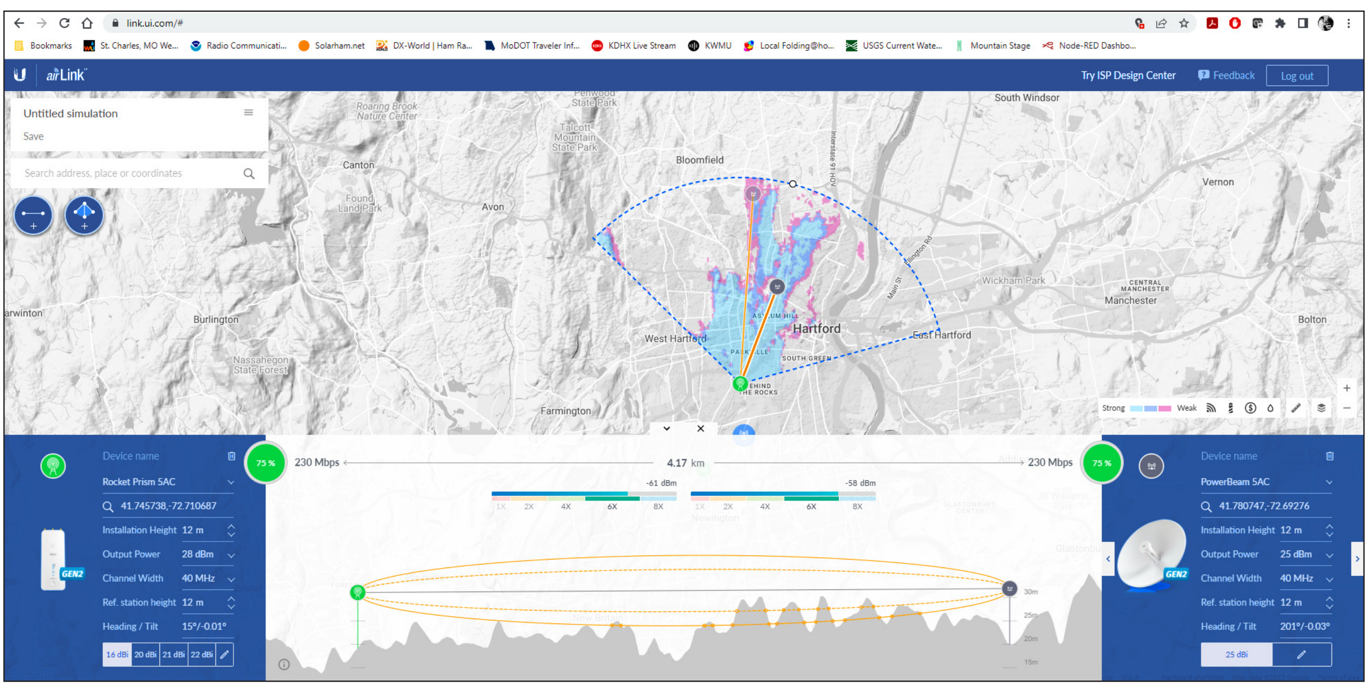


Figure 19.34 — A coverage map for 5 GHz wireless links from the Ubiquiti AirLink coverage and site evaluation tool at link.ui.com. The map and link profile show coverage between ARRL headquarters in Newington, CT, and nearby Hartford, CT.

shows coverage between ARRL headquarters in Newington and nearby Hartford, CT over a 5 GHz link. A step-by-step tutorial is available at **beetledigital.com/how-to-use-the-ubiquiti-airlink-tool-to-design-and-plan-wireless-network-links**.

These are two popular and low-cost tools available to amateurs for use in the VHF, UHF, and microwave range. The AREDN group has developed a very useful guide to wireless network design at **arednmesh.readthedocs.io/en/stable/arednNetworkDesign/network_modeling.html**. It discusses other packages, services, and techniques that you may find valuable. This is an active group and regularly updates its website, so this is a good source for coverage and propagation planning and site evaluation.

19.5 Propagation Predictions for HF Operation

19.5.1 The Big Picture Overhead

There are about 150 vertical-incidence ionosondes around the world. Ionosondes are located on land, even on a number of islands. There are gaps in sounder coverage, however, mainly over large expanses of open ocean. The compilation of all available vertical-incidence data from the worldwide network of ionospheric sounders results in global f_oF_2 maps, such as the map shown in **Figure 19.35**, a simulation from the highly sophisticated *PropLab Pro* computer program (**spacew.com** — listed under Geophysical Software).

This simulation is for 1900 UTC, about four hours before East Coast sunset on September 15, 1998, with a high level of solar activity (SSN of 85) and a planetary A_p index of 5, indicating quiet geomagnetic conditions. (These conditions are typical of what is expected as we move into the peak years of solar Cycle 25.) The contours of f_oF_2 peak over the South American longitudes at around 12 MHz. If you look carefully, you'll see two peaks, or humps, on either side of the geomagnetic equator, at about –12 degrees geographic latitude in the South American sector.

These two "humps" in f_oF_2 form what is known as the *equatorial anomaly* and are caused by upwelling "fountains" of high electron concentration located in daylight areas about ±20 degrees from the geomagnetic equator. The equatorial anomaly is important in transequatorial propagation. Those LU stations in Argentina that you can hear on 28 MHz from the US in the late afternoon, even during low portions of the solar cycle when other stations to the south are not coming through, are benefiting from transequatorial propagation, a form of *chordal hop* propagation, because signals going through this area remain in the ionosphere without lossy intermediate hops to the ground.

From records of f_oF_2 profiles, the underlying electron densities along a path can be computed. And from the electron density profiles computerized "ray tracing" may be done throughout the ionosphere to determine how a wave propagates from a transmitter to a particular receiver location. *PropLab Pro* can do complex ray tracings that explicitly include the effect of the Earth's magnetic field, even taking into effect ionospheric stormy conditions.

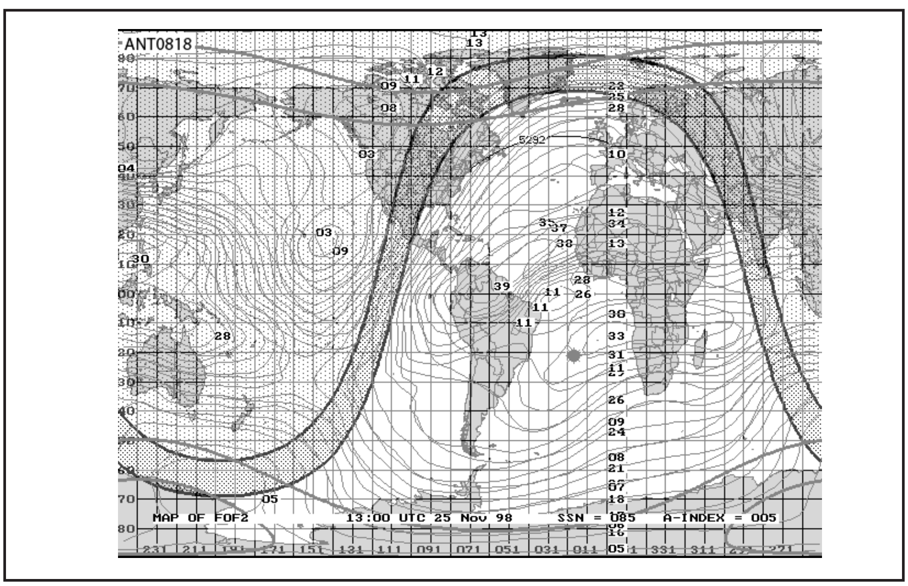


Figure 19.35 — Computer simulation of the f_oF_2 contours for 15 September 1998 at 1900 UTC, for an SSN of 85 and a quiet planetary Ap index of 5. Note the two regions of high f_oF_2 values in the South American sector (they can be seen better in a plot of MUF contours). These are the "equatorial anomalies," regions of high electronic density in the F_2 region that often allow chordal-hop north-south propagation. See also Figure 19.5. (*PropLab Pro V3* simulation courtesy of K9LA)

19.5.2 MUF Prediction

F region MUF prediction is key to forecasting HF communications paths at particular frequencies, dates, and times, but forecasting is complicated by several variables. Solar radiation varies over the course of the day, season, year, and solar cycle. Additionally, the ionization at any given point in the world depends on geomagnetic field activity and events in the lower atmosphere coupling up to the ionosphere. These regular intervals provide the main basis for prediction, yet recurrence is far from reliable. In addition, forecasts are predicated on a quiet geomagnetic field, but the condition of the Earth's magnetic field is most difficult to predict weeks or months ahead. For professional users of HF communications, uncertainty is a nuisance for maintaining reliable communications paths, while for many amateurs it provides an aura of mystery and chance that adds to the fun of DXing. Nevertheless, many amateurs want to know what to expect on the HF bands to make best use of available on-the-air time, plan contest strategy, ensure successful net operations, or engage in other activities.

The online supplement "Frequency Selection for HF Operation" will help you make the best use of your operating time. You may also find an article that appeared in the Summer 2008 issue of *CQ VHF* to be helpful with your 6-meter endeavors: "Predicting 6-meter F2 Propagation," by Carl Luetzelschwab, K9LA.

19.5.3 Solar and Geophysical Data

An amateur radio operator interested in long-distance QSOs on any frequency benefits from being aware of where we are in a solar cycle (solar data), the current state of the Sun's activity with respect to disturbances (geophysical data), and the fundamentals of propagation.

For solar and geophysical data, the internet can be very helpful. For example, the Space Weather Prediction Center (SWPC) website at **www.swpc.noaa.gov** can supply pretty much everything you need to know either directly or through links. Sites providing information on more specific propagation topics are referenced in the appropriate sections. Another source of useful information about solar disturbances is **www.spaceweather.com**.

The SWPC home page includes indexes for radio blackouts, solar radiation storm impacts, and geomagnetic storm impacts. Three videos are provided of recent X-ray activity (for assessment of solar radiation storms and radio blackouts), recent coronal mass ejections (for assessment of geomagnetic storms), and predicted visible aurora (which gives a general indication of radio aurora conditions). Plots of X-ray flux (for assessment of solar radiation storms and radio blackouts), proton flux (for assessment of solar radiation storms), and recent K-index activity (for assessment of geomagnetic storms) are also provided.

Under these six images are numerous links in three major categories of additional data: About Space Weather, Products and Data, and Dashboards for specific interests. The Radio dashboard is most suited to amateur radio.

There are also links to other sources of space weather information not on the SWPC website. For example, entering a specific topic (such as STEREO) in the search area in the upper right-hand corner of the home page brings up many links to NASA's STEREO mission (which allows us to look at the backside of the Sun).

Some other useful websites are: **dx.qsl.net/propagation**, **www.solen.info/solar**, **www.solarham.net**, and **hfradio.org/propagation.html**. You may also access propagation information via your preferred spotting network server. Use the command SH/WWV/*n*, where *n* is the number of reports you wish to see (five is the default).

Another excellent method for obtaining an "equivalent sunspot number" (SSN_e) is to go to the Space Weather site of Northwest Research Services at **spawx.nwra.com/spawx/ssne24.html**. NWRA compares real-time ionospheric sounder data around the world with predictions using various levels of SSN looking for the best match. They thus "back into" the actual effective sunspot number. Note that this is necessarily a best fit of ionospheric sounder data to an equivalent sunspot number — it's not a perfect fit for all the data due to the dynamic hour-to-hour variability of the worldwide F_2 region. **Figure 19.36** is a typical NWRA graph that covers the week ending October 6, 2002. This graph was selected as it clearly shows the effects of a typical space weather event: in this case, a sudden decrease in SSNe after a geomagnetic storm depressed SSNe by more than 50 percent.

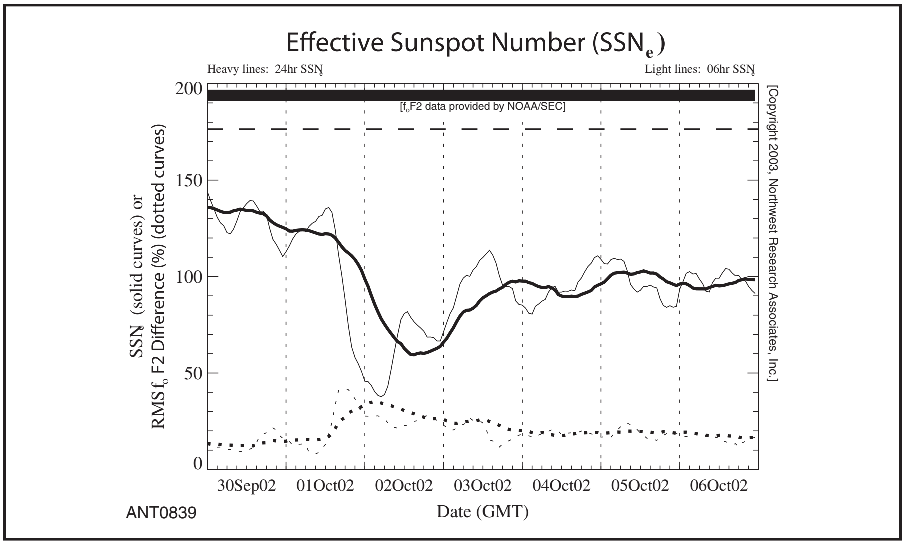


Figure 19.36 — Effective Sunspot Number (SSN_e) produced by NWRA. Note the large drop in effective SSN due to a geomagnetic storm commencing Oct 1, 2002.

GEOPHYSICAL DATA FROM WWV AND WWVH

The standard time station WWV (Fort Collins, Colorado) transmits on 2.5, 5, 10, 15 and 20 MHz, and WWVH (Kauai, Hawaii) transmits on 2.5, 5, 10 and 15 MHz. Both of these stations are popular for propagation monitoring. They transmit 24 hours a day. Daily monitoring of these stations for signal strength and quality can quickly provide a good basic indication of propagation conditions. In addition, each hour they broadcast the geomagnetic A- and K-indexes, the 2800 MHz (10.7 cm) solar flux, and a short forecast of conditions for the next day. These are heard on WWV at 18 minutes past each hour and on WWVH at 45 minutes after the hour. This is the same information published by SWPC and **spaceweather.com**. The K-index is updated every three hours, while the A-index and solar flux are updated after 2100 UTC. These data are useful for making predictions on home computers, especially when averaged over several days of solar flux observations. For more details about the broadcasts, visit **www.nist.gov/pml/time-and-frequency-division/radio-stations/wwv/wwv-and-wwvh-digital-time-code-and-broadcast**.

A word of caution — it's easy to be overwhelmed with all this data. In fact, much of it has little direct relevance to radio propagation — but it certainly is colorful and interesting to look at! In the authors' opinions, just knowing the level and trends of the 10.7 cm solar flux and sunspot number, along with the level and trend of the K-index, will give a good picture of HF propagation. The more esoteric parameters may serve to aid in the analysis of a particular propagation observation.

19.5.4 MUF Forecasts

LONG-RANGE

Long-range forecasts several months ahead provide only the most general form of prediction. For many years, ARRL published charts similar to **Figure 19.37** to forecast average propagation for a one-month period over specific paths. These charts are no longer published, but customizable charts are available online from **www.voacap.com/hf/**. Charts like the one in Figure 19.37 assumed a single average solar flux value for the entire month, and they assumed that the geomagnetic field is undisturbed.

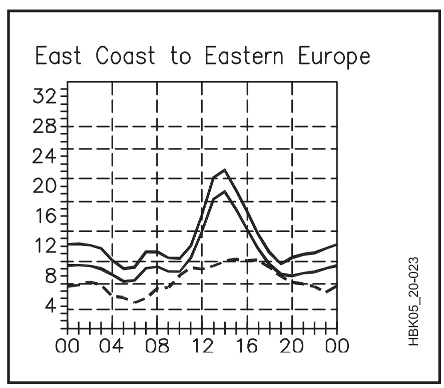


Figure 19.37 — For many years, ARRL published propagation prediction charts like this one for East Coast to Eastern Europe for April 2001. An average 2800 MHz (10.7 cm) solar flux of 159 was assumed for the month. On 10% of the days, the highest frequency propagated is predicted to be at least as high as the uppermost curve (the Highest Possible Frequency, or HPF, approximately 33 MHz), and for 50% of the days as high as the middle curve, the MUF. The lowest curve shows the Lowest Usable Frequency (LUF) for a 1,500 W CW transmitter.

The uppermost curve in Figure 19.37 shows the highest frequency that will be propagated on at least 10% of the days in the month. The given values might be exceeded considerably on a few rare days. On at least half the days, propagation should be possible on frequencies as high as the middle curve. Propagation will exceed the lowest curve on at least 90% of the days. The exact MUF on any particular day cannot be determined from these statistical charts, but you can determine when you should start monitoring a band to see if propagation actually does occur that day — particularly at frequencies above 14 MHz.

SHORT-RANGE

Short-range forecasts of a few days ahead are marginally more reliable than long-range forecasts because underlying solar indexes and geomagnetic conditions can be anticipated with greater confidence. The tendency for disturbances caused by solar phenomena to recur at 27-day intervals may enhance short-term forecasts (see the section 27-Day Recurrence). Daily forecasts may not be any better, as the ionosphere does not instantly react to small changes in solar flux (or sunspot number) and geomagnetic field indexes. Regardless of these limitations, it is always good to know the current solar and geophysical data, as well as understanding warnings provided by observations of the Sun in the visual to X-ray range.

Table 19.3

Features and Attributes of Several Currently Available Propagation Prediction Programs

	ASAPS V. 7	*VOACAP Windows*	*W6ELProp V. 2.70*	*PropLab Pro 3.1*
User Friendliness	Good	Good	Good	Good
Operating System	*Windows*	*Windows*	*Windows*	*Windows*
Uses K-index	No	No	Yes	Yes
User library of QTHs	Yes/Map	Yes	Yes	No
Bearings, distances	Yes	Yes	Yes	Yes
MUF calculation	Yes	Yes	Yes	Yes
LUF calculation	Yes	Yes	No	Yes
Wave angle calculation	Yes	Yes	Yes	Yes
Vary minimum wave angle	Yes	Yes	Yes	Yes
Path regions and hops	Yes	Yes	Yes	Yes
Multipath effects	Yes	Yes	No	Yes
Path probability	Yes	Yes	Yes	Yes
Signal strengths	Yes	Yes	Yes	Yes
S/N ratios	Yes	Yes	Yes	Yes
Long path calculation	Yes	Yes	Yes	No
Antenna selection	Yes	Yes	Indirectly	Yes
Vary antenna height	Yes	Yes	Indirectly	Yes
Vary ground characteristics	Yes	Yes	No	No
Vary transmit power	Yes	Yes	Indirectly	Yes
Graphic displays	Yes	Yes	Yes	2D/3D
UT-day graphs	Yes	Yes	Yes	Yes
Area Mapping	Yes	Yes	Yes	Yes
Documentation	Yes	Online	Yes	Yes
Price class	$AUD385[1]	free[2]	free[3]	$240[4]

[1]See **www.sws.bom.gov.au/Products_and_Services/1/2**. Price as of 2017, subject to change and exchange rate variation.
[2]*VOACAP* available at **www.its.bldrdoc.gov/resources/radio-propagation-software/high-frequency/high-frequency-propagation-models.aspx**
[3]*W6ELProp*, not actively supported, see **www.qsl.net/w6elprop**
[4]*PropLab Pro V3*, see **www.spacew.com/proplab/**

19.5.5 HF Propagation Prediction Software

Like predicting the weather, predicting HF propagation — even with the best computer software available — is not an exact science. The processes that cause a signal to propagate from one point on the Earth to another are enormously complicated and subject to an incredible number of variables. Experience and knowledge of propagation conditions (as related to solar activity, especially unusual solar activity such as flares or coronal mass ejections) are needed when you actually get on the air to check out the bands. Keep in mind, too, that prediction software is written mainly to calculate propagation for great-circle paths via the F region. Scatter, skew-path, auroral, and other such propagation modes may provide contacts when computer predictions indicate no contacts are possible.

Modern programs are designed for quick-and-easy predictions of propagation parameters. See **Table 19.3** for a listing of a number of popular PC programs. (An online description of propagation prediction software is also available at **astrosurf.com/luxorion/qsl-review-propagation-software.htm**.)

The basic input information required is the smoothed sunspot number (R_{12}) or smoothed solar flux (F_{12}), the date (month and day), and the latitudes and longitudes at the two ends of the radio path. The latitude and longitude, of course, are used to determine the great-circle radio path. Most commercial programs tailored for ham use allow you to specify locations by the call sign. The date is used to determine the latitude of the Sun, and this, with the smoothed sunspot number (or smoothed 10.7 cm solar flux converted to a smoothed sunspot number), is used to determine the properties of the ionosphere at critical points on the path.

A very powerful package, *VOACAP* is based on *IONCAP*, short for Ionospheric Communications Analysis and Prediction. It was written by an agency of the US government and has been under development for several decades. The *IONCAP* program has a well-deserved reputation for being difficult to use, since it came from the world of FORTRAN punch cards and mainframe computers.

VOACAP is a version of *IONCAP* adapted to Voice of America predictions, but this one includes a sophisticated Windows interface. The Voice of America (VOA) started work on *VOACAP* in the early 1990s and continued for several years before funding ran out. The program was maintained by a single, dedicated computer scientist, Greg Hand, at NTIA/ITS (Institute for Telecommunication Sciences), an agency of the US Department of Commerce in Boulder, Colorado. More information about *VOACAP* and an online app tailored for amateur radio are available from **www.voacap.com**.

ONLINE PREDICTION SERVICES

As mentioned earlier, *VOACAP* includes the above-the-MUF mode mentioned earlier in the section on HF Scatter modes. If a path can withstand a bit more loss, the QSO may be completed although the MUF is *below* the operating frequency. And with FT8 having the ability to decode signals farther down into the noise than CW, it essentially says the MUF can be even lower than for CW. FT8 will certainly help in the summer sporadic E season as well.

Another propagation prediction website, **soundbytes.asia/proppy/**, is produced in collaboration with the RSGB's Propagation Studies Committee. Both websites have instructions on how to input your data to generate the desired prediction.

Table 19.4
Popular Beacon Frequencies

(MHz)	*Comments*
14.100, 18.110, 21.150, 24.930, 28.200	Northern California DX Foundation beacons
28.2-28.3	Several dozen beacons worldwide
50.0-50.1	Most US beacons are within 50.06-50.08 MHz
70.03-70.13	Beacons in England, Ireland, Gibraltar and Cyprus

PC PREDICTION SOFTWARE

Table 19.3 contains information about four available software packages for the home PC. These programs generally allow predictions from 3 to 30 MHz. Unfortunately, prediction programs are not available on 160 meters (because of an incomplete understanding of the lower ionosphere and ducting mechanisms that contribute to propagation on that band) and on 6 meters (because of an incomplete understanding of openings when the MUF is not predicted to be high enough). As a general guideline, you should look for 160 meter openings when the path to your target station is in darkness and around sunrise/sunset, and you should look for 6 meter F_2 openings in the daytime during winter months near solar maximum.

19.5.6 Beacons

Automated *beacons* in the higher amateur bands can also be useful adjuncts to propagation watching. Beacons are ideal for this purpose because most are designed to transmit 24 hours a day.

One of the best organized beacon systems is the International Beacon Project, sponsored by the Northern California DX Foundation (NCDXF) and International Amateur Radio Union (IARU). The beacons operate 24 hours a day at 14.100, 18.110, 21.150, 24.930 and 28.200 MHz. Eighteen beacons on five continents transmit in successive 10-second intervals (each beacon transmits once every 3 minutes). More on this system can be found at the Northern California DX Foundation web-site **www.ncdxf.org** (click on the *Beacons* link on the left).

A network of automated SDR receivers called the Reverse Beacon Network (**www.reversebeacon.net**) has been created to monitor the HF CW sub-bands for signals that are automatically decoded by *CW Skimmer* and *RTTY Skimmer* software by VE3NEA (**www.dxatlas.com**). The network logs signal strength and location for the received signals, providing real-time information on HF propagation.

A list of many 28 MHz beacons can be found on the 10-10 International website, **www.ten-ten.org** (look for Beacons under the Resources link). Beacons often include location as part of their automated message, and many can be located from their call sign. Thus, even casual scanning of beacon sub-bands can be useful. **Table 19.4** provides the frequencies where beacons useful to HF propagation are most commonly placed.

There are also many beacons on VHF and higher bands. "G3USF's Worldwide List of 50 MHz Beacons" may be found at **www.keele.ac.uk/depts/por/50.htm**. Information on North American beacons on 144 MHz and up is maintained by Ron Klimas, WZ1V, at **www.newsvhf.com/beacons2.html**.

19.6 VHF/UHF Mobile Propagation

Most amateurs are aware that radio signals in free space obey the inverse-square law: the received signal power is inversely proportional to the square of the distance between the transmitting and receiving antennas. That law applies *only* if the transmitting and receiving antennas have an obstruction-free radio path between them.

Imagine two operators using hand-held 144 MHz radios, each standing on a mountaintop so that they have a direct line of sight. How far apart can they be and still maintain reliable communications? Assume 5 W transmitter power, 0 dBi antenna gain (2.15 dB worse than a dipole), 5 dB receiver noise figure, 10 dB S/N ratio, and 12 kHz receiver bandwidth.

Ask experienced VHF mobile operators that question, and you'll generally get guesses in the range of 20 to 30 miles because their experience tells them that's about the most you can expect when not communicating through a repeater. The correct answer, however, is over 9,500 kilometers (5,938 miles) based on the parameters given in the previous paragraph! This also explains how some operators have been able to work the amateur radio station on the International Space Station using only a handheld transceiver.

The discrepancy is explained by the fact that the line-of-sight scenario is not realistic for a mobile station located close to ground level. At distances greater than a few miles, there usually is no line of sight — the signal is reflected at least once on its journey from transmitter to receiver. As a result, path loss is typically proportional to distance to the third or fourth power, not the second power as the inverse-square law implies.

19.6.1 Rayleigh Fading

Not only is the signal reflected, but it usually arrives at the receiver by several different paths simultaneously (see **Figure 19.38**). Because the length of each path is different, the signals are not in phase. If the signals on two paths happen to be 180 degrees out of phase and at the same amplitude, they will cancel. If they are in phase, then their amplitudes will add. As the mobile station moves about, the phases of the various paths vary in a random fashion. However, they tend to be uncorrelated over distances greater than λ/4 or so, which is about 20 inches on the 2 meter band. That is why if the repeater you are listening to drops out when you are stopped at a traffic light, you can often

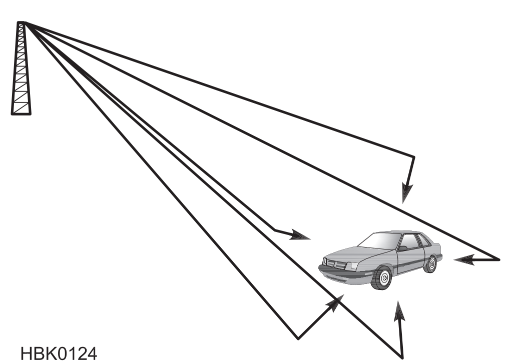


Figure 19.38 — At distances greater than a few miles, there normally is no line-of-sight path to the mobile station. Each path experiences at least one reflection. (Because the radio paths are reciprocal, propagation is the same for both receiving and transmitting.)

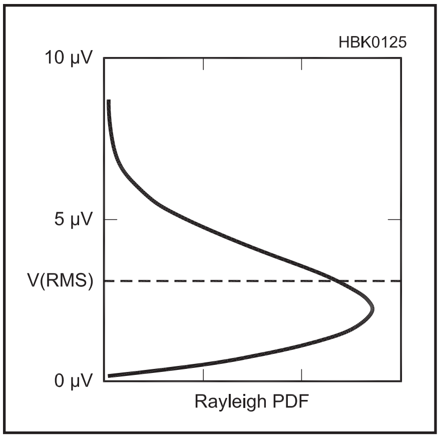


Figure 19.39 — The horizontal axis is the Rayleigh probability density function, which is the relative probability of the different signal levels shown on the vertical axis. For this graph, an RMS value of 3.16 µV has been selected to represent a typical average signal level in a marginal-coverage area.

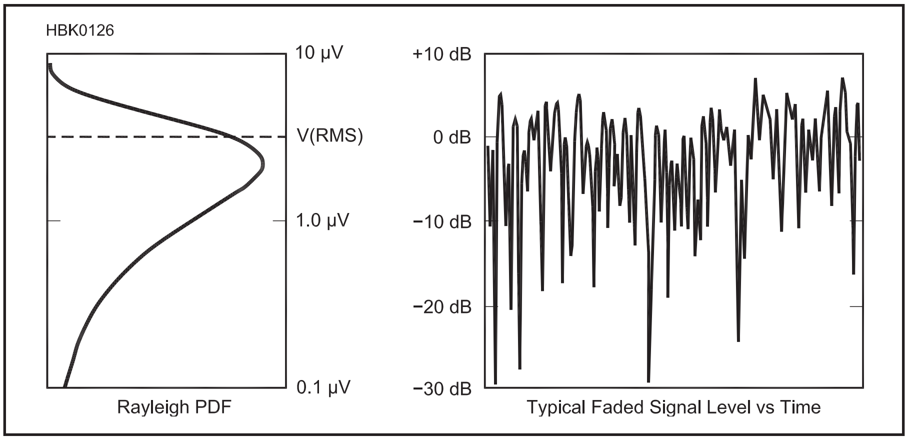


Figure 19.40 — The graph at the left is the same as Figure 19.31 except that the vertical axis is logarithmic (proportional to dB). At the right is a typical Rayleigh-faded signal of the same RMS voltage level plotted using the same vertical scale.

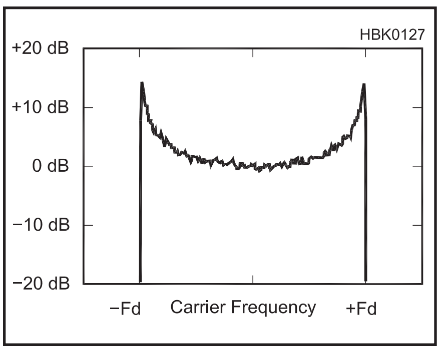


Figure 19.41 — Rayleigh fading spectrum of a CW (unmodulated) signal. The maximum deviation (F_d) from the center frequency is typically less than 10 – 15 Hz on the 144 MHz band.

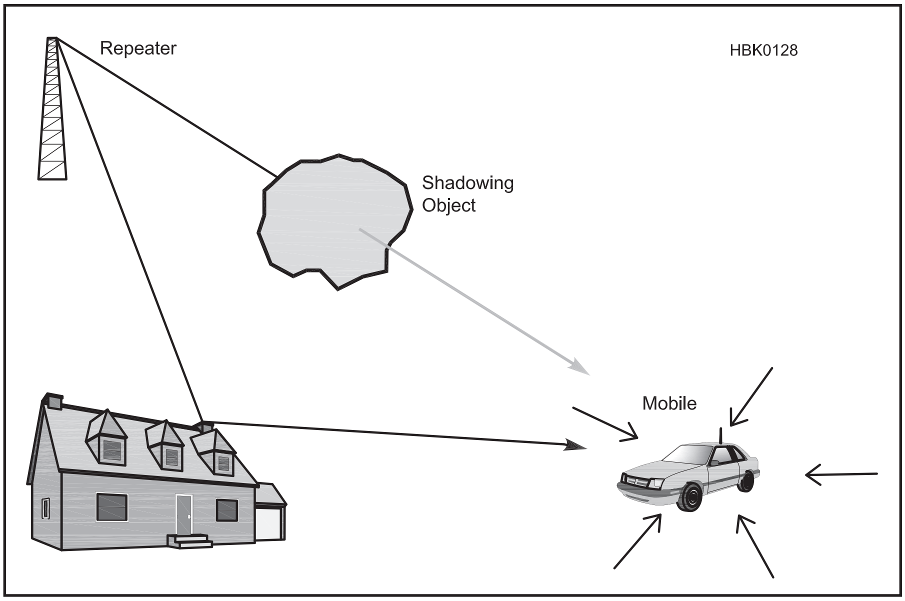


Figure 19.42 — When multipath propagation occurs, each main path is typically Rayleigh-faded by multiple reflectors close to the mobile station.

get it back again by creeping forward a few inches.

Because there are typically dozens of paths, it is rare for their amplitudes and phases to be such that they all cancel perfectly. Fades of 20 to 30 dB or more are common. The range of signal strengths has a *Rayleigh* distribution, named after the physicist/mathematician who first derived the mathematical formula. That is why the phenomenon is called *Rayleigh fading*. **Figure 19.39** shows the relative probability of various signal strengths. **Figure 19.40** is the same graph plotted on a logarithmic (dB) scale, along with a typical plot of signal strength versus time as the mobile station moves down the road.

The closer a reflecting object is to the antenna, the smaller is the path loss. A reflector that is close to the transmitter or receiver antenna gives a much stronger signal than one located halfway between. Even a weak reflector, such as a tree branch or telephone pole, is significant if it is close to the mobile station. Because there are many such close-in reflectors, many rays arrive from all directions.

Rays arriving from in front of a forward-moving vehicle experience a positive Doppler frequency shift, and rays from the rear have a negative Doppler shift. Those from the sides are somewhere in-between, proportional to the cosine of the angle of arrival. The received signal is the sum of all those rays, which results in *Doppler spreading* of the signal as illustrated in **Figure 19.41**. At normal vehicle speeds on the 2-meter band, the Doppler spread is only plus and minus 10 or 15 Hz, calculated from:

Doppler frequency = F_c v/c

where

F_c = the carrier frequency,
v = the vehicle speed, and
c = the speed of light.

Use the same units for v and c. On an FM voice signal the only effect is a slight distortion of the audio, but Doppler spreading can severely affect digital signals, as will be discussed later.

19.6.2 Multipath Propagation

In addition to scattering by local reflectors, it is not uncommon also to have more than one main radio path caused by strong reflectors, such as large metal buildings located some distance away (see **Figure 19.42**). Each main path typically does not reach the mobile station directly but is separately Rayleigh-

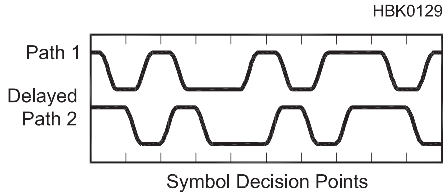


Figure 19.43 — Multipath propagation can cause inter-symbol interference (ISI). At the symbol decision points, where the receiver decoder samples the signal, the path 2 data is often opposing the data on path 1.

faded by the local reflectors.

As the mobile station moves around, the shadowing of various paths by intervening hills, buildings, and other objects causes the average signal level to fade in and out, but at a much slower rate than Rayleigh fading. This is called *shadowing* or *slow fading*. It is also called *log-normal fading* because the distribution of average signal levels tends to follow a log-normal curve. That means that the *logarithm* of the signal level (on a dB scale, if you will) has a *normal* distribution (the famous bell-shaped curve). This effect typically causes the average signal level on each path to vary plus and minus 10 – 20 dB (at two standard deviations) from the mean value. This is in addition to the signal variation due to Rayleigh fading.

Under weak-signal conditions Rayleigh fading causes the signal to drop out periodically, even though the average signal level would be high enough to maintain reliable communications if there were no fading. *Picket fencing*, as such rapid periodic dropout is called, is a common occurrence when traveling in a weak-signal area at highway speeds. With analog modulation, normally the only solution is to stop at a location where the signal is strong. Moving the vehicle forward or backward a few inches is often enough to change an unreadable signal to solid copy.

Another possible solution is to employ *diversity reception*. If two (or more) mobile receiver antennas are spaced a half-wavelength or more apart, their Rayleigh fading will be almost entirely uncorrelated. That means it is relatively rare for both to experience a deep fade at the same time. The receiving system must have circuitry to determine which of the antennas has a stronger signal at any given time and to automatically combine the signals using some scheme that minimizes the probability of signal dropout. (One engineering text that has a fairly readable discussion of fading is *Cellular Radio Performance Engineering* by Asha Mehrotra; see the "References and Bibliography" section at the end of this chapter.)

One low-tech scheme is to use stereo headphones with each channel connected to a separate receiver and antenna. That method works better with linear modulation (AM, SSB, CW) than with FM because of the noise burst that occurs when the FM signal drops out.

Diversity antennas can also be used at a repeater site. The conditions are different because most repeater antennas are located in the clear with few local reflectors. The diversity antennas must be located much farther apart, typically on the order of 10 to 20 wavelengths, for the fading to be uncorrelated.

FADING AND DIGITAL SIGNALS

Digitally modulated signals, such as those used in the cellular telephone industry, use several techniques to combat Rayleigh fading. One is *error-correcting coding*, which adds redundant bits to the transmitted signal in a special way such that the receiver can "fill in" missing bits to obtain error-free reception. That technique does not work if the signal drops out completely for longer than a few consecutive bits. The solution often employed to counter longer signal drops is called *interleaving*. This takes data bits that represent points close together in time in the original voice signal and shuffles them into several different time slots for transmission. That way, a single brief dropout does not affect all the bits for that time period. Instead, the lost data are scattered over several different time periods. Since only a few bits are missing at any one point, the error-correcting decoder in the receiver has enough information to reconstruct the missing information.

As the signal gradually gets weaker, the error correction in a digital receiver produces nearly perfect voice quality until the signal gets too weak for the decoder to handle. At that point reception stops abruptly and the call is dropped. With an analog signal, reception gets scratchier as the signal gets weaker; this gives advance warning before the signal drops out completely.

The main paths of a multipath-faded signal can differ in length by several miles. A 10 kilometers (6 mile) difference in path length results in a difference in propagation delay of over 30 μs. While that is not noticeable on an FM voice signal, it can wreak havoc with digital signals by causing *intersymbol interference* (*ISI*) (see **Figure 19.43**). If the delay difference is on the order of one symbol, the receiver sees adjacent symbols superimposed. In effect, the signal interferes with itself.

One solution is to use an *equalizer*. This is a special type of digital filter that filters the demodulated signal to remove the delay differences so that multiple paths become time-aligned. Since the path characteristics change as the mobile station moves around, a special *training sequence* is sent periodically so that the receiver can re-optimize the filter coefficients based on the known symbols in the training sequence.

ISI is an even bigger problem at HF than at VHF/UHF because the path lengths are much greater. It is not unusual to have path length differences up to 3,000 kilometers (1,800 miles), which correspond to propagation delay differences of up to 10 ms. That is why digital modes on HF with symbol periods of less than about 10 to 20 ms (that is, with symbol rates greater than 50 to 100 baud) are not very practical without some method of equalization.

There is much more detailed information available about mobile radio propagation, but unfortunately most of it is written at an engineering level. For example, Keysight Technologies (**keysight.com**) offers fading simulator software that operates in conjunction with their N5182B MXG X-Series RF Vector Signal Generator.

For those who would like to explore the subject further, a *Mathcad* file with equations and explanatory text related to Rayleigh fading is available at **www.arrl.org/qst-in-depth**. Look in the 2006 section for Bloom0806.zip. The file was used to generate some of the graphics in this section. For those without access to *Mathcad*, a read-only PDF version of the file is available in the same directory.

19.7 Special Propagation Modes and Topics

19.7.1 *WSJT-X* and WSPR

WSJT-X (Weak Signal Communication, see **physics.princeton.edu/pulsar/k1jt/wsjtx.html**) is a suite of digital protocols optimized for weak signal communications on HF and VHF/UHF. See the **Digital Protocols and Modes** chapter's section on Structured Digital Modes and this chapter's section on E Region Propagation. This software provides a wide variety of modes tailored for specific types of propagation. For example, FT8 is optimized for use at HF and 50 MHz; JT65 for EME on the VHF and UHF bands; JT4 for microwave bands; and JT9 especially for LF and MF. Any of these modes can be used on the HF bands to make worldwide contacts with a few watts and compromise antennas.

The WSPR mode implements a protocol that is specially designed for probing potential propagation paths with low power transmissions. WSPR transmissions carry a station's call sign, Maidenhead grid locator, and transmitter power in dBm. The program can decode signals with a signal-to-noise ratio as low as −28 dB in a 2500 Hz bandwidth. For more details on the WSPR mode and its capabilities, visit **www.wsprnet.org** and **physics.princeton.edu/pulsar/k1jt/wspr.html**.

19.7.2 Sporadic E

Short skip, long familiar on the 10-meter band during the summer months, affects the VHF bands as high as 222 MHz. *Sporadic E*, as this phenomenon is properly called, commonly propagates 28, 50, and, less frequently, 144 MHz radio signals between 500 and 2,300 kilometers (300 and 1,400 miles). Signals are apt to be exceedingly strong, allowing even modest stations to make E_s contacts. At 21 MHz, the skip distance may only be a few hundred kilometers. During the most intense E_s events, skip may shorten to less than 200 kilometers (120 miles) on the 10 meter band, with no skip zone at all on 15 meters. The first confirmed 220 MHz E_s contact was made in June 1987, but such contacts are likely to remain very rare. Much of what is known about E_s has come as the result of amateur pioneering in the VHF range.

Note that sporadic E can also be written as *E-subscript-s* (E_s) but is often written simply as Es (pronounced E ess). Sporadic E results from ionization at the lower boundary of the E-region, but of different origin and communication potential from the E-region that affects mainly our lower amateur frequencies. *[The amateur and professional literature is not strict about the name, with sporadic E and E_s used regularly — Ed.]*

CAUSES OF SPORADIC E

Efforts to predict mid-latitude E_s have not been successful, probably because its causes are complex and not yet well understood. Studies have demonstrated that thin and unusually dense patches of ionization in the E region, between 100 and 110 kilometers (60 and 70 miles) altitude and 10 to 100 kilometers (6 to 60 miles) in extent, are responsible for most E_s reflections. Note that "patch" is a more accurate term than "cloud" in describing the thin regions of ionization that create E_s propagation, but the term "cloud" is far more commonly used.

The formative mechanism for mid-latitude E_s is believed to be wind shear. This explains ambient ionization (believed to be meteoroid ablation — dust from meteors) being distributed and compressed into a thin, high-density region (a couple kilometers thick), without the need for production of extra ionization. Neutral winds of high velocity, flowing in opposite directions at slightly different altitudes, produce wind shears. In the presence of the Earth's magnetic field, the ions are collected at an altitude of about 120 kilometers, slowly drifting down to about 95 kilometers, forming a thin, over-dense layer. Data from rockets entering E_s regions confirm the electron density, wind velocities, and height parameters. The patches of ionization last only minutes to hours and are distributed randomly. They vary in density and, in the middle latitudes of the Northern Hemisphere, move at up to 100 mph, mostly from south to north along magnetic field lines. For a more detailed technical understanding of sporadic E, see the Reference entry for Whitehead.

WHEN SPORADIC E OCCURS

Sporadic E at mid latitudes (roughly 15 to 45 degrees) may occur at any time of the year, but it is most common in the Northern Hemisphere during May, June, and July, with a less intense season from the end of December to early January, near the summer and winter solstices. Its appearance is independent of the solar cycle. E_s propagation is most likely to occur from 9 AM to noon local time and again early in the evening between 5 PM and 8 PM, but can occur any time between dawn and midnight. Mid-latitude E_s events may last only a few minutes or can persist for many hours. In contrast, E_s is an almost constant feature near the auroral oval at night and the geomag-

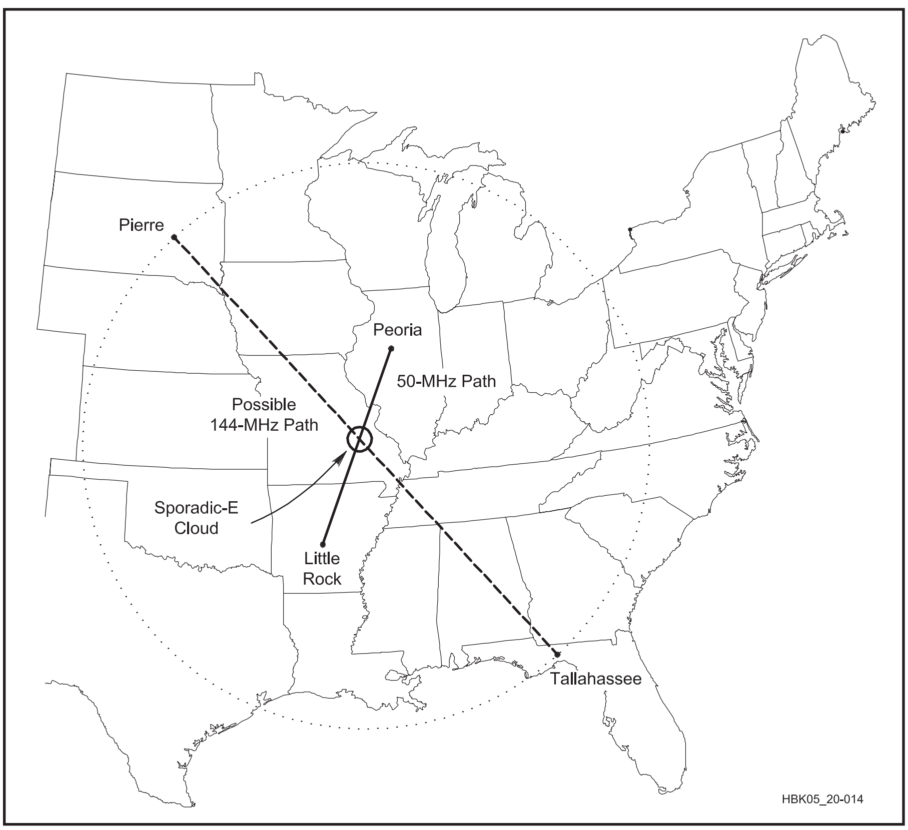


Figure 19.44 — 50 MHz sporadic E contacts of 700 kilometers (435 miles) or shorter (such as between Peoria and Little Rock) indicate that the MUF on longer paths is above 144 MHz. Using the same sporadic E region reflecting point, 144 MHz contacts of 2,200 kilometers (1,400 miles), such as between Pierre and Tallahassee, should be possible.

netic equator during the day.

At the peak of the long E_s season, ionization becomes extremely dense and widespread. This extends the usable range from the more common "single-hop" maximum of about 1,400 miles to longer "multi-hop" distances discussed below. With 50-MHz techniques and interest improving in recent years, it has been shown that distances considerably beyond 2,500 miles can be covered, especially during June and July in the Northern Hemisphere. The evolution of the digital FT8 mode has also opened up new possibilities on 50 MHz.

The seasons and distribution in the Southern Hemisphere are not so well known. Australia and New Zealand seem to have conditions much like those in the US, but with the timing of the seasons reversed, of course.

RANGE OF SPORADIC E

Sporadic E clouds exhibit an MUF that can rise from 28 MHz through the 50 MHz band and higher in just a few minutes. When the skip distance on 28 MHz is as short as 400 or 500 kilometers (250 or 310 miles), it is an indication that the MUF has reached 50 MHz for longer paths at low launch angles. Contacts at the maximum one-hop E_s distance, about 2,300 kilometers (1,400 miles), should then be possible at 50 MHz. *E-skip* (yet another term for sporadic E) contacts as short as 700 kilometers (435 miles) on 50 MHz, in turn, may indicate that 144 MHz contacts in the 2,300-kilometer (1,400-mile) range can be completed (see **Figure 19.44**). Sporadic E openings occur about a tenth as often at 144 MHz as they do at 50 MHz and for much shorter periods.

Sporadic E can also have a detrimental effect on HF propagation by masking or blanketing the F_2 region from below. HF signals may be prevented from reaching the higher levels of the ionosphere and the possibilities of long F_2 skip. Reflections from the tops of E_s patches can also have a masking effect, but they may also lengthen the F_2 propagation path with a top-side intermediate hop that never reflects from the Earth.

E_s has supported contacts on 28 and 50 MHz beyond 4,000 kilometers, up to 10,000 kilometers (6,200 miles), and more than 3,000 kilometers (1,900 miles) on 144 MHz. The term "multi" hop is probably not technically accurate, since it is likely that cloud-to-cloud paths are involved. This is an example of "above-the-MUF" propagation involving chordal hops between the patches of ionization.

There may also be "no-hop" E_s. On very rare occasions, the very high ionization density produces critical frequencies up to the 50-MHz range, with no skip distance at all. It is often said that the E_s mode is a great equalizer. With the reflecting region practically overhead, even a simple dipole close to the ground may do as well over a few hundred miles as a large, stacked antenna array designed for low-angle radiation. It's a great mode for low power and simple antennas on 28 and 50 MHz and a good reason to have high-angle antennas available.

E_s can also "link-up" with other modes. For example, those in the northern continental US normally can't take advantage of TEP (Trans-Equatorial Propagation — see the F Region Propagation section) because they are too far north. But E_s can provide a link to TEP. This hybrid mode is most likely to be experienced on our 50 MHz band. E_s can also provide a link to normal F_2 propagation.

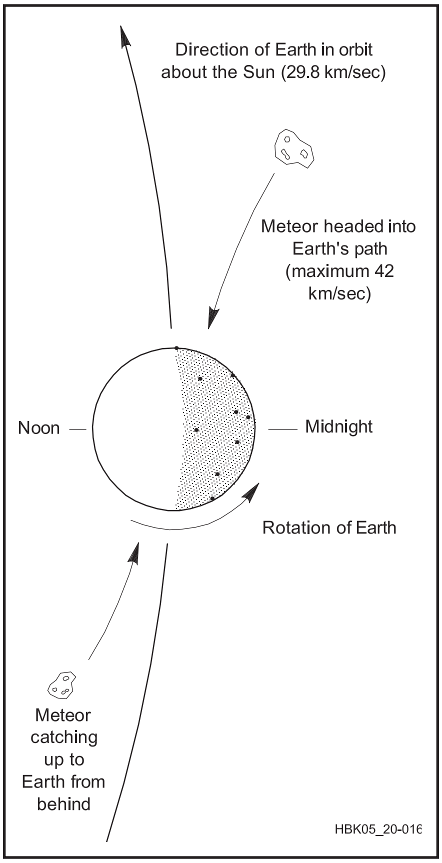


Figure 19.45 — The relative velocity of meteors that meet the Earth head on is increased by the rotational velocity of the Earth in orbit. Fast meteors strike the morning side of the Earth because their velocity adds to the Earth's rotational velocity, while the relative velocity of meteors that "catch up from behind" is reduced.

19.7.3 Meteor Scatter

Contacts between 800 and 2,300 kilometers (500 and 1,400 miles) can be made at 28 through 432 MHz via reflections from the ionized trails left by meteors as they travel through the atmosphere. The kinetic energy of meteors no larger than grains of rice are sufficient to ionize a column of air 20 kilometers (12 miles) long in the E region. The particle itself evaporates and never reaches the ground, but the ionized column may persist for a few seconds to a minute or more before it dissipates. This is enough time to make very brief contacts by reflections from the ionized trails. Millions of meteors enter the Earth's atmosphere every day, but few have the required size, speed, and orientation to the Earth to make them useful for meteor-scatter propagation.

Radio signals in the 30 to 100 MHz range are reflected best by meteor trails, making the 50 MHz band prime for meteor-scatter work. The early morning hours around dawn are usually the most productive, because the morning side of the Earth faces in the direction of the planet's orbit around the Sun. The relative velocity of meteors that head toward the Earth's morning side are thus increased by up to 30 km/sec, which is the average rotational speed of the Earth in orbit (see **Figure 19.45**). The maximum velocity of meteors in orbit around the Sun is 42 km/sec. Thus when the relative velocity of the Earth is considered, most meteors must enter the Earth's atmosphere somewhere between 12 and 72 km/sec.

Meteor contacts ranging from a second or two to more than a minute can be made nearly any morning at 28 or 50 MHz. Meteor scatter contacts at 144 MHz and higher are more difficult because reflected signal strength and duration drop sharply with increasing frequency. A meteor trail that provides 30 seconds of communication at 50 MHz will last only a few seconds at 144 MHz, and less than a second at 432 MHz.

Meteor scatter opportunities are somewhat better during July and August for North America because the average number of

Table 19.5
Major Annual Meteor Showers

Name	*Peak Dates*	*Approximate Rate (meteors/hour)*
Quadrantids	Jan 3	50
Arietids	Jun 7-8	60
Perseids	Aug 11-13	80
Orionids	Oct 20-22	20
Geminids	Dec 12-13	60

meteors entering the Earth's atmosphere peaks during those months. The best times are during one of the great annual *meteor showers*, when the number of useful meteors may increase 10-fold over the normal rate of 5 to 10 per hour (see **Table 19.5**). A meteor shower occurs when the Earth passes through a relatively dense stream of particles, thought to be the remnants of a comet in orbit around the Sun. The most-productive showers are relatively consistent from year to year, although several can occasionally produce great storms.

A technique allowing even smaller VHF/UHF stations to take advantage of meteor scatter and other modes (ionospheric scatter and even moonbounce) is available as the MSK144 mode, which is part of the *WSJT-X* software package, allowing meteor scatter communication to as much as 10 dB below the received noise level.

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