Contents

Propagation of Radio Signals

Radio waves, like light waves — and all other forms of electromagnetic radiation, normally travel in straight lines. Obviously this does not happen all the time, because long-distance communication depends on radio waves traveling beyond the horizon. How radio waves propagate in other than straight-line paths is a complicated subject, but one that need not be a mystery. This chapter, by Emil Pocock, W3EP, with updates by Carl Luetzelschwab, K9LA, provides 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.

Chapter 19 — CD-ROM Content

Supplemental Articles

- "The Penticton Solar Flux Receiver" by John White, VA7JW and Ken Tapping
- "Hands-On Radio: Recording Signals" by Ward Silver, NØAX

Projects

- "Build a Homebrew Radio Telescope" by Mark Spencer, WA8SME

19.1 Fundamentals of Radio Waves

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 and thus the lowest frequency of this group. See **Table 19.1**.

Electromagnetic waves are composed of an inter-related 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 **Fig 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.

19.1.1 Velocity

Radio waves, like all forms of electromagnetic radiation, travel nearly 300,000 km (186,400 miles) per second in a vacuum. Radio waves travel more slowly through any other medium. 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% that in free space, and the speed can be even slower in other media.

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 hertz
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 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 in English units, λ in feet = 984 divided by

Table 19.1

The Electromagnetic Spectrum

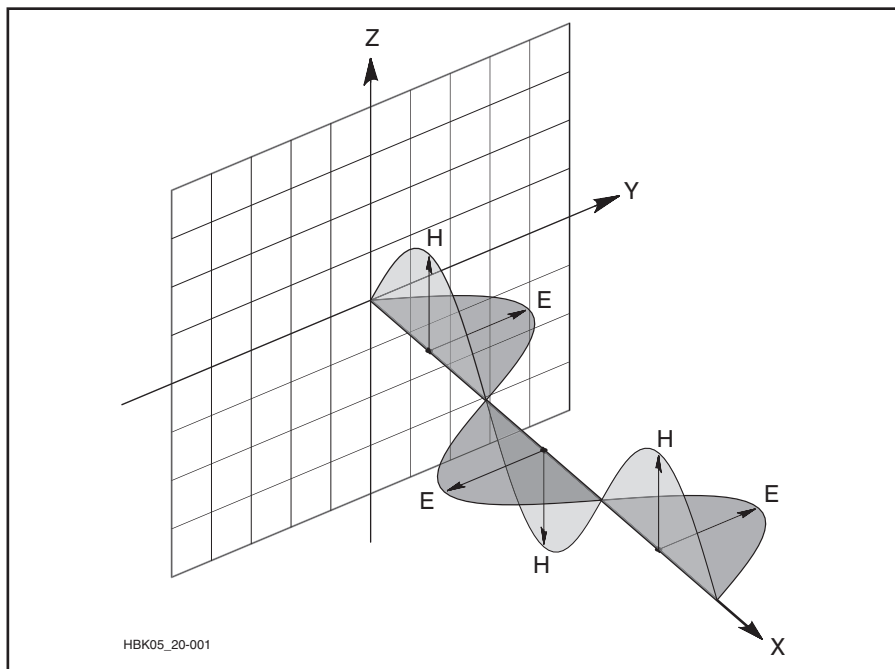| Radiation	Frequency	Wavelength
Radio	10 kHz – 300 GHz	30 km – 1 mm
Infrared	300 GHz – 428.6 THz	1 mm – 700 nm
Visible light	428.6 THz – 750 THz	700 nm – 400 nm
Ultraviolet	750 THz – 3×10^3 THz	400 nm – 100 nm
Extreme Ultraviolet	3×10^3 THz – 3×10^4 THz	100 nm – 10 nm
"Soft" X-ray	3×10^4 THz – 3×10^5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

Fig 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.

the frequency in MHz.

Wavelength decreases in other media because the propagating speed is slower. In a piece of wire, the wavelength of a 30 MHz signal shortens to about 9.5 meters. This factor must be taken into consideration in antenna designs, in transmission line designs, and in other applications.

19.1.2 Free Space Attenuation and Absorption

The intensity of a radio wave decreases as it travels. There are two mechanisms by which the intensity decreases: free space attenuation and absorption.

Free-space attenuation results from the spherical spreading of radio energy from its source. See **Fig 19.2**. Attenuation grows
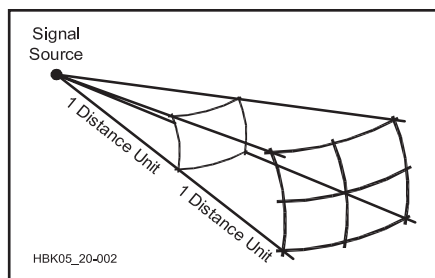

Fig 19.2 — Radio energy disperses as the square of the distance from its source. For the change of one distance unit shown the signal's power per unit of area is only one quarter as strong. Each spherical section has the same surface area.

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 distance.) If the distance between transmitter and receiver is increased from 1 km to 10 km (0.6 to 6 miles), the signal power will be reduced by a factor of 100. Attenuation increases with frequency as well. Free space attenuation (path loss) can be expressed as

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

where

    L_{fs} = free space path loss in dB
    d = distance in km
    f = frequency in MHz

Free-space attenuation is a major factor governing signal strength, but radio signals undergo a variety of other losses as well. Energy is lost to absorption when radio waves travel through media other than a vacuum. Radio waves propagate through the atmosphere or solid material (like a wire) by exciting electrons, which then reradiate energy at the same frequency. This process is not perfectly efficient, so some radio energy is transformed into heat and retained by the medium. The amount of radio energy lost in this way depends on the characteristics of the medium and on the frequency. Attenuation in the atmosphere is minor from 10 MHz to 3 GHz, but at higher frequencies, absorption due to water vapor and oxygen can be high.

Radio energy is also lost during refraction,

diffraction and reflection — the very phenomena that 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 Layer absorption in the lower HF bands. These topics will be covered later. 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).

19.1.3 Refraction Below the Ionosphere

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. Radio waves behave no differently from other familiar forms of electromagnetic radiation in this regard. The apparent bending of a pencil partially immersed in a glass of water demonstrates this principle quite dramatically.

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

The amount of bending increases with the ratio of the *refractive indices* of the two media. Refractive index is simply the velocity of a
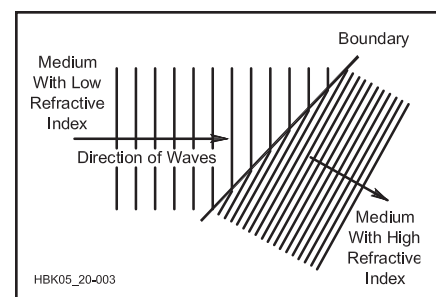
Fig 19.3 — Radio waves are refracted as they pass at an angle between dissimilar media. The lines represent the crests of a moving wave front and the distance between them is the wavelength. The direction of the wave changes because one end of the wave slows down before the other as it crosses the boundary 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.

radio wave in free space divided by its velocity in the medium. The refractive properties of air may be calculated from temperature, moisture and atmospheric pressure. The index of refraction of air, at a very wide range of frequencies, may be calculated from:

$$N = \frac{77.6\,p}{T} + \frac{3.73 \times 10^5\,e}{T^2}$$

where

    N = index of refraction, N units (number of millionths by which the index of refraction exceeds 1.0)
    p = atmospheric pressure, millibars (mb)
    e = partial pressure of water vapor, millibars
    T = temperature, Kelvins

Note that the index of refraction below the ionosphere is greater than 1, causing more bending.

The refraction of radio signals is a function of the change in the index of refraction with altitude. N varies between 290 and 400 at the Earth's surface and normally diminishes with altitude at the rate of 40 N units per kilometer within the first few kilometers.

Radio waves are commonly refracted when they travel through different layers of the atmosphere, whether the highly charged ionospheric layers roughly 100 km (60 miles) and higher, or the weather-sensitive area near the Earth's surface. When the ratio of the refractive indices of two media is great enough, radio waves can be reflected, just like light waves striking a mirror. The Earth is a rather lossy reflector, but a metal surface works well if it is several wavelengths in diameter.

19.1.4 Scattering

The direction of radio waves can also be altered through *scattering*. 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.

If the scattering objects are arranged in some alignment or order, scattering takes place only at certain angles. A rainbow provides a good analogy for *field-aligned scattering* of light waves. The arc of a rainbow can be seen only at a precise angle away from the Sun, while the colors result from the variance in scattering across the light-wave frequency range. Ionospheric electrons can be field-aligned by magnetic forces in auroras and under other unusual circumstances. Scattering in such cases

is best perpendicular to the Earth's magnetic field lines.

19.1.5 Reflection

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 km. Two stations need only beam toward a common reflector, whether stationary or moving.

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 km (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.

19.1.6 Knife-Edge Diffraction

Radio waves can also pass behind solid objects with sharp upper 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. **Fig 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.

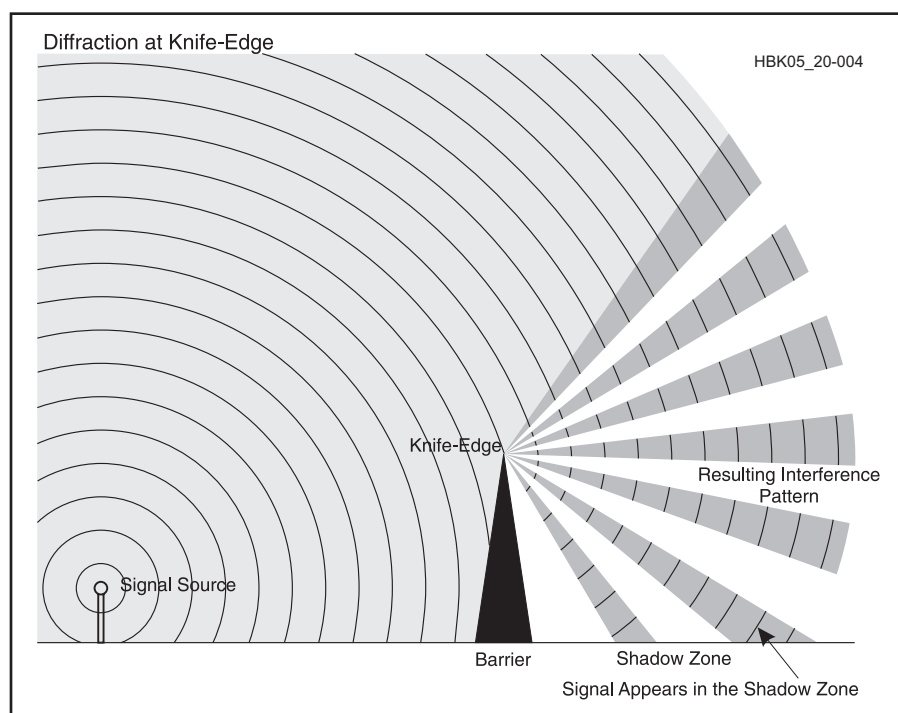Fig 19.4 — VHF and UHF radio waves, light and other waves are diffracted around the sharp edge of a solid object that is large in terms of wavelengths. Diffraction results from interference between waves right at the knife-edge and those that are passing above it. Some signals appear behind the knife-edge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

Propagation Summary, by Band

OUR ONLY MEDIUM FREQUENCY (MF) BAND

1.8-2.0 MHz (160 meters)

Top band, as it is sometimes called, suffers from daytime D layer absorption. Daytime communication is limited to ground-wave coverage and a single E hop out to about 1500 km 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 layer quickly disappears and worldwide 160 meter communication becomes possible via F_2 layer skip and ducting. 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 lowest two bands in this range share many daytime characteristics with 160 meters. 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 layer 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, 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 will fall in between that achievable on the 80 meter and 40 meter bands. 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 has a clearly defined skip zone during the day due to insufficient ionization to refract high angles. D layer absorption is not as severe as on the lower bands, so short-distance skip via the E and F layers is possible. During the day, a typical station can cover a radius of approximately 800 km (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 may be 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 layer absorption is not a significant factor. Communication up to 3000 km (1900 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 some 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. The 30 meter band shows the least variation in conditions over the 11-year solar cycle, thus making it generally useful for long-distance communication anytime.

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 layer 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 layer 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 this is not common and 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 layer conditions. It provides single-hop communication from 300 to 2300 km (190 to 1400 miles) and multiple-hop opportunities of 4500 km (2800 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, auroral E and transequatorial propagation provide the means of making contacts out to 2300 km (1400 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 layer skip appears on 50 MHz during solar cycle peaks. Sporadic E and several other E layer 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 km (190 miles) via tropospheric scatter, depending on terrain, power, receiver capabilities and antenna. Weak-signal troposcatter allows the best stations to make 500 km (310 mile) contacts nearly any time. Weather effects may extend the normal range by a few hundred km, especially during the summer months, but true tropospheric ducting is rare.

During the peak of the 11-year sunspot cycle (especially during the winter months), worldwide 50 MHz DX is possible via the F_2 layer during daylight hours. F_2 backscatter provides an additional propagation mode for contacts as far as 4000 km (2500 miles) when the MUF is just below 50 MHz. TE paths as long as 8000 km (5000 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 2300 km (370 to 1400 miles), primarily during the spring and early summer. Multiple-hop E_s provides transcontinental contacts several times a year, and contacts between the US and South America, Europe and Japan via multiple-hop E-skip occur nearly every summer.

Other types of E layer ionospheric propagation make 6 meters an exciting band. Maximum distances of about 2300 km (1400 miles) are typical for all types of E layer modes. 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 4000 km (2500 miles) and sometimes farther across the northern states and Canada, usually after midnight. Meteor scatter provides brief contacts during the early morning hours, 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 layer propagation is unknown except for TE, which is responsible for the current 144 MHz terrestrial DX record of nearly 8000 km (5000 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 2300 km (1400 miles). Multiple-hop sporadic E contacts greater than 3000 km (1900 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.

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 km (190 to 370 mile) range of well-equipped stations to 800 km (500 miles) and more, especially during the summer and early fall. Tropospheric ducting extends this range to 2000 km (1200 miles) and farther over the continent and at least to 4000 km (2500 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 layer 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 km (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 1500 km (930 miles) and farther over land. The current 432 MHz terrestrial DX record of more than 4000 km (2500 miles) was accomplished by ducting over water.

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 km or more that might otherwise be entirely obstructed by mountains or seemingly impossible terrain.

19.1.7 Ground Wave

A *ground wave* is the result of a special form of diffraction that primarily affects longer-wavelength vertically polarized radio waves. It is most apparent in the 80 and 160 meter amateur bands, where practical ground-wave distances may extend beyond 200 km (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.

Radio waves are bent slightly as they pass over a sharp edge, but the effect extends to edges that are considerably rounded. At medium and long wavelengths, the curvature of the Earth looks like a rounded edge. Bending results when the lower part of the wave front loses energy due to currents induced in the ground. This slows down the lower part of the wave, causing the entire wave to tilt forward slightly. This tilting follows the curvature of the Earth, thus allowing low- and medium-wave radio signals to propagate over distances well beyond line of sight.

Ground wave is most useful during the day at 1.8 and 3.5 MHz, when D layer 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 worst over dry and rocky land.

19.2 Sky-Wave Propagation and the Sun

The Earth's atmosphere is composed primarily of nitrogen (78%), oxygen (21%) and argon (1%), with smaller amounts of a dozen other gases. Water vapor can account for as much as 5% of the atmosphere under certain conditions. This ratio of gases is maintained until an altitude of about 80 km (50 miles), when the mix begins to change. At the highest levels, helium and hydrogen predominate.

Solar radiation acts directly or indirectly on all levels of the atmosphere. Adjacent to the surface of the Earth, solar warming controls all aspects of the weather, powering wind, rain and other familiar phenomena. *Solar ultraviolet (UV) radiation* creates small concentrations of ozone (O_3) molecules between 10 and 50 km (6 and 30 miles). Most UV radiation is absorbed by this process and never reaches the Earth.

At even higher altitudes, UV 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 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.

19.2.1 Structure of the Earth's Atmosphere

The atmosphere, which reaches to more than 600 km (370 miles) altitude, is usually divided into a number of regions based on a transitioning characteristic of the atmosphere — like temperature. For propagation purposes, the important regions are shown in **Fig 19.5**. The weather-producing *troposphere* lies between the surface and an average altitude of 10 km (6 miles). Between 10 and 50 km (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 km to about 600 km (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 UV 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.

The *magnetosphere* begins around 600 km (370 miles) and extends as far as 160,000 km (100,000 miles) into space. The predominant component of atmospheric gases gradually shifts from atomic oxygen, to helium and finally to hydrogen at the highest levels. The lighter gases may reach escape velocity or be swept off the atmosphere by the *solar wind* (electrically charged particles emitted by the Sun and traveling through space). At about 3200 and 16,000 km (2000 and 9900 miles, respectively), the Earth's magnetic field traps energetic electrons and protons in two bands, known as the *Van Allen belts*.

These have only a minor effect on terrestrial radio propagation.

19.2.2 The Ionosphere

The ionosphere plays a basic role in long-distance communications in all the amateur bands from 1.8 MHz to 30 MHz. The effects of the ionosphere are less apparent at the very high frequencies (30-300 MHz), but they persist at least through 432 MHz. As early as 1902, Oliver Heaviside and Arthur E. Kennelly independently suggested the existence of a layer in the upper atmosphere that could account for the long-distance radio transmissions made the previous year by Guglielmo Marconi and others. Edward Appleton confirmed the existence of the Kennelly-Heaviside layer in publications beginning in 1925 and used the letter E on his diagrams to designate the strength of the electric field of the waves that were apparently reflected from the layer he measured.

In late 1927 Appleton reported the existence of an additional layer in the "ionosphere." (Robert Watson-Watt coined the term "ionosphere", but it wasn't commonly used until 1932.) The additional higher-altitude layer was named "F" and subsequently another was termed "D." For a time during the 1930s, a "C" layer was proposed, and later discarded. Appleton was reluctant to alter this arbitrary nomenclature for fear of discovering yet other lower layers, so it has stuck to the present day. The basic physics of ionospheric propagation was largely worked out by the 1930s, yet both amateur and professional experimenters made further discoveries during the 1930s, 1940s and 1950s. Sporadic E, aurora, meteor scatter and several types of field-aligned scattering were among additional ionospheric phenomena that required explanation.

Although the term "layer" is used in this chapter, this could lead to the erroneous assumption that the ionosphere consists of distinct thin sheets separated by emptiness in between. This is not so, and as we'll see later in the chapter the ionosphere is a continuous electronic density versus altitude, with definite peaks and inflections points that define the D, E, and F regions. Studies have shown that the height of the various layers may also vary by latitude. Research into ionospheric physics is ongoing in an attempt to better understand the variability of the ionosphere.

19.2.3 Ionospheric Refraction

The refractive index of an ionospheric layer decreases from a value of 1.00 as the density of free-moving electrons increases (this is opposite from the refractive index in the troposphere since the ionosphere is a dispersive medium). In the densest regions of the F layer, that density can reach a trillion electrons per cubic meter (10^{12} e/m^3). Even at this high level, radio waves are refracted gradually over a considerable vertical distance, usually amounting to tens of km. Radio waves become useful for terrestrial propagation only when they are refracted enough to bring them back to Earth. See **Fig 19.6**.

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 layer is the equivalent altitude of a reflection that would produce the same effect as the actual refraction. The virtual height of

Fig 19.5 — Regions of the lower atmosphere and the ionosphere.

Fig 19.6 — Gradual refraction in the ionosphere allows radio signals to be propagated long distances. It is often convenient to imagine the process as a reflection with an imaginary reflection point at some virtual height above the actual refracting region. The other figures in this chapter show ray paths as equivalent reflections, but you should keep in mind that the actual process is a gradual refraction.

Fig 19.7 — Simplified vertical incidence ionogram showing echoes returned from the E, F_1 and F_2 layers. The critical frequencies of each layer (4.1, 4.8 and 6.8 MHz) can be read directly from the ionogram scale.

Fig 19.8 — 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 c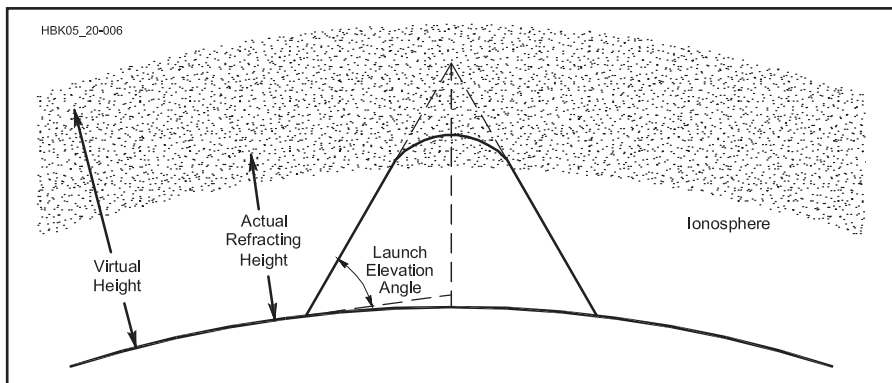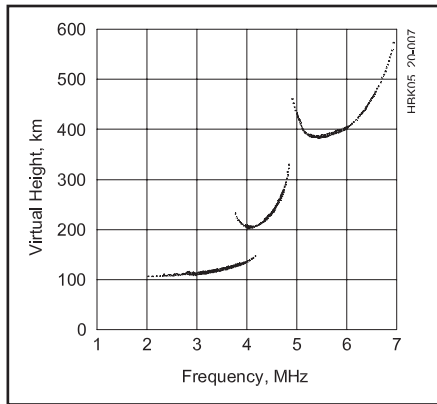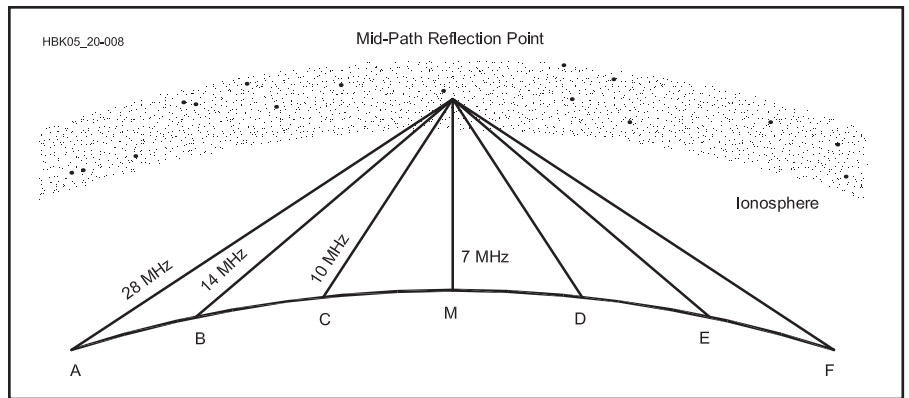ommunicate by the ionosphere at 14 MHz. Stations at points B and E (and beyond) can communicate because signals at this frequency are refracted back to Earth because they encounter the ionosphere at an oblique angle of incidence. At greater distances, higher frequencies can be used because the MUF is 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.

any ionospheric layer 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*. **Fig 19.7** depicts a simple ionogram. Real-time ionograms can be found online at the Digital Ionogram Database, sponsored by the University of Massachusetts Lowell (**http://umlcar.uml.edu/DIDBase/**). For an extensive discussion of ionogram interpretation, download *UAG-23A: URSI Handbook of Ionogram Interpretation and Reduction* from the Australian IPS (Ionospheric Prediction Service) website at **www.ips.gov.au/ IPSHosted/INAG/uag_23a/uag_23a.html**.

The highest frequency that returns echoes from the E and F regions at vertical incidence is known as the *vertical incidence* or *critical frequency*. (There is a D region critical frequency, but its value is well below 1 MHz and thus has minimal impact on our Amateur Radio bands.) 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 call any electron density in any part of the ionosphere a *plasma frequency*, because technically gases in the ionosphere are in a plasma, or partially ionized state. F layer critical frequencies commonly range from about 1 MHz to as high as 15 MHz.

19.2.4 Maximum and Lowest Usable Frequencies

When the frequency of a vertically incident signal is raised above the critical frequency

of an ionospheric layer, that portion of the ionosphere is unable to refract the signal back to Earth. However, a signal above the critical frequency may be returned to Earth if it enters the layer 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 **Fig 19.8**.

The highest frequency supported by the ionosphere 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 electromagnetic 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 layer of the ionosphere at that location. This maximum distance is about 4000 km (2500 miles) for the F_2 layer and about 2000 km (1250 miles) for the E layer. See **Fig 19.9**.

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. For path lengths at the
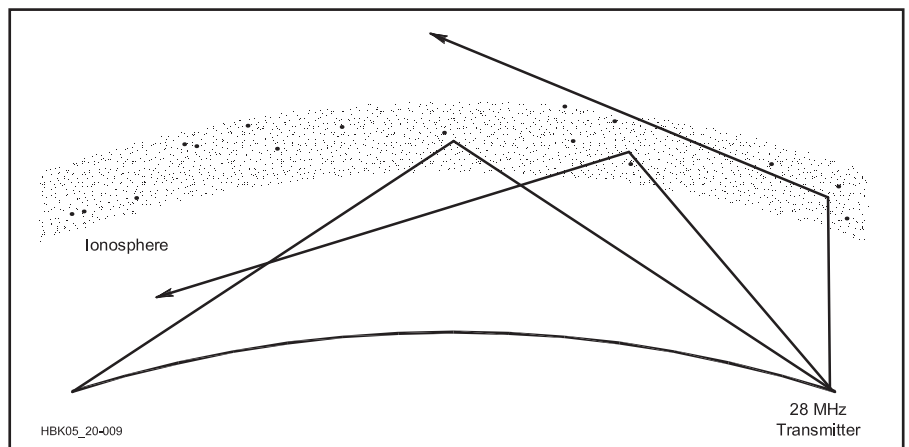

Fig 19.9 — Signals at the MUF propagated at a low angle to the horizon provide the longest possible one-hop distances. In this example, 28 MHz signals entering the ionosphere at higher angles are not refracted enough to bring them back to Earth.

limit of one-hop propagation, the MUF can be several times the critical frequency. The ratio between the MUF and the critical frequency is known as the *M-factor*.

The M-factor can be estimated using simple geometry in a spherical model of the Earth-ionosphere system. The angle of incidence on the ionosphere of an electromagnetic wave launched from the ground depends on the launch angle and the height of the ionospheric region. Due to the spherical geometry of the Earth-ionosphere system, the angle of incidence on the ionosphere does not approach zero as the launch angle approaches zero — it is limited to approximately 19º and 11º for the F_2 and E regions, respectively, which then limits the M-factor to approximately 3 and 5 for these two regions (from the equation MUF = 1 / the sine of the angle of incidence on the ionosphere). See **Table 19.2** for typical M-factors of the various regions.

The term *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 said to be 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 other mechanisms if they are close enough. There is no skip zone at frequencies below the MUF.

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. In this case, the frequency is said to be below the *lowest usable frequency* (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. 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. This is a common occurrence on 160 meters during the day due to too much absorption; another scenario would be too much noise on the higher bands due to thunderstorm activity or man-made noise. When the LUF is higher than the MUF, there is no frequency that supports communication on the particular path at that time.

19.2.5 NVIS Propagation

In the previous section, the statement was made that *stations within the skip zone may be able to work each other at a lower frequency, or by ground wave if they are close enough.* This statement summarizes the purpose of *Near Vertical Incidence Skywave* (*NVIS*) propagation — to bridge the gap between where ground wave is too weak and where the skip zone ends. By going to lower frequencies, communications can be maintained over these relatively short distances.

Propagation over short distances means high elevation angles — this is not DXing in which lower angles in general are most effective. For example, a path from San Francisco to Sacramento is 75 miles, and requires an average elevation angle of 78 degrees. To radiate maximum energy at these higher angles, relatively low height antennas need to be used.

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 height. 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.*

19.2.6 Ionospheric Fading

HF signal strengths typically rise and fall over periods of a few seconds to several minutes, and rarely hold at a constant level for very long. Fading is generally caused by the interaction of several radio waves from the same source arriving along different propagation paths. Waves that arrive in-phase combine to produce a stronger signal, while those out-of-phase cause destructive interference and lower net signal strength. Short-term variations in ionospheric conditions may change individual path lengths or signal strengths enough to cause fading. Even signals that arrive primarily over a single path may vary as the propagating medium changes. Fading may be most notable at sunrise and sunset, especially near the MUF, when the ionosphere undergoes dramatic transformations. Other ionospheric traumas, such as auroras and geomagnetic storms, also produce severe forms of HF fading.

19.2.7 Polarization at HF

Although the ionosphere varies on a short-term basis and results in somewhat random polarization, there is more order to polarization than realized. The ionosphere is immersed in the Earth's magnetic field, and the result of an electromagnetic wave propagating through an ionized medium (called a plasma, which is what our ionosphere is) immersed in a magnetic field is the propagation of two characteristic waves: the ordinary wave (O-wave) and the extraordinary wave (X-wave). Ordinary and extraordinary are terms borrowed from the science of optics. These two waves are generally elliptically polarized (the tip of the polarization vector traces out an ellipse), and are orthogonal to each other.

Upon entering the ionosphere, and depending on the location and the heading, a linearly polarized wave (from our horizontal or vertical antenna) will either couple all of its energy into the O-wave, all of its energy into the X-wave, or divide its energy into the O-wave and X-wave. Our horizontal antenna will couple best into one characteristic wave, and our vertical antenna will couple best into the other characteristic wave. The same coupling issue is present when the characteristic waves exit the ionosphere. The bottom line is that on the HF bands of 80 meters and higher, both characteristic waves generally propagate with similar absorption, and thus the use of a vertical or horizontal antenna is not too critical with respect to polarization. One of the characteristic waves will couple into whichever antenna is being used.

On 160 meters, though, the X-wave is heavily absorbed, leaving the O-wave. In general, vertical polarization is best for those of us in North America and at high northern latitudes. However, 160 meter operators have observed that under some conditions,

Table 19.2

Maximum Usable Frequency Factors (M-factors) for 2000 km E Hops and 3000 km F Hops

Layer	Maximum Critical Frequency (MHz)	M-factor	Useful Operating Frequencies (MHz)
F_2	15.0	3.3-4.0	1-60
F_1*	5.5	4.0	10-20
E*	4.0	4.8	5-20
Es	30.0	5.3	20-160

*Daylight only

horizontally polarized antennas outperform vertically polarized antennas.

19.2.8 The 11-Year Solar Cycle

The density of ionospheric layers 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 rotation and the 11-year cycle of solar activity. One visual indicator of both the Sun's rotation and the solar cycle is the periodic appearance of dark spots on the Sun, which have been observed continuously since the mid-18th century. On average, the number of *sunspots* reaches a maximum every 10.7 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. **Fig 19.10** shows monthly mean sunspot numbers for the past five cycles (it also includes the smoothed values).

Sunspots are cooler areas on the Sun's surface associated with high magnetic activity. Active regions adjacent to sunspot groups, called *plages*, are capable of producing great flares and sustained bursts of radiation in the radio through X-ray spectrum. 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 as a consequence, resulting in higher critical frequencies, particularly in the F_2 layer. The possibilities for long-distance communications are considerably improved during solar maxima, especially in the higher-frequency bands.

One key to forecasting F layer critical frequencies, and thus long-distance propagation, is the intensity of ionizing UV and X-ray radiation. Until the advent of satellites, 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 complicated formula that takes into consideration size, number and grouping. The smoothed sunspot number (equivalent to a running average of monthly mean sunspot numbers from 6 months before to 6 months after the desired month) varies from near zero during the solar cycle minimum to over 200 during an extremely active solar cycle.

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 (10^{-22} W m^{-2} Hz^{-1}). 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 **Fig 19.11** (note that this is only valid for converting between smoothed values). The Dominion Radio Astrophysical Observatory, Penticton, British Columbia, measures the 2800 MHz solar flux three times a day
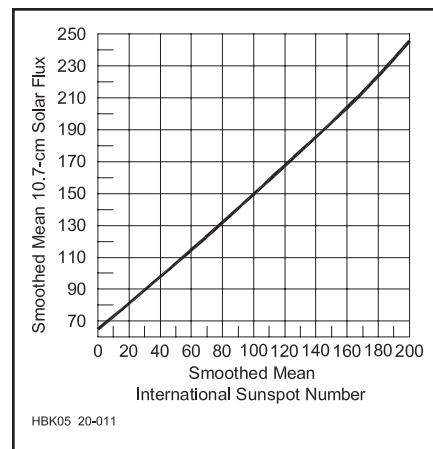

Fig 19.11 — Approximate conversion between solar flux and sunspot number. Note that this is for smoothed values of Solar Flux and Sunspot Numbers.

(centered on local noon). (A supplemental article, "The Penticton Solar Flux Receiver" from February 2013 *QST* is on the CD-ROM that comes with this book.) 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. Solar flux and other useful data is also available online at **www.swpc.noaa.gov**.

The Penticton solar flux is employed in a wide variety of other applications. Daily, weekly, monthly and even smoothed solar flux readings are commonly used in propagation predictions (but be aware that our HF propagation predictions are based on the correlation between smoothed solar flux or smoothed sunspot number and monthly median ionospheric parameters — more on this later in the chapter).

High flux values generally result in higher MUFs, but the actual procedures for predicting the MUF at any given hour and path is quite complicated. Solar flux is not the sole determinant, as the angle of the Sun to the Earth, season, time of day, exact location of the radio path and other factors must all be taken into account. MUF forecasting a few days or months ahead involves additional variables and even more uncertainties.

TRENDS IN SOLAR CYCLES

If one looks at all 23 recorded solar cycles, three characteristics stand out. First, we see a cyclic nature to the maximum smoothed sunspot numbers. Second, we've been through 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), and we appear to be headed into a third low cycle period. Third, we've lived through the highest period of high cycle activity (but this is currently being challenged by solar scientists through an
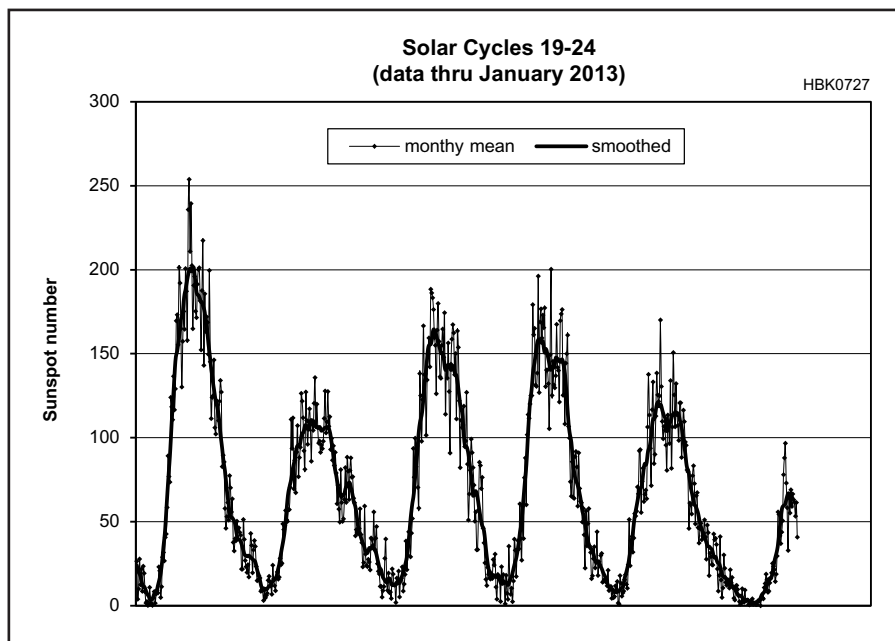

Fig 19.10 — Monthly mean sunspot numbers for Solar Cycles 19 to 24 (through February 2013). This data also includes the smoothed values.

Status of Solar Cycle 24

(This information was prepared in early February 2013.)

Fig 19A1 updates the monthly mean 10.7 cm solar flux data through February 2013 and the smoothed 10.7 cm solar flux through July 2012. The most obvious observation of this data is the peak in the smoothed solar flux in early 2012 (as a reminder, the smoothed data is how solar cycles are officially measured). This peak is earlier than the two most notable predictions from solar scientists (at ISES, the International Space Environment Service, and at MSFC, the Marshall Space Flight Center). Both of these predictions peg the maximum this year — not last year.

The January 2013 monthly mean data certainly showed a nice increase in solar activity. But if it doesn't continue in the months to come, then indeed early 2012 may be the peak of Cycle 24.

I believe the best way to approach this is to assume that the peak of Cycle 24 occurred, and take advantage of the higher bands (15 meters, 12 meters and especially 10 meters) *right now*. They should be good through the fall of 2013, but after that consistent worldwide propagation will begin waning. And looking at the peaks of all 23 solar cycles suggests we're headed into several cycles of low activity. See **Fig 19A2**. So taking the attitude that "I'll wait for Cycle 25" may not be a viable solution. — *Carl Luetzelschwab, K9LA*

Fig 19A1 — Monthly mean and smoothed 10.7 cm solar flux data through February 2013 and July 2012, respectively.

Fig 19A2 — Maximum smoothed sunspot number of all 23 solar cycles, showing three periods of high activity (large solar cycles) and two periods of low activity (small solar cycles). We appear to be headed for a period of low activity (small cycles).
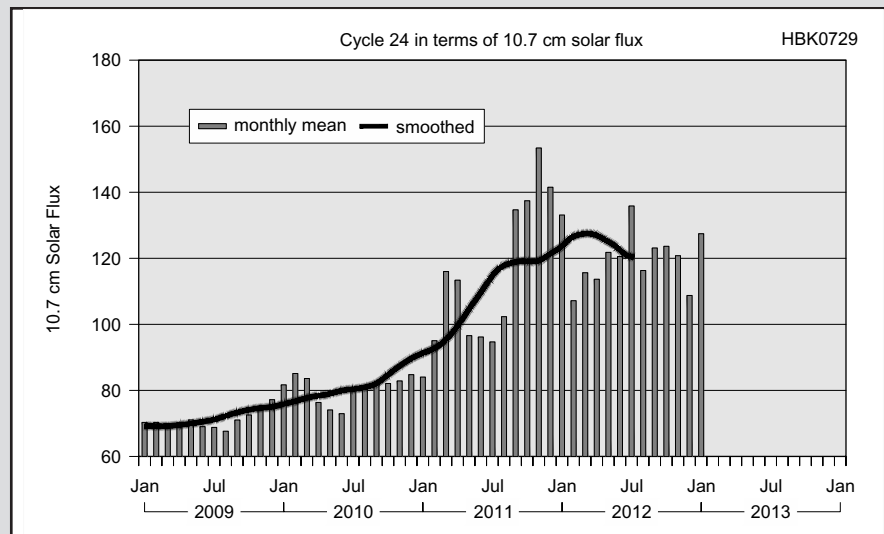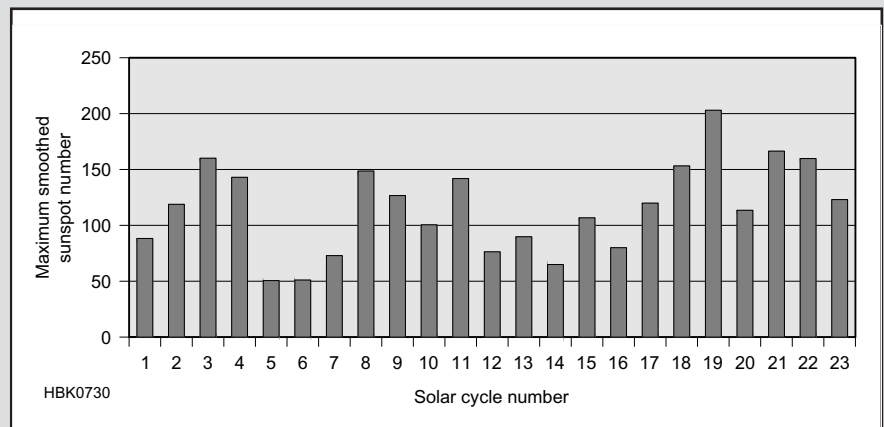
in-depth review of old sunspot records), which has allowed excellent worldwide propagation on the higher frequency bands and provided great enjoyment for radio amateurs.

If we look at solar cycles prior to recorded history through various proxies for solar activity (for example, carbon-14 in trees and beryllium-10 in ice cores), we'll see extended periods of very low solar activity referred to as Grand Minima (for example, the Maunder Minimum between 1640 and 1710 AD). 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 a 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 our lifetimes we have experienced minimum periods of approximately 24 months — much shorter than the average. This leads us to believe this recent solar minimum period was unusual. But historical data, with its great amount of variation, says otherwise.

19.2.9 The Sun's 27-Day Rotation

Sunspot observations also reveal that the Sun rotates on 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 that affect the Earth's ionosphere, which appear almost entirely within 35° of the Sun's equator, take about 26 days for one rotation. After taking into account the Earth's movement around the Sun, the apparent period of solar rotation is about 27 days.

Active regions must face the Earth in the proper orientation to have an impact on the ionosphere. They may face the Earth only once before rotating out of view, but they often persist for several solar rotations. The net effect is that solar activity often appears in 27-day cycles corresponding to the Sun's rotation, even though the active regions themselves may

last for several solar rotations.

The CD-ROM that accompanies this book includes supplemental articles about observing solar phenomena, including a *QST* article by Mark Spencer, WA8SME on building your own radio telescope. Numerous online sources such as **http://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 Viewing" by Jeff Medkeff (**www.skyandtelescope.com/observing/objects/sun/3309106.html**).

19.2.10 Disturbances to Propagation

Like a campfire that occasionally spits out a flaming ember, our Sun sometimes erupts spasmodically — but on a much grander scale than a summer campfire here on Earth. After all, any event that violently releases as much as 10 billion tons of solar material traveling up to four and a half million miles per hour or releases large amounts of electromagnetic radiation at extremely short wavelengths has to be considered pretty impressive!

Following the lead of the Space Weather Prediction Center, there are three types of disturbances to propagation: geomagnetic storms (designated G), solar radiation storms (designated S) and radio blackouts (designated R). For more details and the scaling associated with these designators, visit **www.swpc.noaa.gov/NOAAscales/**.

GEOMAGNETIC STORMS

Geomagnetic storms are generally caused by *coronal mass ejections* and high speed wind streams from *coronal holes*. A *coronal mass ejection* (CME) originates in the Sun's outer atmosphere — its corona. With several sophisticated satellites launched in the mid 1990s, we have gained powerful new tools to monitor the intricacies of solar activity. Using the latest satellite technology (and also some re-engineered earthbound instruments), scientists have observed many CMEs, greatly expanding our knowledge about them. Previously, the only direct observations we had of coronal activity were during solar eclipses — and eclipses don't occur very often. CMEs are observed with an instrument called a *coronagraph*, which has an occulting disk to block out the main portion of the Sun. In essence a coronagraph creates an artificial eclipse.

A *coronal hole* is a region on the Sun where the magnetic field is open to the interplanetary magnetic field (IMF) and ionized particles can escape into the solar wind. Normally the solar wind blows at approximately 400 km per second. During CMEs and coronal holes, solar wind speeds can increase to 2000 km per second.

Coronal holes and coronal mass ejections that are Earth-directed (these are also called full halo CMEs, as the explosion surrounds the occulting disk of a coronagraph) concurrent with the IMF oriented in a southerly direction result in the most disturbance to propagation. It usually takes up to a couple days for a CME or the effects of a coronal hole to reach and impact the Earth's ionosphere, so this generally gives us ample warning of the impending disturbance.

SOLAR RADIATION STORMS AND RADIO BLACKOUTS

Solar radiation storms and radio blackouts are caused by large *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 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 noise in the VHF radio bands. It is the X-ray radiation that results in radio blackouts on the daytime side of the Earth due to increased D region absorption, and this is called a *sudden ionospheric disturbance* (SID). The lower frequencies are affected for the longest period. In extreme cases, nearly all background noise will be gone as well. SIDs may last up to an hour, after which ionospheric conditions return to normal.

A large solar flare can also release matter into space, mainly in the form of very energetic protons. These cause solar radiation storms, whereby increased absorption in the polar cap (that area inside the auroral oval) degrades over-the-pole 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.

At one time, scientists believed that solar flares and CMEs were causally related, but now they recognize that many CMEs occur without an accompanying flare. And while many flares do result in an ejection of some solar material, many do not. It now seems clear that flares don't cause CMEs and vice versa.

Since geomagnetic storms have the most impact to propagation, it is instructive to understand their occurrence statistics. The number of geomagnetic storms varies considerably from year to year, but peak geomagnetic activity follows the peak of solar activity. See **Fig 19.12**. Also, geomagnetic activity affects the ionosphere mostly in the equinox months (March and September).
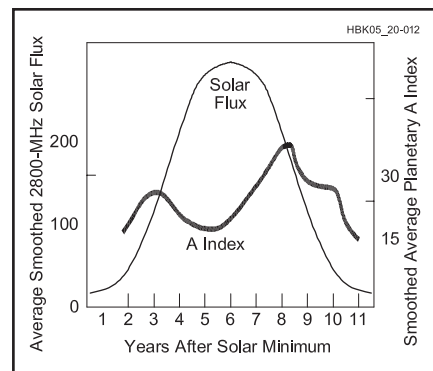
Fig 19.12 — Geomagnetic activity (measured as the A index) also follows an 11-year cycle. Average values over the past few cycles show that geomagnetic activity peaks before and after the peak of solar flux.

MONITORING GEOMAGNETIC ACTIVITY

Geomagnetic activity is monitored by devices known as *magnetometers*. These may be as simple as a magnetic compass rigged to record its movements. Small variations in the geomagnetic field are scaled to two measures known as the K and A indices. The *K index* provides an indication of magnetic activity on a finite logarithmic scale of 0-9, and it is updated every three hours. Very quiet conditions are reported as 0 or 1, while geomagnetic storm levels begin at 4. See **Table 19.3** for the latest NOAA descriptions of geomagnetic storms.

A worldwide network of magnetometers constantly monitors the Earth's magnetic field, because the Earth's magnetic field varies with location. K indices that indicate average planetary conditions are indicated as K_p. 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 indices after converting the K indices to a linear scale). The A index commonly varies between 0 and 30 during quiet to active conditions, and up to 100 or higher during geomagnetic storms.

At 18 minutes past the hour, radio station WWV broadcasts the solar flux measured at 2000 UTC, the prior day's planetary A Index and the latest mid latitude K Index. In addition,

Table 19.3

Geomagnetic Storms

Typical Kp	Description	Days per Solar Cycle
9	Extreme	4
8	Severe	60
7	Strong	130
6	Moderate	360
5	Minor	900

they broadcast a descriptive account of the condition of the geomagnetic field and a forecast for the next three hours. For more details about WWV broadcasts, visit **www.nist.gov/pml/div688/grp40/wwv_format.cfm**. You should keep in mind that the A Index is a description of what happened yesterday. Strictly speaking, the K Index is valid only for mid latitudes. However, the trend of the K Index is very important for propagation analysis and forecasting. A rising K foretells worsening HF propagation conditions, particularly for transpolar paths. At the same time, a rising K alerts VHF operators to the possibility of enhanced auroral activity, particularly when the K Index rises above 3. Another source of useful information about solar disturbances is **www.spaceweather.com**.

19.2.11 D Layer Propagation

The *D layer* is the lowest region of the ionosphere, situated between 55 and 90 km (30 and 60 miles). See **Fig 19.13**. It is ionized primarily by the strong emission of solar hydrogen at 121.5 nanometers and short-wavelength X-rays (so-called hard X-rays), both of which penetrate through the upper atmosphere to ionize nitric oxide (radiation at 121.5 nm) and all other constituents (hard X-rays). The D layer exists only during daylight, because constant radiation is needed to replenish ions that quickly recombine into neutral molecules. The D layer abruptly disappears at night so far as amateur MF and HF signals are concerned. D layer ionization varies a small amount over the solar cycle. It is unsuitable as a refracting medium for MF and HF radio signals, but it is very important for VLF signals.

During daylight hours, radio energy as high as 5 MHz is effectively absorbed by the D

Fig 19.13 — Typical electron densities for the various ionospheric regions.

layer, severely limiting the range of daytime 1.8- and 3.5 MHz signals. Signals at 7 MHz and 10 MHz pass through the D layer and on to the E and F layers only at relatively high angles. Low-angle waves, which must travel a much longer distance through the D layer, are subject to greater absorption. As the frequency increases above 10 MHz, radio waves pass through the D layer with increasing ease (less absorption).

D layer ionization falls 100-fold as soon as the Sun sets and the source of ionizing radiation is removed. Low-band HF signals are then free to pass through to the E layer (also greatly diminished at night) and on to the F layer, where the MUF is almost always high enough to propagate 1.8 and 3.5 MHz signals half way around the world. Long-distance propagation at 7 and 10 MHz generally improves at night as well, because absorption is less and low-angle waves are able to reach the F layer.

19.2.12 E Layer Propagation

The *E layer* lies between 90 and 150 km (60 and 90 miles) altitude, but a narrower region centered at 95 to 120 km (60 to 70 miles) is more important for radio propagation. In the E layer nitric oxide and molecular oxygen are ionized by short-wavelength UV and long-wavelength X-ray radiation (so-called soft X-rays). The normal E layer exists primarily during daylight hours, because like the D layer, it requires a constant source of ionizing radiation. Recombination is not as fast as in the denser D layer and absorption is much less. The E layer has a daytime critical frequency that varies between 3 and 4 MHz with the solar cycle. At night, the normal E layer 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 E LAYER

The E layer 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 layer skip might be useful between 5 and 20 MHz at distances up to 2300 km (1400 miles). In practice this is not the case, because the potential for E layer skip is severely limited by D layer 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 layer. Only high-angle signals pass through the D layer at these frequencies, but high-angle E layer skip is typically limited to 1200 km (750 miles) or so. Signals at 14 MHz penetrate the D layer 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 layer or higher-angle F layer propagation.

An astonishing variety of other propagation modes find their home in the E layer, and this perhaps more than makes up for its ordinary limitations. Each of these other modes — sporadic E, field-aligned irregularities, aurora, auroral E and meteor scatter — are related forms of E layer propagation with unique characteristics. They are primarily useful only on the highest HF and lower VHF bands.

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* (E_s), as this phenomenon is properly called, commonly propagates 28, 50 and 144 MHz radio signals between 500 and 2300 km (300 and 1400 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 km. During the most intense E_s events, skip may shorten to less than 200 km (120 miles) on the 10 meter band and disappear entirely on 15 meters. Multiple-hop E_s has supported contacts up to 10,000 km (6200 miles) on 28 and 50 MHz and more than 3000 km (1900 miles) on 144 MHz. The first confirmed 220 MHz E_s contact was made in June 1987, but such contacts are likely to remain very rare.

Sporadic E at mid latitudes (roughly 15° to 45°) may occur at any time, but it is most common in the Northern Hemisphere during May, June and July, with a less-intense season at the end of December and early January. Its appearance is independent of the solar cycle. Sporadic E 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. Mid latitude E_s events may last only a few minutes or can persist for many hours. In contrast, sporadic E is an almost constant feature of the polar regions at night and the equatorial belt during the day.

Efforts to predict mid latitude E_s have not been successful, probably because its causes are complex and not well understood. Studies have demonstrated that thin and unusually dense patches of ionization in the E layer, between 100 and 110 km (60 and 70 miles) altitude and 10 to 100 km (6 to 60 miles) in extent, are responsible for most E_s reflections. Sporadic E clouds may form suddenly, move quickly from their birthplace, and dissipate within a few hours. Professional studies have recently focused on the role of heavy metal ions, probably of meteoric origin, and wind shears as two key factors in creating the dense patchy regions of E layer ionization.

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 km (250 or 310 miles), it is an indication
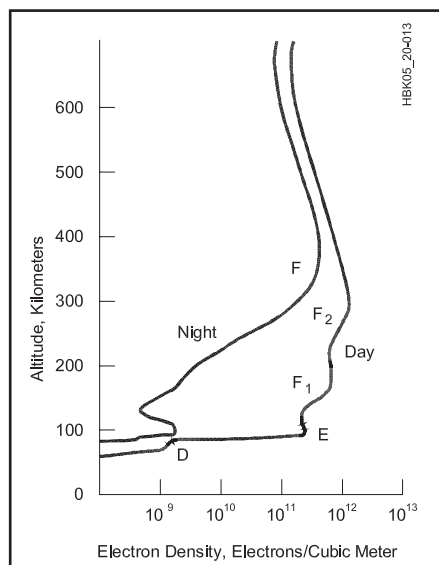
Fig 19.14 — 50 MHz sporadic E contacts of 700 km (435 miles) or shorter (such as between Peoria and Little Rock) indicate that the MUF on longer paths is above 144 MHz. Using the same sporadic E region reflecting point, 144 MHz contacts of 2200 km (1400 miles), such as between Pierre and Tallahassee, should be possible.

that the MUF has reached 50 MHz for longer paths at low launch angles. Contacts at the maximum one-hop sporadic E distance, about 2300 km (1400 miles), should then be possible at 50 MHz. *E-skip* (yet another term for sporadic E) contacts as short as 700 km (435 miles) on 50 MHz, in turn, may indicate that 144 MHz contacts in the 2300 km (1400 mile) range can be completed. See **Fig 19.14**. 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 the F_2 layer 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 sporadic E clouds can also have a masking effect, but they may also lengthen the F_2 propagation path with a top-side intermediate hop that never reaches the Earth.

E LAYER FIELD-ALIGNED IRREGULARITIES

Amateurs have experimented with a little-known scattering mode known as *field-aligned irregularities* (FAI) at 50 and 144 MHz since 1978. FAI commonly appears directly after

sporadic E events and may persist for several hours. Oblique-angle scattering becomes possible when electrons are compressed together due to the action of high-velocity ionospheric acoustic (sound) waves. The resulting irregularities in the distribution of free electrons are aligned parallel to the Earth's magnetic field, in something like moving vertical rods. A similar process of electron field-alignment takes place during radio aurora, making the two phenomena quite similar.

Most reports suggest that 8 PM to midnight may be the most productive time for FAI. Stations attempting FAI contacts point their antennas toward a common scattering region that corresponds to an active or recent E_s reflection point. The best direction must be probed experimentally, for the result is rarely along the great-circle path. Stations in south Florida, for example, have completed 144 MHz FAI contacts with north Texas when participating stations were beamed toward a common scattering region over northern Alabama.

FAI-propagated signals are weak and fluttery, reminiscent of aurora signals. Doppler shifts of as much as 3 kHz have been observed in some tests. Stations running as little as 100 W and a single Yagi should be able to complete FAI contacts during the most

favorable times, but higher power and larger antennas may yield better results. Contacts have been made on 50 and 144 MHz, and 222 MHz FAI seems probable as well. Expected maximum distances should be similar to other forms of E layer propagation, or about 2300 km (1400 miles).

AURORA

Radar signals as high as 3000 MHz 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 north toward the center of aurora activity, oblique paths between stations up to 2300 km (1400 miles) apart can be completed. See **Fig 19.15**. 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 south.

The appearance of auroras is closely linked to solar activity. During massive geomagnetic storms, low energy particles that were trapped in the magnetosphere flow into the atmosphere near the polar regions, where they ionize the gases of the E layer and higher. This unusual ionization produces spectacular visual auroral displays, which often spread southward into the mid latitudes. Higher energy electrons get down to lower altitudes to cause auroral ionization (via collisions with neutral particles) in the E layer, and this scatters radio signals in the VHF and UHF ranges.

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 most 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 high-speed wind streams from coronal holes). Radio aurora activity is usually heard first in late
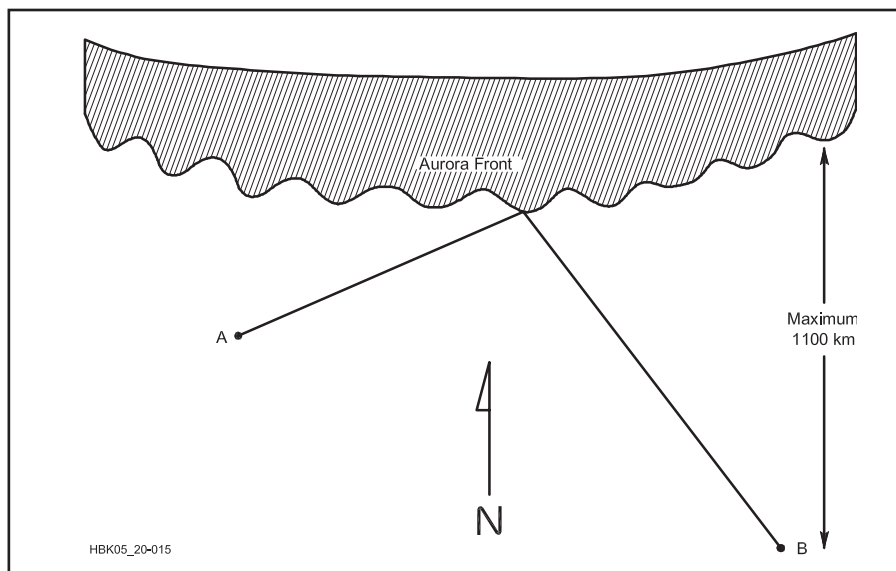
Fig 19.15 — Point antennas generally north to make oblique long-distance contacts on 28 through 432 MHz via aurora scattering. Optimal antenna headings may shift considerably to the east or west depending on the location of the aurora. This necessitates moving your antenna azimuth direction for best propagation, and continuing to do so as the aurora progresses.

afternoon and may reappear later in the evening. Auroras may be anticipated by following the A and K indices reports on WWV. A K index of five or greater and an A index of at least 30 are indications that a geomagnetic storm is in progress and an aurora likely. The probability, intensity and southerly extent of auroras increase as the two index numbers rise. Stations north of 42° latitude in North America experience many auroral openings each year, while those in the Gulf Coast states may hear auroral signals no more than once a year, if that often.

Aurora-scattered signals are easy to identify. On 28- and 50 MHz SSB, signals sound very distorted and somewhat wider than normal; at 144 MHz and above, the distortion may be so severe that only CW is useful. Auroral CW signals have a distinctive note variously described as a buzz, hiss or mushy sound. This characteristic auroral signal is due to Doppler broadening, caused by the movement of electrons within the aurora. An additional Doppler shift of 1 kHz or more may be evident at 144 MHz and several kilohertz at 432 MHz. This second Doppler shift is the result of massive electrical currents that sweep electrons toward the Sun side of the Earth during magnetic storms. Doppler shift and distortion increase with higher frequencies, while signal strength dramatically decreases.

It is not necessary to see an aurora to make auroral contacts. Useful auroras may be 500-1000 km (310-620 miles) away and below the visual horizon. Antennas should be pointed generally north and then probed east and west to peak signals, because auroral ionization is field aligned. This means that for any pair of stations, there is an optimal direction for aurora scatter. Offsets from north are usually greatest when the aurora is closest and often provide the longest contacts. There may be some advantage to antennas that can be elevated, especially when auroras are high in the sky.

AURORAL E

Radio auroras may evolve into a propagation mode known as *auroral E* at 21, 28, 50 and rarely 144 MHz. Auroral E is essentially sporadic E in the auroral zone. Doppler distortion disappears and signals take on the characteristics of sporadic E. The most effective antenna headings shift dramatically away from oblique aurora paths to direct great-circle bearings. The usual maximum distance is 2300 km (1400 miles), typical for E layer modes, but 28 and 50 MHz auroral E contacts of 5000 km (3100 miles) are sometimes made across Canada and the northern US, apparently using two hops. Contacts at 50 MHz between Alaska and the east coasts of Canada and the northern US have been completed this way. Transatlantic 50 MHz auroral E paths are also likely.

Typically, 28 and 50 MHz auroral E appears across the northern third of the US and southern Canada when aurora activity is diminishing. This usually happens after midnight on the eastern end of the path. Auroral E signals sometimes have a slightly hollow sound to them and build slowly in strength over an hour or two, but otherwise they are indistinguishable from sporadic E. Auroral E paths are almost always east-west oriented, perhaps because there are few stations at very northern latitudes to take advantage of this propagation. A common auroral E path on 28 MHz and 21 MHz is from North America in the late afternoon hours in the autumn months to the Scandinavian countries. This path is open when normal F layer propagation is not possible — even to more southern locations in Europe.

Auroral E may also appear while especially intense auroras are still in progress, as happened during the great aurora of March 1989. On that occasion, 50 MHz propagation shifted from Doppler-distorted aurora paths to clear-sounding auroral E over a period of a few minutes. Many 6 meter operators as far south as Florida and Southern California made single- and double-hop auroral E contacts across the country. At about the same time, the MUF reached 144 MHz for stations west of the Great Lakes to the Northeast, the first time auroral E had been reported so high in frequency.

METEOR SCATTER

Contacts between 800 and 2300 km (500 and 1400 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 km (12 miles) long in the E layer. 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 **Fig 19.16**. 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.
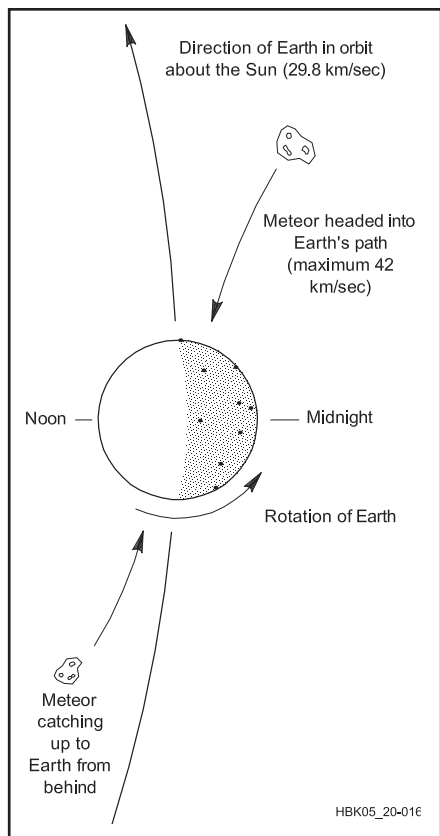
Fig 19.16 — The relative velocity of meteors that meet the Earth head-on is increased by the rotational velocity of the Earth in orbit. Fast meteors strike the morning side of the Earth because their velocity adds to the Earth's rotational velocity, while the relative velocity of meteors that "catch up from behind" is reduced.

Meteor scatter opportunities are somewhat better during July and August for North America because the average number of 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 ten-fold over the normal rate of five to ten per hour. See **Table 19.4**. 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

Table 19.4

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

showers are relatively consistent from year to year, although several can occasionally produce great storms.

Because meteors provide only fleeting moments of communication even during one of the great meteor showers, special operating techniques are often used to increase the chances of completing a contact. Prearranged schedules between two stations establish times, frequencies and precise operating standards. Usually, each station transmits on alternate 15-second periods until enough information is pieced together a bit at a time to confirm contact. High-speed Morse code of several hundred words per minute, generated and slowed down by special computer programs, can make effective use of very short meteor bursts. Non-scheduled random meteor contacts are common on 50 MHz and 144 MHz, but short transmissions and alert operating habits are required.

It is helpful to run several hundred watts to a single Yagi, but meteor-scatter can be used by modest stations under optimal conditions. During the best showers, a few watts and a small directional antenna are sufficient at 28 or 50 MHz. At 144 MHz, at least 100 W output and a long Yagi are needed for consistent results. Proportionately higher power is required for 222 and 432 MHz even under the best conditions.

A technique allowing even smaller VHF/UHF stations to take advantage of meteor scatter and other modes (ionospheric scatter and even moonbounce) is available in software called *WSJT*. This software uses the sound card in a PC and a variety of modulation and coding techniques to allow reception of signals up to 10 dB below your noise level. For more information, visit **www.physics.princeton.edu/pulsar/K1JT/**.

19.2.13 F Layer Propagation

The region of the *F layers*, from 150 km (90 miles) to over 400 km (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 layers. The F_1 layer forms between 150 and 250 km (90 and 160 miles), is most prevalent in the summer months, and disappears at night. The F_2 layer extends above 250 km (160 miles), with a peak of ionization around 300 km (190 miles). At night, F-region ionization collapses into one broad layer at 300-400 km (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.

F₁ LAYER

The daytime F_1 layer 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 layer, because they are either absorbed by the D layer or refracted by the E layer. Signals higher than 20 MHz that pass through both of the lower ionospheric regions are likely to pass through the F_1 layer 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 layer during the day. Some useful F_1 layer refraction may take place between 10 and 20 MHz during summer days, yielding paths as long as 3000 km (1900 miles), but these would be practically indistinguishable from F_2 skip.

F₂ AND NIGHTTIME F LAYERS

The F_2 layer forms between 250 and 400 km (160 and 250 miles) during the daytime and persists throughout the night as a single consolidated F region 50 km (30 miles) higher in altitude. Typical ion densities are the highest of any ionospheric layer, with the possible exception of some unusual E layer phenomenon. In contrast to the other ionospheric layers, 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 layer the most important for long-distance HF communications.

The F_2 layer 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 and stay above 14 MHz throughout the night. The virtual height of the F_2 region averages 330 km (210 miles), but varies between 200 and 400 km (120 and 250 miles). Maximum one-hop distance is about 4000 km (2500 miles). Near-vertical incidence skywave propagation just below the critical frequency provides reliable coverage out to 200-300 km (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 5000 to 12,000 km under certain conditions, but most operators will not be able to distinguish Pedersen Ray paths from normal F layer propagation. A Pederson ray is a path that follows the contour of the Earth near the height of the maximum F_2 region electron density, and requires a fairly stable ionosphere. Pedersen ray paths are most evident over high-latitude east-west paths at frequencies near the MUF.
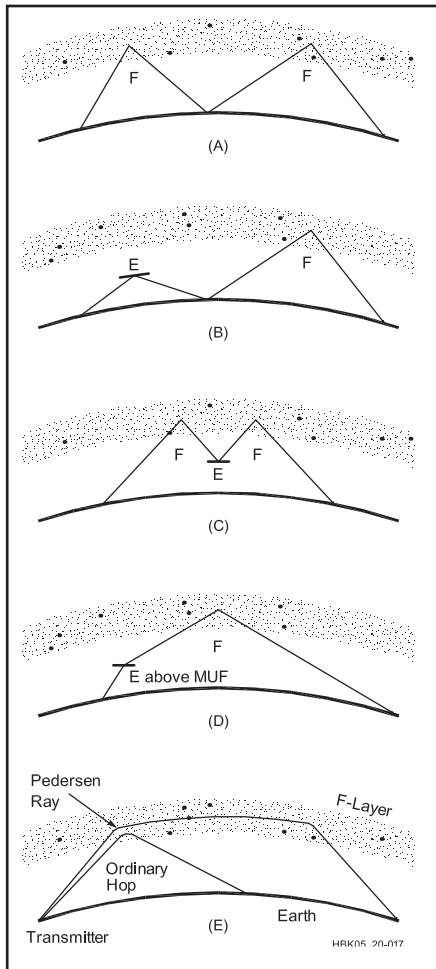
Fig 19.17 — Multihop paths can take many different configurations, including a mixture of E and F layer hops. (A) Two F layer hops. Five or more consecutive F layer hops are possible. (B) An E layer hookup to the F layer. (C) A top-side E layer reflection can shorten the distance of two F layer hops. (D) Refraction in the E layer above the MUF is insufficient to return the signal to Earth, but it can go on to be refracted in the F layer. (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, 5000 km (3100 miles) or more. This is considerably further than the normal 4000 km (2500 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 Fig 19.21 and Fig 19.22.

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 5000 km contacts. See part E in **Fig 19.17**.

At any given location on Earth, in general both F_2 layer 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 within 20° 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

In contrast to all the other ionospheric layers, daytime ionization in the winter F_2 layer 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 layer 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.

MULTIHOP F LAYER PROPAGATION

Most HF communication beyond 4000 km (2500 miles) takes place via multiple ionospheric hops. Radio signals are reflected from the Earth back toward space for additional ionospheric refractions. A series of ionospheric refractions and terrestrial reflections commonly create paths half-way 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 layer may at times bypass ground reflections altogether, creating what are known as *chordal hops*, with lower total attenuation. It takes a radio signal about 0.14 seconds to make an around-the-world trip.

Multihop paths can take on many different configurations, as shown in the examples of Fig 19.17. E layer (especially sporadic E) and F layer hops may be mixed. In practice, multihop 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 layer absorption, possible reflections from the tops of sporadic E layers, 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°). During the main part of the opening, the elevation angle is higher — generally in the range of 5° to 20°. This is why stations with extremely high antennas (which have higher gain at lower takeoff angles) perform better at band openings and closings.

F LAYER 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 km (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 km (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.

Sometimes there is 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 layer *blanketing* (when the E-region ionization is high enough to keep waves from penetrating, regardless of elevation angle), D layer absorption or F layer 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 layer MUFs that occur over the sunlit portions of the Earth.

F LAYER GRAY-LINE

Gray-line paths can be considered a special form of long-path propagation that takes 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. It is not precisely a line, for the distinction between daylight and darkness is a gradual transition due to atmospheric scattering. On one side, the gray line heralds sunrise and the beginning of a new day; on the opposite side, it marks sunset and the end of the day.

The ionosphere undergoes a significant transformation between night and day. As day begins, the highly absorbent D and E layers are recreated, while the F layer MUF rises from its pre-dawn minimum. At the end of the day, the D and E layers quickly disappear, while the F layer MUF continues its slow decline from late afternoon. For a brief period just along the gray-line transition, the D and E layers are not well formed, yet the F_2 MUF usually remains higher than 5 MHz. This provides a special opportunity for stations at 1.8 and 3.5 MHz.
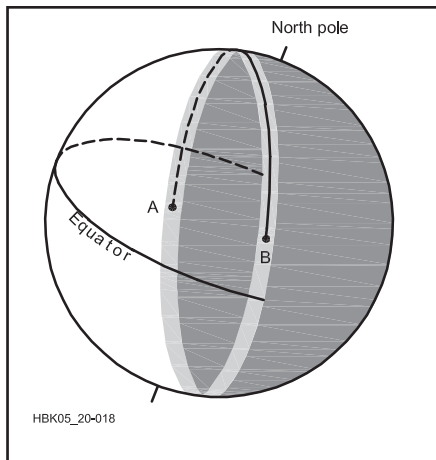
Fig 19.18 — The gray line encircles the Earth, but the tilt at the equator to the poles varies over 46° with the seasons. Long-distance contacts can often be made halfway around the Earth along the gray line, even as low as 1.8 and 3.5 MHz. The strength of the signals, characteristic of gray-line propagation, indicates that multiple Earth-ionosphere hops are not the only mode of propagation, since losses in many such hops would be very great. Chordal hops, where the signals are confined to the ionosphere for at least part of the journey, may be involved.
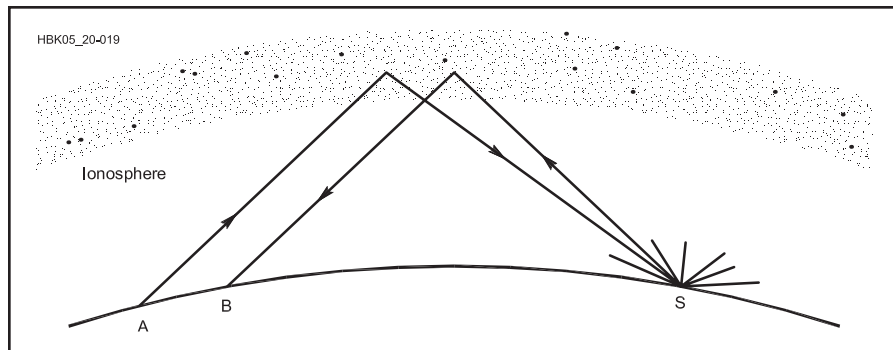

Fig 19.19 — Schematic of a simple backscatter path. Stations A and B are too close to make contact via normal F layer ionospheric refraction. Signals scattered back from a distant point on the Earth's surface (S), often the ocean, may be accessible to both and create a backscatter circuit.
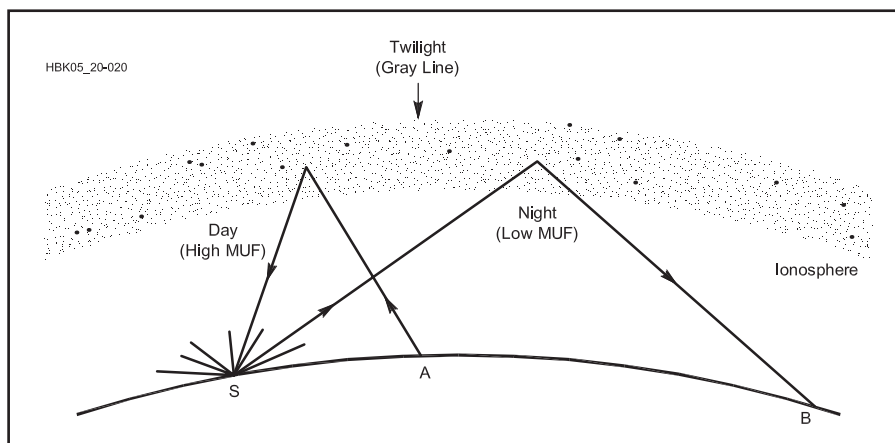

Fig 19.20 — Backscatter path across the gray line. Stations A and B are too close to make contact via normal ionospheric refraction, but may hear each other's signals scattered from point S. Station A makes use of a high-angle refraction on the day side of the gray line, where the MUF is high. Station B makes use of a night-time refraction, with a lower MUF and lower angle of propagation. Note that station A points away from B to complete the circuit.

Normally, long-distance communication on the lowest two amateur bands can take place only via all-darkness paths because of daytime D layer absorption. The gray-line propagation path, in contrast, extends completely around the world. See **Fig 19.18**. This unusual situation lasts less than an hour at sunrise and sunset when the D layer is largely absent, and may support contacts that are difficult or impossible at other times.

The gray line generally runs north-south, but it varies by 23° 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° extremes on June 21 and December 20. Over a one-year period, the gray line crosses a 46° 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.

A web based application to calculate worldwide sunrise and sunset times is available at **http://aa.usno.navy.mil/data/docs/RS_OneDay.html**. An alternative method of determining sunrise and sunset times, along with seeing great circle paths on the same plot, is W6EL's *W6ELProp* software, available free at **www.qsl.net/w6elprop**. For an online gray line map, visit **http://dx.qsl.net/propagation/greyline.html**.

F LAYER BACKSCATTER AND SIDESCATTER

Special forms of F layer scattering can create unusual paths within the skip zone. *Backscatter* and *sidescatter* signals are usually observed just below the MUF for the direct path and allow communications not normally possible by other means. Stations using backscatter point their antennas toward a common scattering region at the one-hop distance, rather than toward each other. Backscattered signals are generally weak and have a characteristic hollow sound. Useful communication distances range from 100 km (60 miles) to the normal one-hop distance of 4000 km (2500 miles).

Backscatter and sidescatter are closely related and the terminology does not precisely distinguish between the two. Backscatter usually refers to single-hop signals that have been scattered by the Earth or the ocean at some distant point back toward the transmitting station. Two stations spaced a few hundred km apart can often communicate via a backscatter path near the MUF. See **Fig 19.19**.

Sidescatter usually refers to a circuit that is oblique to the normal great-circle path and is sometimes referred to as *skew path*. Two stations can make use of a common side-scattering region well off the direct path, often toward the south. European and North American stations sometimes complete 28 MHz contacts via a scattering region over Africa. U.S. and Finnish 50 MHz operators observed a similar effect early one morning in November 1989 when they made contact by beaming off the coast of West Africa.

When backscattered signals cross an area where there is a sharp gradient in ionospheric
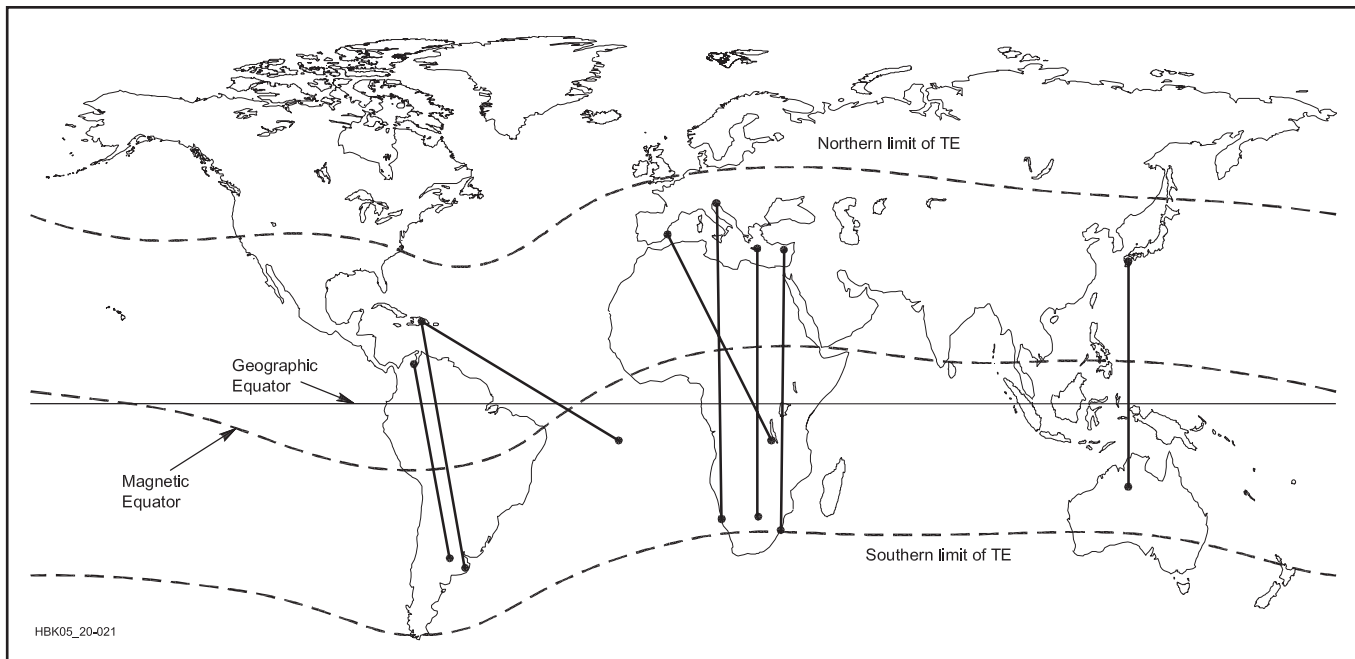
Fig 19.21 — Transequatorial propagation takes place between stations equidistant across the geomagnetic equator. Distances up to 8000 km (5000 miles) are possible on 28 through 432 MHz. Note the geomagnetic equator is considerably south of the geographic equator in the Western Hemisphere.
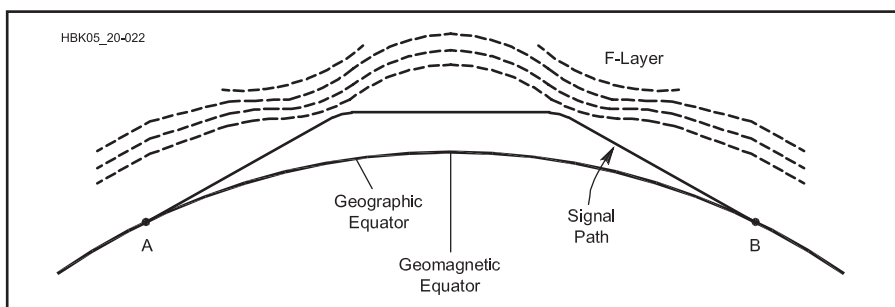

Fig 19.22 — Cross-section of a transequatorial signal path, showing the effects of ionospheric bulging and a double refraction above the normal MUF.

density, such as between night and day, the path may take on a different geometry, as shown in **Fig 19.20**. In this case, stations can communicate because backscattered signals return via the day side ionosphere on a shorter hop than the night side. This is possible because the dayside MUF is higher and thus the skip distance shorter. The net effect is to create a backscatter path between two stations within the normal skip zone.

TRANSEQUATORIAL PROPAGATION

Discovered by Amateur Radio operators in 1947, *transequatorial propagation* (commonly abbreviated TE or TEP) supports propagation between 5000 and 8000 km (3100 and 5000 miles) across the magnetic equator from 28 MHz to as high as 432 MHz. 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.

Unfortunately for most continental US stations, the *geomagnetic equator* dips south of the geographic equator in the Western Hemisphere, as shown in **Fig 19.21**, making only the most southerly portions of Florida and Texas within TE range. TE contacts from the southeastern part of the country may be possible with Argentina, Chile and even South Africa.

Transequatorial propagation peaks between 5 PM and 10 PM during the spring and fall equinoxes, especially during the peak years of the solar cycle. The lowest probability is during the summer. 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.

TE propagation depends on bulges of intense F_2 layer 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 km (60-120 miles) north and south of the geomagnetic equator and 500-3000 km (310-1900 miles) wide. It moves west with the setting Sun. The MUF may increase to twice its normal level 15° either side of the geomagnetic equator. See **Fig 19.22**.

19.2.14 Emerging Theories of HF and VHF Propagation

Although much is known about the ionosphere and propagation, there are still many instances of unusual propagation that cannot be easily explained with our textbook knowledge. It is encouraging to note that Amateur Radio operators continue to be at the forefront of trying to understand many of these unusual modes. Several recent studies have included:

1) The tie between polar mesospheric summer echoes and 6 meter propagation in "Polar Mesospheric Summer Echoes," *Worldradio On-Line*, Feb 2009, **www.cq-amateur-radio.com**. These summer echoes are also called SSSP (summer solstice short path), a mode that Japanese amateurs have noted.

2) Theta aurora and 6 meter propagation across the polar cap in "More Alaska to EU on 6 m," at **http://myplace.frontier.com/~k9la**.

3) The impact of galactic cosmic rays

on 160 meter *ducting* in "A Theory on the Role of Galactic Cosmic Rays in 160-Meter Propagation," *CQ*, Nov 2008. *Ducting* refers to an electromagnetic wave successively refracting between a lower boundary and an upper boundary (for example, between the top of the E region and the bottom of the F region for 160 meters at night)

4) Discovery of single-day enhancements in the F_2 region that do not be appear to be tied to geomagnetic activity. This came from an interesting paper that was published in the *Journal of Geophysical Research* in late 2010. The paper was by Michael David and Jan J. Sojka, who were with the Center for Atmospheric and Space Sciences at Utah State University. The title of the paper is "Single-day dayside density enhancements over Europe: A survey of a half-century of ionosonde data."

5) Although not a propagation issue, there is evidence that we may have missed a small solar cycle way back in the 1790 time frame. See the *WorldRadio Online* Propagation column by Carl Luetzelschwab K9LA, November 2011.

6) Another topic not tied directly to propagation is the on-going research into better models of the ionosphere. We already pretty much understand solar radiation and we've recently developed a much better model of how elevated geomagnetic indices affect the ionosphere (it's not simply applying a single K index). Research is on-going to better understand the physics behind events in the lower atmosphere coupling up to the ionosphere. Understanding these three processes is leading the way towards a true daily model of the ionosphere.

19.3 MUF Predictions

F layer 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.

19.3.1 MUF Forecasts

Long-range forecasts several months ahead provide only the most general form of prediction. A series of 48 charts on the members-only ARRL website (**www.arrl.org/propagation**), similar to **Fig 19.23**, forecast average propagation for a one-month period over specific paths. The charts assume a single average solar flux value for the entire month and they assume that the geomagnetic field is undisturbed.

The uppermost curve in Fig 19.23 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 forecasts of a few days ahead are marginally more reliable than long-range forecasts, because underlying solar indices and geomagnetic conditions can be anticipated with greater confidence. The tendency for solar disturbances to recur at 27-day intervals may enhance short-term forecasts. 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 indices. Regardless of these limitations, it is always good to know the current solar and

Fig 19.23 — Propagation prediction chart for East Coast to Eastern Europe from the ARRL web members-only site 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 1500-W CW transmitter.

geophysical data, as well as understanding warnings provided by observations of the Sun in the visual to X-ray range.

The CD-ROM bundled with *The ARRL Antenna Book* contains even more detailed propagation-prediction tables from more than 150 locations around the world for six levels of solar activity, for the 12 months of the year. Again, keep in mind that these long-range forecasts assume quiet geomagnetic conditions. Real-time MUF forecasts are also available in a variety of text and graphical forms on the web. Forecasts can also be made by individuals using one of several popular programs for personal computers, including *ASAPS*, *VOACAP*, and *W6ELProp*. (See the sidebar, "MUF Prediction on the Home Computer.")

19.3.2 Statistical Nature of Propagation Predictions

The model of the ionosphere in propagation prediction software is a monthly median model — thus the results (usually MUF and signal strength) are statistical over a month's time frame. The median aspect means that the predicted value will actually occur on at least half the days of the month — but unfortunately it's tough to tell which are the "better" days and which are the "worse" days.

This monthly median model came about due to the efforts of scientists to correlate what the ionosphere was doing to what the Sun was doing. The best correlation was between a smoothed solar index (smoothed sunspot number or smoothed 10.7 cm solar flux) and monthly median ionospheric parameters. Thus our propagation prediction software was never intended to give daily predictions. One good way to achieve better short-term predictions is to use the concept of an effective sunspot number — SSNe.

EFFECTIVE SUNSPOT NUMBER (SSNe)

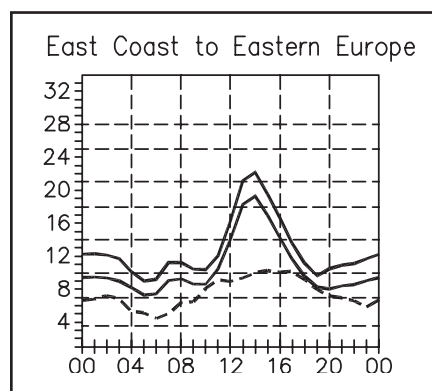The concept of SSNe is quite simple. The

F_2 layer critical frequency data from worldwide ionosondes is monitored, and then the sunspot number in an F_2 layer model of the ionosphere is varied until it provides a best fit to the monitored data. The current SSNe comes from Northwest Research Associates in Tucson (AZ), and can be found at **www. nwra.com/spawx/ssne.html**. By plugging the current SSNe into your favorite propagation prediction program, you will have a better (but not perfect) picture of what the ionosphere is doing "now."

19.3.3 Direct Observation

Propagation conditions can be determined directly by listening to the HF bands. The simplest method is to tune higher in frequency until no more long-distance stations are heard. This point is roughly just above the MUF to anywhere in the world at that moment. The highest usable amateur band would be the next lowest one. If HF stations seem to disappear around 23 MHz, for example, the 15 meter band at 21 MHz might make a good choice for DXing. By carefully noting station locations as well, the MUF in various directions can also be determined quickly.

The shortwave broadcast bands (see **Table 19.5**) are most convenient for MUF browsing, because there are many high-powered stations on regular schedules. Take care to ensure that programming is actually transmitted from the originating country. A Radio Moscow or BBC program, for example, may be relayed to a transmitter outside Russia or England for retransmission. An excellent guide to shortwave broadcast stations is the *World Radio TV Handbook*, available through the ARRL.

19.3.4 WWV and WWVH

The standard time stations WWV (Fort Collins, Colorado) and WWVH (Kauai, Hawaii), which transmit on 2.5, 5, 10, 15 and 20 MHz, are also 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 indices, 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. The same information, along with a lot more space weather information, is available at various websites, such as **www.swpc.noaa.gov** or **www.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.

19.3.5 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 website **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 subbands for signals that are automatically decoded by *CW Skimmer* software by VE3NEA (**www.dxatlas.com/ cwskimmer**). 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 subbands can be useful. **Table 19.6** provides the frequencies

Table 19.5
Shortwave Broadcasting Bands

Frequency (MHz)	Band (meters)
2.300-2.495	120
3.200-3.400	90
3.900-4.000	75
4.750-5.060	60
5.959-6.200	49
7.100-7.300	41
9.500-9.900	31
11.650-12.050	25
13.600-13.800	22
15.100-15.600	19
17.550-17.900	16
21.450-21.850	13
25.600-26.100	11

Table 19.6
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

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**.

19.3.6 Space Weather Information

Living in the space age results in a wealth of information about the Sun-Earth environment. Not only do we have measurements available, but we also have extensive tutorials available on what is being measured, how it is measured, and its general impact to propagation.

SPACE WEATHER SATELLITES

Three of the most beneficial satellites for propagation information are the Advanced Composition Explorer (ACE), the Solar and Heliospheric Observatory (SOHO), and the STEREO mission.

ACE is on a line from the Earth to the Sun, and is about 1 million miles from the Earth. Its primary purpose is to measure solar wind characteristics. For example, it measures the direction of the IMF (interplanetary magnetic field), the solar wind speed, and the dynamic solar wind pressure. More detailed information about ACE can be found at **www.srl.caltech. edu/ACE/**.

SOHO moves around the Sun in step with Earth — it always faces the Sun. Its primary purpose is to study the Sun. For example, it views coronal mass ejections, and in conjunction with the Michelson Doppler Imager (MDI), allows scientists to "see" sunspots on the far side of the Sun. More detailed information about SOHO and MDI can be found at **http://sohowww.nascom.nasa.gov** and **http://soi.stanford.edu**, respectively.

The STEREO mission consists of two spacecraft that are in heliocentric orbits leading and lagging the Earth. Each spacecraft provides a unique observing vantage point, and taken together, they enable a stereoscopic view of the Sun, solar activity, and the solar environment between the Sun and Earth. More information can be found at **www.swpc.noaa.gov/stereo.**

More satellite data can be found at **www. swpc.noaa.gov** and at **www.spaceweather. com**.

MUF Prediction on the Home Computer

Like predicting the weather, predicting HF propagation — even with the best computer software available — is not an exact science. The processes occurring as a signal is propagated 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 ordinary computer programs are written mainly to calculate propagation for great-circle paths via the F layer. Scatter, skew-path, auroral and other such propagation modes may provide contacts when computer predictions indicate no contacts are possible.

What follows is some brief information about commercially available propagation-prediction programs for the IBM PC and compatible computers. See **Table 19.A**. 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.

You may find an article that appeared in the Summer 2008 issue of *CQ VHF* to be helpful with your 6m endeavors: "Predicting 6-meter F_2 Propagation," by Carl Luetzelschwab, K9LA.

ASAPS Version 6.1

An agency of the Australian government has developed the *ASAPS* program, which stands for Advanced Stand-Alone Prediction System. It rivals *IONCAP* (see below) in its analysis capability and in its prediction accuracy. It is a *Windows* program that interacts reasonably well with the user, once you become accustomed to the acronyms used. If you change transmit power levels, antennas and other parameters, you can see the new results almost instantly without further menu entries. Available from IPS Radio and Space Services. See **www.ips.gov.au/Products_and_Services/1/1**.

IONCAP and VOACAP

IONCAP, short for Ionospheric Communications Analysis and Prediction, was written by an agency of the US government and has been under development for about 30 years in one form or another. 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. Greg Hand is now retired, but considerable documentation can be found at the website referenced below, along with links to other VOACAP-related websites. Although *VOACAP* is not specifically designed for amateurs (and thus doesn't include some features that amateurs are fond of, such as entry of locations by ham radio call signs and multiple receiving antennas), it is available for free by downloading from **http://elbert.its.bldrdoc.gov/hf.html**.

W6ELProp, Version 2.70

In 2001, W6EL ported his well known *MINIPROP PLUS* program into the *Windows* world. It uses the same Fricker-based F_2 region computation engine as its predecessor. (This method was developed by Raymond Fricker of the BBC.) *W6ELProp* has a highly intuitive, ham-friendly user interface. It produces detailed output tables, along with a number of useful charts and maps, including the unique and useful "frequency map," which shows the global MUFs from a given transmitting location for a particular month/day/time and solar-activity level. *W6ELProp* is available for free by downloading from **www.qsl.net/w6elprop**.

PropLab Pro, Version 3.0

PropLab Pro by Solar Terrestrial Dispatch represents the high end of propagation-prediction programs. It is the only

19.4 Propagation in the Troposphere

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.

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 change 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 1.15 times farther away than the visual horizon. Under unusual conditions, tropospheric refraction may extend this range significantly.

commercial program presently available that can do complete 3D ray tracing through the ionosphere, even taking complex geomagnetic effects and electron-neutral collisions (what causes absorption) into account. The number of computations is huge, especially in the full-blown 3D mode and operation can be slow and tedious. The *Windows* based user interface is easier to use than previous versions, which were complex and difficult to learn. It is fascinating to see exactly how a signal can bend off-azimuth or how it can split into the ordinary and extraordinary waves. It is best considered a propagation analysis tool, as opposed to a propagation prediction program. See **www.spacew.com/proplab**.

Table 19.A

Features and Attributes of Several Currently Available Propagation Prediction Programs

	ASAPS V. 6.1	VOACAP Windows	W6ELProp V. 2.70	PropLab Pro 3.0
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	$AUD350[1]	free[2]	free[3]	$240[4]

Prices are for early 2013 and are subject to change.

[1]See **www.ips.gov.au/Products_and_Services/1/1**. Be advised that the price will depend on the exchange rate.
[2]*VOACAP* available at **elbert.its.bldrdoc.gov/hf.html**
[3]*W6ELProp*, see **www.qsl.net/w6elprop**
[4]*PropLab Pro V3*, see **www.spacew.com/proplab/index.html**

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
h = height above average terrain, ft.

and

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

where

d = distance to the radio horizon, km
h = height above average terrain, m.

The distance to the radio horizon for an antenna 30 meters (98 ft) above average terrain is thus 22.6 km (14 miles). A station on top of a 1000 meter (3280 ft) mountain has a radio horizon of 130 km (80 miles).

ATMOSPHERIC ABSORPTION

Atmospheric gases, most notably oxygen and water vapor, absorb radio signals, but neither is a significant factor below 10 GHz. See

Fig 19.24. Attenuation from rain becomes important at 3.3 GHz, where signals passing through 20 km (12 miles) of heavy showers incur an additional 0.2 dB loss. That same rain would impose 12 dB additional losses at 10 GHz and losses continue to increase with frequency. Heavy fog is similarly a problem only at 5.6 GHz and above.

19.4.2 Tropospheric Scatter

Contacts beyond the radio horizon out to a working distance of 100 to 500 km (60-310 miles), depending on frequency, equip-
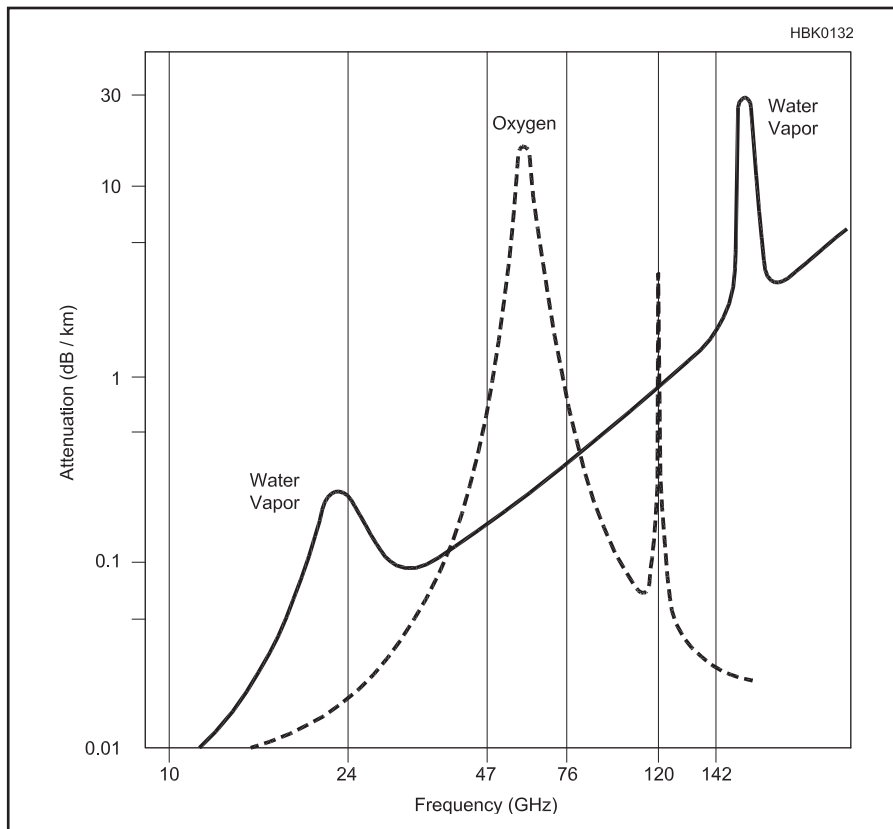
Fig 19.24 — Attenuation caused by oxygen and water vapor at 10 grams per cubic meter (equivalent to 40% humidity at 25 °C). There is little attenuation caused by atmospheric gases at 10 GHz and lower. Note that the 24 GHz band lies near the center of a peak of water vapor absorption and the 120 GHz band is near a peak of oxygen absorption.
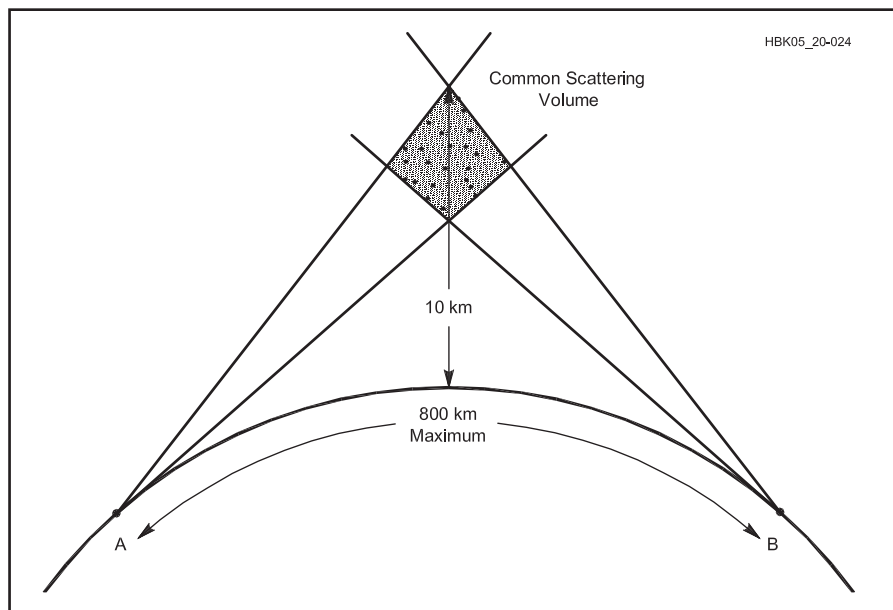

Fig 19.25 — Tropospheric-scatter path geometry. The lower boundary of the common scattering volume is limited by the take-off angle of both stations. The upper boundary of 10 km (6 miles) altitude is the limit of efficient scattering in the troposphere. Signal strength increases with the scattering volume.

ment and local geography, are made every day without the aid of obvious propagation enhancement. At 1.8 and 3.5 MHz, local communication is due mostly to ground wave. At higher frequencies, especially in the VHF range and above, the primary mechanism is scattering in the troposphere, or *troposcatter*.

Most amateurs are unaware that they use troposcatter even though it plays an essential role in most local communication. Radio signals through the VHF range are scattered primarily by wavelength sized gradients in the index of refraction of the lower atmosphere due to turbulence, along with changes in temperature. Radio signals in the microwave region can also be scattered by rain, snow, fog, clouds and dust. That tiny part that is scattered forward and toward the Earth creates the over-the-horizon paths. Troposcatter path losses are considerable and increase with frequency.

The maximum distance that can be linked via troposcatter is limited by the height of a scattering volume common to two stations, shown schematically in **Fig 19.25**. The highest altitude for which scattering is efficient at amateur power levels is about 10 km (6 miles). An application of the distance-to-the-horizon formula yields 800 km (500 miles) as the limit for troposcatter paths, but typical maxima are about half that. Tropospheric scatter varies little with season or time of day, but it is difficult to assess the effect of weather on troposcatter alone. Variations in tropospheric refraction, which is very sensitive to the weather, probably account for most of the observed day-to-day differences in troposcatter signal strength.

Troposcatter does not require special operating techniques or equipment, as it is used unwittingly all the time. In the absence of all other forms of propagation, especially at VHF and above, the usual working range is essentially the maximum troposcatter distance. Ordinary working range increases most dramatically with antenna height, because that lowers the take-off angle to the horizon. Working range increases less quickly with antenna gain and transmitter power. For this reason, a mountaintop is the choice location for extending ordinary troposcatter working distances.

RAIN SCATTER IN THE TROPOSPHERE

Scatter from raindrops is a special case of troposcatter practical in the 3.3 to 24 GHz range. Stations simply point their antennas toward a common area of rain. A certain portion of radio energy is scattered by the raindrops, making possible over-the-horizon or obstructed-path contacts, even with low power. The theoretical range for rain scatter is as great as 600 km (370 miles), but the experience of amateurs in the microwave bands suggests that expected distances are less than 200 km (120 miles). Snow and hail make less efficient scattering media unless the ice particles are

partially melted. Smoke and dust particles are too small for extraordinary scattering, even in the microwave bands.

19.4.3 Refraction and Ducting in the Troposphere

Radio waves are refracted by natural gradients in the index of refraction of air with altitude, due to changes in temperature, humidity and pressure. Refraction under standard atmospheric conditions extends the radio horizon somewhat beyond the visual line of sight. Favorable weather conditions further enhance normal tropospheric refraction, lengthening the useful VHF and UHF range by several hundred kilometers and increasing signal strength. Higher frequencies are more sensitive to refraction, so its effects may be observed in the microwave bands before they are apparent at lower frequencies.

Ducting takes place when refraction is so great that radio waves are bent back to the surface of the Earth. When tropospheric ducting conditions exist over a wide geographic area, signals may remain very strong over distances of 1500 km (930 miles) or more. Ducting results from the gradient created by a sharp increase in temperature with altitude, quite the opposite of normal atmospheric conditions. A simultaneous drop in humidity contributes to increased refractivity.

Normally the temperature steadily decreases with altitude, but at times there is a small portion of the troposphere in which the temperature increases and then again begins decreasing normally. This is called an *inversion*. Useful temperature inversions form between 250 and 2000 meters (800-6500 ft) above ground. The elevated inversion and the Earth's surface act something like the boundaries of a natural open-ended waveguide. Radio waves of the right frequency range caught inside the duct will be propagated for long distances with relatively low losses. Several common weather conditions can create temperature inversions.

RADIATION INVERSIONS IN THE TROPOSPHERE

Radiation inversions are probably the most common and widespread of the various weather conditions that affect propagation. Radiation inversions form only over land after sunset as a result of progressive cooling of the air near the Earth's surface. As the Earth cools by radiating heat into space, the air just above the ground is cooled in turn. At higher altitudes, the air remains relatively warmer, thus creating the inversion. A typical radiation-inversion temperature profile is shown in **Fig 19.26A**.

The cooling process may continue through the evening and predawn hours, creating inversions that extend as high as 500 meters (1500 ft). Deep radiation inversions are most common during clear, calm, summer evenings.
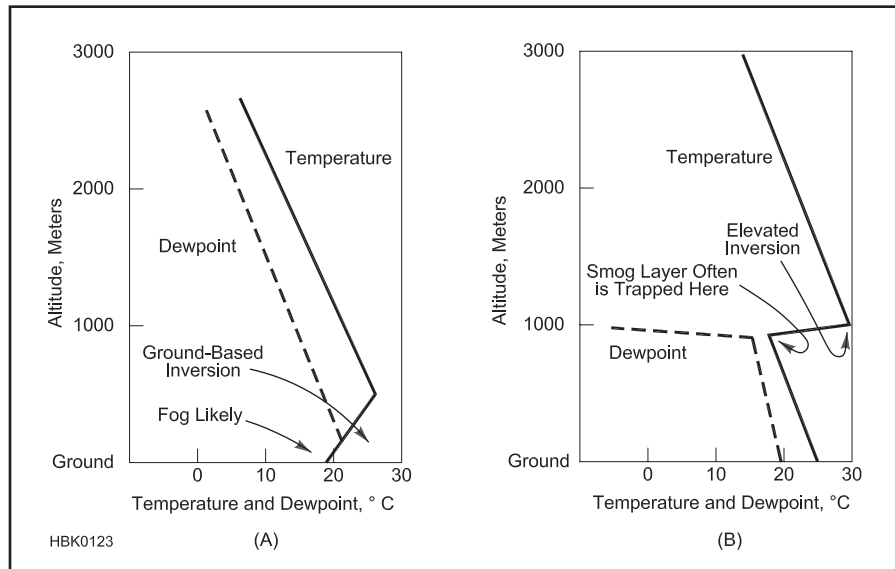

Fig 19.26 — Temperature and dew point profile of an early-morning radiation inversion is shown at A. Fog may form near the ground. The midday surface temperature would be at least 30 °C. At B, temperature and humidity profile across an elevated duct at 1000 meters altitude. Such inversions typically form in summertime high-pressure systems. Note the air is very dry in the inversion.

They are more distinct in dry climates, in valleys and over open ground. Their formation is inhibited by wind, wet ground and cloud cover. Although radiation inversions are common and widespread, they are rarely strong enough to cause true ducting. The enhanced conditions so often observed after sunset during the summer are usually a result of this mild kind of inversion.

HIGH-PRESSURE WEATHER SYSTEMS

Large, sluggish, high-pressure systems (or *anticyclones*) create the most dramatic and widespread tropospheric ducts due to *subsidence*. Subsidence inversions in high-pressure systems are created by air that is sinking. As air descends, it is compressed and heated. Layers of warmer air — temperature inversions — often form between 500 and 3000 meters (1500-10,000 ft) altitude, as shown in Fig 19.26B. Ducts usually intensify during the evening and early morning hours, when surface temperatures drop and suppress the tendency for daytime ground-warmed air to rise. In the Northern Hemisphere, the longest and strongest radio paths usually lie to the south of high-pressure centers. See **Fig 19.27**.
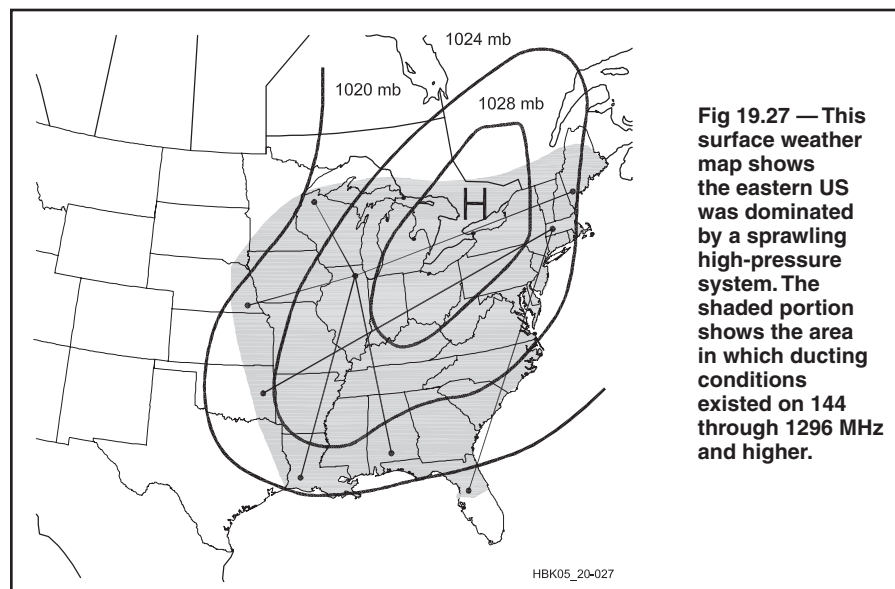

Fig 19.27 — This surface weather map shows the eastern US was dominated by a sprawling high-pressure system. The shaded portion shows the area in which ducting conditions existed on 144 through 1296 MHz and higher.

Sluggish high-pressure systems likely to contain strong temperature inversions are common in late summer over the eastern half of the US. They generally move southeastward out of Canada and linger for days over the Midwest, providing many hours of extended propagation. The southeastern part of the country and the lower Midwest experience the most high-pressure openings; the upper Midwest and East Coast somewhat less frequently; the western mountain regions rarely.

Semi-permanent high-pressure systems, which are nearly constant climatic features in certain parts of the world, sustain the longest and most exciting ducting paths. The Eastern Pacific High, which migrates northward off the coast of California during the summer, has been responsible for the longest ducting paths reported to date. Countless contacts in the 4000 km (2500 mile) range have been made from 144 MHz through 5.6 GHz between California and Hawaii. The *Bermuda High* is a nearly permanent feature of the Caribbean area, but during the summer it moves north and often covers the southeastern US. It has supported contacts in excess of 2800 km (1700 miles) from Florida and the Carolinas to the West Indies, but its full potential has not been exploited. Other semi-permanent highs lie in the Indian Ocean, the western Pacific and off the coast of western Africa.

WAVE CYCLONE

The *wave cyclone* is a more dynamic weather system that usually appears during the spring over the middle part of the American continent. The wave begins as a disturbance along a boundary between cooler northern and warmer southern air masses. Southwest of the disturbance, a cold front forms and moves rapidly eastward, while a warm front moves slowly northward on the eastward side. When the wave is in its open position, as shown in **Fig 19.28**, north-south radio paths 1500 km (930 miles) and longer may be possible in the area to the east of the cold front and south of the warm front, known as the warm sector. East-west paths nearly as long may also open in the southerly parts of the warm sector.

Wave cyclones are rarely productive for more than a day in any given place, because the eastward-moving cold front eventually closes off the warm sector. Wave-cyclone temperature inversions are created by a southwesterly flow of warm, dry air above 1000 meters (3200 ft) that covers relatively cooler and moister Gulf air flowing northward near the Earth's surface. Successive waves spaced two or three days apart may form along the same frontal boundary.

WARM FRONTS AND COLD FRONTS

Warm fronts and cold fronts sometimes bring enhanced tropospheric conditions, but rarely true ducting. A warm front marks the surface boundary between a mass of warm air flowing over an area of relatively cooler and more stationary air. Inversion conditions may be stable enough several hundred kilometers ahead of the warm front to create extraordinary paths.

A cold front marks the surface boundary between a mass of cool air that is wedging itself under more stationary warm air. The warmer air is pushed aloft in a narrow band behind the cold front, creating a strong but highly unstable temperature inversion. The best chance for enhancement occurs parallel to and behind the passing cold front.

OTHER CONDITIONS ASSOCIATED WITH DUCTS

Certain kinds of wind may also create useful inversions. The *Chinook* wind that blows off the eastern slopes of the Rockies can flood the Great Plains with warm and very dry air, primarily in the springtime. If the ground is cool or snow-covered, a strong inversion can extend as far as Canada to Texas and east to the Mississippi River. Similar kinds of *foehn* winds, as these mountain breezes are called, can be found in the Alps, Caucasus Mountains and other places.

The *land breeze* is a light, steady, cool wind that commonly blows up to 50 km (30 miles) inland from the oceans, although the distance may be greater in some circumstances. Land breezes develop after sunset on clear summer evenings. The land cools more quickly than the adjacent ocean. Air cooled over the land flows near the surface of the Earth toward the ocean to displace relatively warmer air that is rising. See **Fig 19.29**. The warmer ocean air, in turn, travels at 200-300 meters (600-1000 ft) altitude to replace the cool surface air. The land-sea circulation of cool air near the ground and warm air aloft creates a mild inversion that may remain for hours. Land-breeze inversions often bring enhanced conditions and occasionally allow contacts in excess of 800 km (500 miles) along coastal areas.
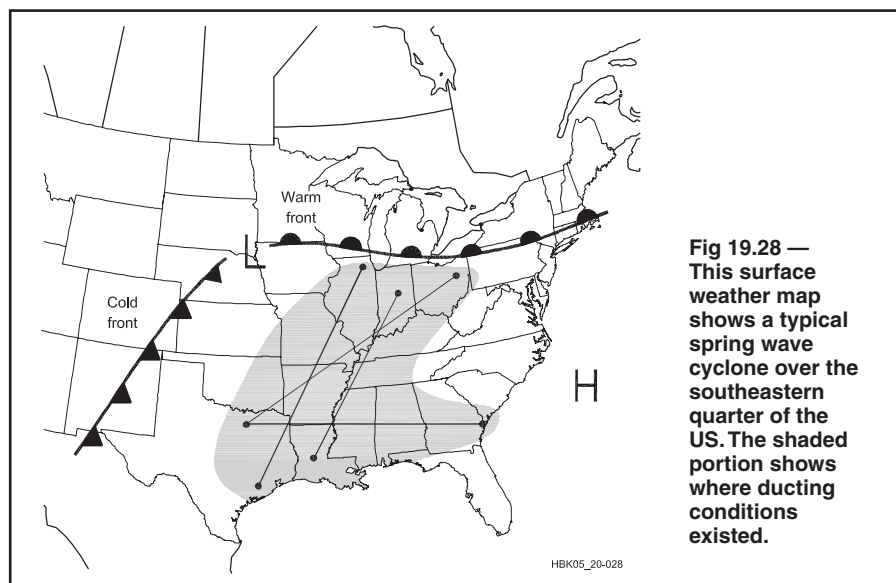
In southern Europe, a hot, dry wind known as the *sirocco* sometimes blows northward from the Sahara Desert over relatively cooler and moister Mediterranean air. Sirocco inversions can be very strong and extend from Israel and Lebanon westward past the Straits of Gibraltar. Sirocco-type inversions are probably responsible for record-breaking microwave contacts in excess of 1500 km (930 miles) across the Mediterranean.

MARINE BOUNDARY LAYER EFFECTS

Over warm water, such as the Caribbean and other tropical seas, *evaporation inversions* may create ducts that are useful in the microwave region between 3.3 and 24 GHz. This inversion depends on a sharp drop in water-vapor content rather than on an increase in temperature to create ducting conditions. Air just above the surface of water at least 30°C is saturated because of evaporation. Humidity drops significantly within 3 to 10 meters (10 to 30 ft) altitude, creating a very shallow but stable duct. Losses due to water vapor absorption may be intolerable at the highest ducting frequencies, but breezes may raise the effective height of the inversion and open the duct to longer wavelengths. Stations must be set up right on the beaches to ensure being inside an evaporation inversion.

TROPOSPHERIC DUCTING FORECASTS

To help decide if weather conditions may support tropospheric ducting, visit "William Hepburn's Worldwide Tropospheric Ducting Forecasts" at **www.dxinfocentre.com/tropo.html**. The principal content on this
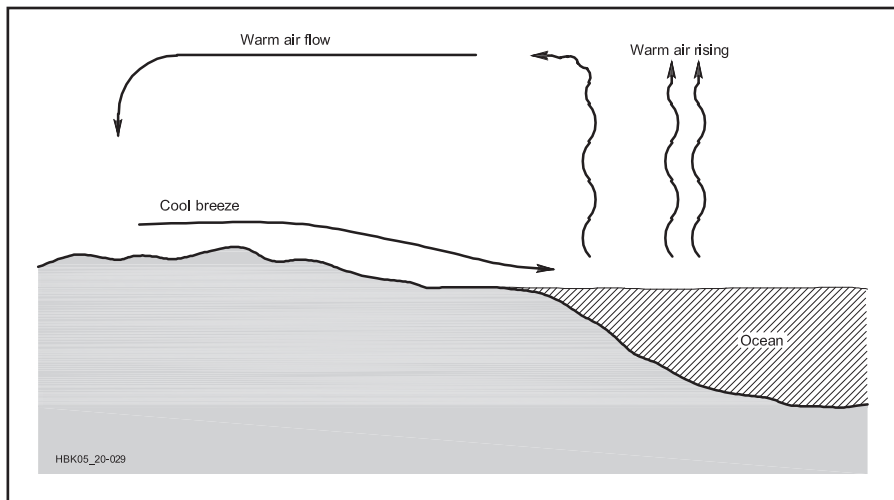

Warm front

Cold front

L

H

Fig 19.28 — This surface weather map shows a typical spring wave cyclone over the southeastern quarter of the US. The shaded portion shows where ducting conditions existed.

HBK05_20-028

Fig 19.29 — Land-breeze convection along a coast after sunset creates a temperature inversion over the land.

could potentially disrupt signal paths and cause unusual and sometimes rapid variations in signal strengths

19.4.4 Tropospheric Fading

Because the atmosphere is not homogeneous, radio signals are refracted slightly as they encounter variations in density and humidity. A signal may arrive at the receiver by two or more different paths simultaneously, causing addition or partial cancellation depending on the relative phases and amplitudes of the paths. As the wind blows, the paths change, which causes the net amplitude of the received signal to vary slowly, a process known as *scintillation fading*. This is the same process that causes the stars to twinkle in the visible portion of the electromagnetic spectrum. The higher the frequency and the longer the path length, the more pronounced the effect. While scintillation is generally not significant for short-range VHF/UHF repeater work, it can be the main limitation on power budgets for microwave point-to-point links.

Fast-flutter fading at 28 MHz and above is often the result of an airplane that temporarily creates a second propagation path. Flutter results as the phase relationship between the direct signal and that reflected by the airplane changes with the airplane's movement.

website is the forecast maps — 6-day preview as well as 42-hour preview (in 6-hour increments) maps for virtually every region of the world.

The purpose of these maps is to display potential duct paths for VHF, UHF and microwave signals, indicated by the color shading on the maps using the Hepburn Tropo Index.

This index indicates the degree of tropospheric bending forecast to occur over a particular area. It is an indication of the overall tropospheric radio signal strength on a linear scale from 0 to 10 (with 10 representing an "extremely intense opening" for propagation by ducting).

Also shown on the maps are predicted "unstable signal areas" where weather conditions

19.5 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 9500 km (5938 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.

19.5.1 Rayleigh Fading

Not only is the signal reflected, but it usually arrives at the receiver by several different paths simultaneously. See **Fig 19.30**. Because the length of each path is different, the signals are not in phase. If the signals on two paths happen to be 180° 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 $\lambda/4$ 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 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,
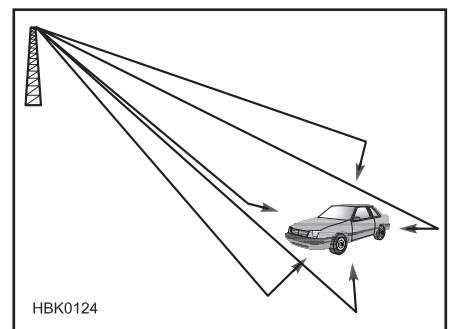

Fig 19.30 — At distances greater than a few miles, there normally is no line-of-sight path to the mobile station. Each path experiences at least one reflection. (Because the radio paths are reciprocal, propagation is the same for both receiving and transmitting.)
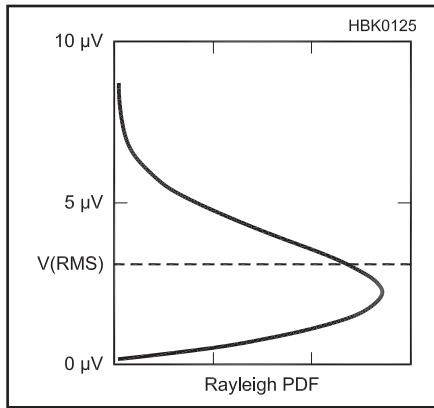
Fig 19.31 — The horizontal axis is the Rayleigh probability density function (PDF), which is the relative probability of the different signal levels shown on the vertical axis. For this graph, an RMS value of 3.16 µV has been selected to represent a typical average signal level in a marginal-coverage area.

Fig 19.33 — 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.

named after the physicist/mathematician who first derived the mathematical formula. That is why the phenomenon is called *Rayleigh fading*. **Fig 19.31** shows the relative probability of various signal strengths. **Fig 19.32** 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.

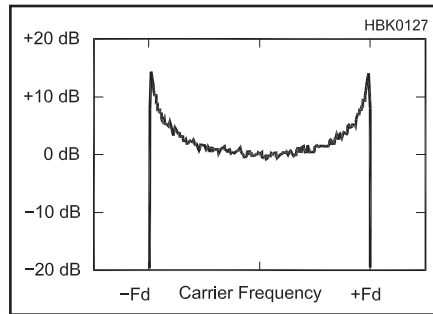Rays arriving from in front of a forward-moving vehicle experience a positive Doppler frequency shift and rays from the rear have a negative Doppler shift. Those from the sides are somewhere in-between, proportional to the cosine of the angle of arrival. The received signal is the sum of all those rays, which results in *Doppler spreading* of the signal as illustrated in **Fig 19.33**. 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
 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.

19.5.2 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 **Fig 19.34**. Each main path typically does not reach the mobile station directly, but is separately Rayleigh-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.

19.5.3 Effect on the Receiver

Radio direction finding (RDF) enthusiasts have noticed that their RDF receivers usually do not give stable or accurate indications unless located on a hilltop or other location with a clear line of sight to the transmitter because of fading and reflections. The best technique is to record the bearing to the hidden transmitter from a high location clear of nearby reflecting objects, then drive in that direction and take the next reading from another (hopefully closer) hilltop. Only when close to the transmitter will the RDF equipment typically give good readings while the vehicle is in motion.

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
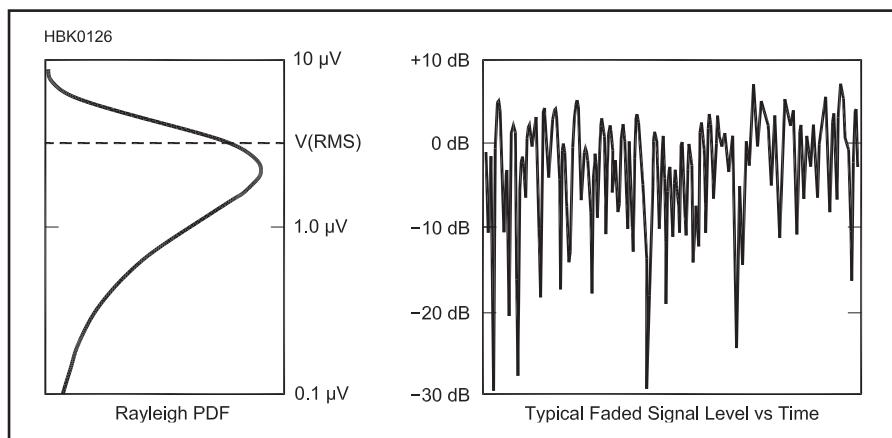

Fig 19.32 — The graph at the left is the same as Fig 19.31 except that the vertical axis is logarithmic (proportional to dB). At the right is a typical Rayleigh-faded signal of the same RMS voltage level plotted using the same vertical scale.
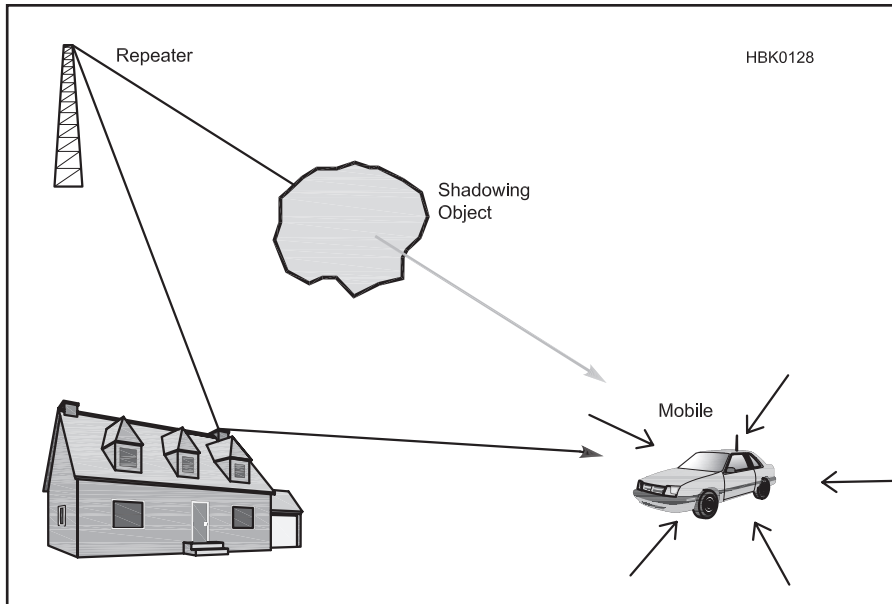
Fig 19.34 — When multipath propagation occurs, each main path is typically Rayleigh-faded by multiple reflectors close to the mobile station.
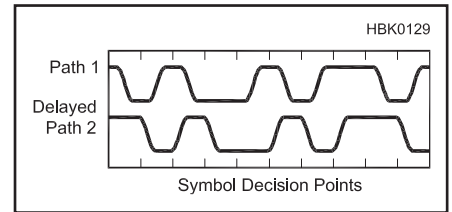

Fig 19.35 — Multipath propagation can cause inter-symbol interference (ISI). At the symbol decision points, where the receiver decoder samples the signal, the path 2 data is often opposing the data on path 1.

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. (The TEN-TEC Orion operating manual, downloadable from **www.tentec.com**, has a nice discussion of diversity reception.) 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 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 km (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 **Fig 19.35**. 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 3000 km (1800 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, Agilent Technologies manufactures a fading simulator that operates in conjunction with their E4438C ESG signal generator. The simulator software may be downloaded for free from **www.agilent.com** — search for the product number N5115A. Although a license must be purchased to make it actually work with a signal generator, it is instructive to play with the user interface, and there is quite a bit of tutorial material on fading in the help file.

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.

19.6 Propagation for Space Communications

Communication of all sorts into space has become increasingly important. Amateurs confront extraterrestrial propagation when accessing satellite repeaters or using the moon as a reflector. (More information on these modes may be found in the **Space Communications** supplement on the *Handbook* CD.) Special propagation problems arise from signals that travel from the Earth through the ionosphere (or a substantial portion of it) and back again. Tropospheric and ionospheric phenomena, so useful for terrestrial paths, are unwanted and serve only as a nuisance for space communication. A phenomenon known as *Faraday rotation* may change the polarization of radio waves traveling through the ionosphere, presenting special problems to receiving weak signals. Cosmic noise also becomes an important factor when antennas are intentionally pointed into space.

19.6.1 Faraday Rotation

Magnetic and electrical forces rotate the polarization of radio waves passing through the ionosphere. For example, signals that leave the Earth as horizontally polarized and return after a reflection from the moon may not arrive with the same polarization. Additional path loss can occur when polarization is shifted by 90°, resulting in fading of the received signal.

Faraday rotation is difficult to predict and its effects change over time and with operating frequency. At 144 MHz, the polarization of space waves may shift back into alignment with the antenna within a few minutes, so often just waiting can solve the Faraday problem. At 432 MHz, it may take half an hour or longer for the polarization to become realigned. Use of circular polarization completely eliminates this problem, but creates a new problem for EME paths. The sense of circularly polarized signals is reversed with reflection, so two complete antenna systems are normally required, one with left-hand polarization and one with right-hand polarization.

19.6.2 Scintillation

Extraterrestrial signals experience scintillation fading as they travel through the lower atmosphere, as described previously in the *Tropospheric Fading* section. However, they also experience scintillation fading as they traverse the ionosphere. The rule of thumb is that the ionosphere dominates below about 2 GHz and the atmosphere is usually more significant above 2 GHz. Scintillation in the ionosphere is more complex than in the troposphere because, unlike the troposphere, the ionosphere is highly anisotropic and irregularities tend to be aligned with the Earth's magnetic field lines.

Ionospheric scintillation varies with geographical location, time of day, the 11-year sunspot cycle, and the presence of geomagnetic storms. **Fig 19.36** shows the worldwide areas where scintillation occurs. The most intense and frequent disturbances are located within about 20 degrees of the Earth's magnetic equator. Fading depth in this region can be as much as 20 to 30 dB. Scintillation fading also is common within about 30 degrees of the magnetic poles, although fade depths are generally no more than 10 dB or so. At mid latitudes ionospheric scintillation is rarely an issue. Longitude is important as well. In South America, Africa and India, the frequency of occurrence is significantly lower in the southern hemisphere winter (May-August) than during the summer, while the pattern is exactly opposite in the central Pacific.

In the polar regions disturbances occur at any time of day, but in the equatorial region they tend to start an hour or so after sunset and last a few hours, from perhaps 1900-2400 local time at the equinox. Fading events are sometimes intermittent, starting abruptly and ending abruptly some minutes later. The signal paths to slow-moving sources, such as the moon or geostationary satellites, tend to fade about once or twice a second. While not much work has been done on characterizing ionospheric scintillation fading on low Earth orbit (LEO) satellites, the fade rate should be more than an order of magnitude faster since the orbital period is typically on the order of 1.5 hours, much less than the Earth's 24-hour rotational period.

As might be expected, sunspots also are important. Ionospheric scintillation is much more severe and frequent near the peak of the 11-year solar cycle. Geomagnetic storms also have a major effect, principally in the polar regions.

19.6.3 Earth-Moon-Earth

Amateurs have used the moon as a reflector on the VHF and UHF bands since 1960. Maximum allowable power and large antennas, along with the best receivers, are normally required to overcome the extreme free-space and reflection losses involved in Earth-Moon-Earth (EME) paths. More modest stations make EME contacts by scheduling operating times when the moon is at perigee (on the horizon). The moon, which presents a target only one-half degree wide, reflects only 7% of the radio signals that reach it. Techniques have to be designed to cope with Faraday rotation, cosmic noise, Doppler shift (due to the moon's movements) and other difficulties. In spite of the problems involved, hundreds (and possibly thousands) of amateur stations have made contacts via the moon on all bands from 50 MHz to 10 GHz. The techniques of EME communication are discussed in the **Space Communications** supplement on the *Handbook* CD.

19.6.4 Satellites

Accessing amateur satellites generally does not involve huge investments in antennas and equipment, yet station design does have to take into account special challenges of space propagation. Free-space loss is a primary consideration, but it is manageable when satellites are only a few hundred kilometers distant. Free-space path losses to satellites in high-Earth orbits are considerably
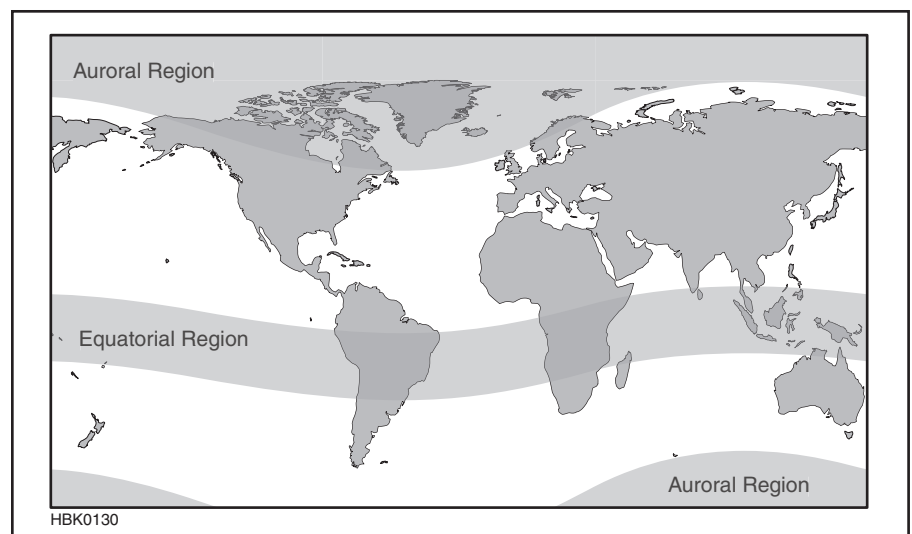

Fig 19.36 — Regions of the world (shaded) where scintillation fading effects can be especially severe.

greater, and appropriately larger antennas and higher powers are needed.

Satellite frequencies below 30 MHz can be troublesome. Ionospheric absorption and refraction may prevent signals from reaching space, especially to satellites at very low elevations. In addition, man-made and natural sources of noise are high. VHF and especially UHF are largely immune from these effects, but free-space path losses are greater. Problems related to polarization, including Faraday rotation, intentional or accidental satellite tumbling and the orientation of a satellite's antenna in relation to terrestrial antennas, are largely overcome by using circularly polarized antennas. More on using satellites can be found in the **Space Communications** supplement on the *Handbook* CD.

19.7 Noise and Propagation

Noise simply consists of unwanted electromagnetic radiation that interferes with desired communications. In some instances, noise imposes the practical limit on the lowest usable frequencies. Noise may be classified by its sources: man-made, terrestrial (atmospheric) and cosmic. Interference from other transmitting stations on adjacent frequencies is not usually considered noise and may be controlled, to some degree anyway, by careful station design or by simply moving to a frequency further away from the interference. (Additional information on noise can be found in the **RF Techniques** and **Receivers** chapters.)

19.7.1 Man-Made Noise

Many unintentional radio emissions result from man-made sources. Broadband radio signals are produced whenever there is a spark, such as in contact switches, electric motors, gasoline engine spark plugs and faulty electrical connections. Household appliances, such as fluorescent lamps, microwave ovens, lamp dimmers and anything containing an electric motor may all produce undesirable broadband radio energy. Devices of all sorts, especially computers and anything controlled by microprocessors, television receivers and many other electronics also emit radio signals that may be perceived as noise well into the UHF range. In many cases, these sources are local and can be controlled with proper measures. See the **RF Interference** chapter.

High-voltage transmission lines and associated equipment, including transformers, switches and lightning arresters, can generate high-level radio signals over a wide area, especially if they are corroded or improperly maintained. Transmission lines may act as efficient antennas at some frequencies, adding to the noise problem. Certain kinds of street lighting, neon signs and industrial equipment also contribute their share of noise.

Fig 19.37 shows typical noise levels versus frequency, in terms of power, for various noise environments. Note that man-made noise prevails below roughly 14 MHz, and it, rather than the sensitivity of your receiver (here depicted as the MDS — the minimum discernible signal), determines how weak a signal you can hear.

19.7.2 Lightning

Static is a common term given to the ear-splitting crashes of noise commonly heard on nearly all radio frequencies, although it is most severe on the lowest frequency bands. Atmospheric static is primarily caused by lightning and other natural electrical discharges. Static may result from close-by thunderstorms, but most static originates with tropical storms. Like any radio signals, lightning-produced static may be propagated over long distances by the ionosphere. Thus static is generally higher during the summer, when there are more nearby thunderstorms, and at night, when radio propagation generally improves. Static is often the limiting factor on 1.8 and 3.5 MHz, making winter a more favorable time for using these frequencies. (Note that the quiet "winter" months in the Southern Hemisphere are June through August.)

19.7.3 Precipitation Static and Corona Discharge

Precipitation static is an almost continuous hash-type noise that often accompanies various kinds of precipitation, including snowfall. Precipitation static is caused by rain drops, snowflakes or even wind-blown dust, transferring a small electrical charge on contact with an antenna. Electrical fields under thunderstorms are sufficient to place many objects such as trees, hair and antennas, into corona discharge. *Corona noise* may sound like a harsh crackling in the radio — building in intensity, abruptly ending, and then building again, in cycles of a few seconds to as long as a minute. A corona charge on an antenna may build to some critical level and then discharge in the atmosphere with an audible pop before recharging. Precipitation static and corona discharge can be a nuisance from LF to well into the VHF range.

19.7.4 Cosmic Sources

The Sun, distant stars, galaxies and other cosmic features all contribute radio noise well into the gigahertz range. These *cosmic sources* are perceived primarily as a more-or-less constant background noise at HF. In the VHF range and higher, specific sources of cosmic noise can be identified and may be a limiting factor in terrestrial and space communications. The Sun is by far the greatest source of radio noise, but its effects are largely absent at night. The center of our own galaxy is nearly as noisy as the Sun. Galactic noise is especially noticeable when high-gain VHF and UHF antennas, such as may be used for satellite or EME communications, are pointed toward the center of the Milky Way. Other star clusters and galaxies are also radio hot-spots in the sky. Finally, there is a much lower cosmic background noise that seems to cover the entire sky.
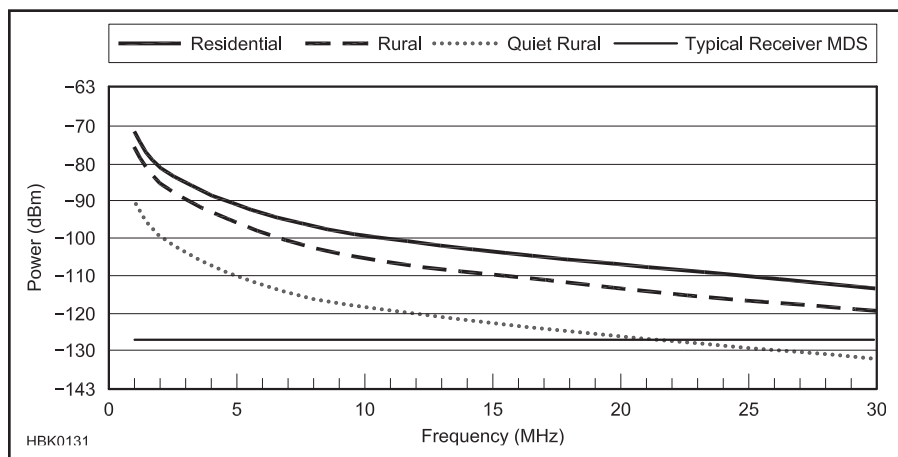

Fig 19.37 — Typical noise levels versus frequency for various environments. (Man-made noise in a 500-Hz bandwidth, from Rec. ITU-R P.372.7, *Radio Noise*)

19.8 Propagation Below the AM Broadcast Band

In his column "It Seems to Us — Two New Bands?" in February 2013 *QST*, ARRL CEO David Sumner, K1ZZ reviewed the status of Amateur Radio frequency allocations below the AM broadcast band. Two bands at these low frequencies are under consideration: 135.7-137.8 kHz and 472-479 kHz. If and when we are allowed access to these bands is anyone's guess, but it would be beneficial to review some fundamental issues with respect to propagation in these bands.

Three important parameters are involved in determining the likelihood of a signal getting from Point A to Point B. These parameters are refraction, absorption and polarization. Although propagation is certainly different on 160 meters and 6 meters, an electromagnetic wave on both of these bands follows the same laws of physics. Thus understanding how these three parameters change versus frequency will give us insight into propagation on our potentially new low frequency bands.

Fig 19.38 is a ray trace at night (0500 UTC) in mid January at moderate solar activity for frequencies from 10.65 MHz down to 150 kHz. All rays are launched at a low elevation angle of 5 degrees. (This figure was made using *Proplab Pro V3* — see the section MUF Prediction on the Home Computer for more details on this software package.)

The MUF is not high enough for 10.65 MHz under these conditions, and it goes through the ionosphere. But frequencies of 8.9 MHz and lower are successively refracted at lower heights, which results in shorter hops. So RF on 135.7-137.8 kHz and 472-479 kHz will take short hops.

Table 19.7 summarizes absorption (data from the ray trace) on 5.4 MHz, 3.65 MHz, 1.9 MHz and 150 kHz for a 1500 km hop under the same conditions as the ray traces in Fig 19.38. Note that as the frequency decreases from 5.4 MHz to 1.9 MHz, the loss due to ionospheric absorption increases as expected. But at 150 kHz the absorption is significantly reduced. This is due to the wave not getting very high into the ionosphere — in
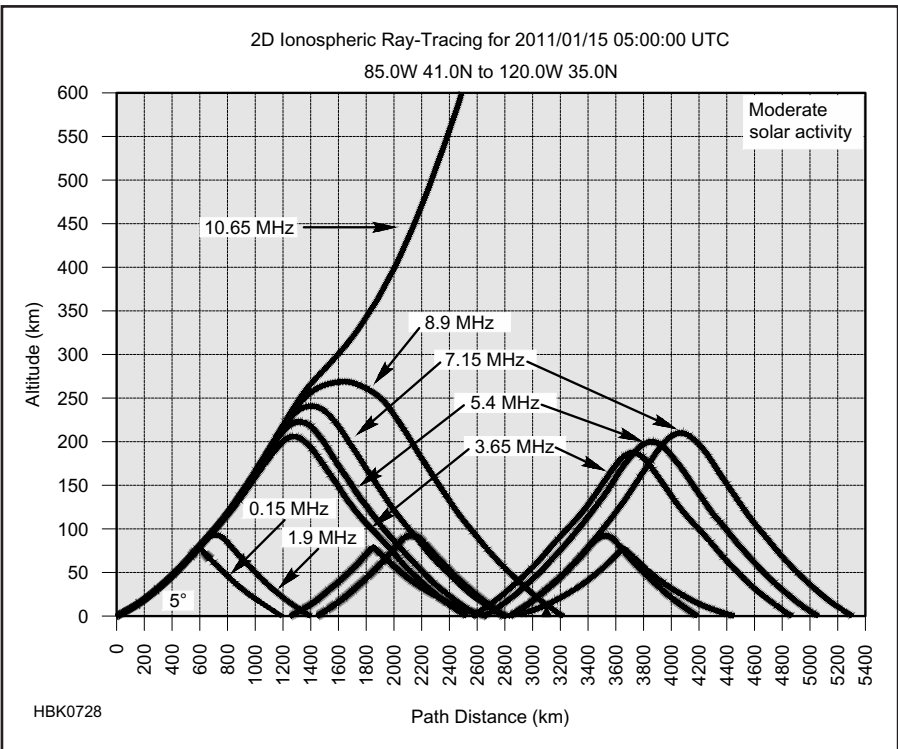

Fig 19.38 — Low frequency ray traces showing more bending as the frequency is lowered.

Table 19.7

Absorption vs Frequency

Frequency (MHz)	Absorption per Hop (dB)
5.4	0.8
3.65	2.3
1.9	17.8
0.150	4.0

fact, the residual nighttime D region ionization is sufficient to refract this low frequency with minimal absorption. So RF on 135.7-137.8 kHz and 472-479 kHz will not suffer as much absorption as on 160 meters.

In theory, highly elliptical polarization will prevail for these low frequencies. It is likely that most antennas for these bands will be vertically polarized, which should be a good match to couple the most energy into the ordinary wave.

In summary, skywave propagation on 135.7-137.8 kHz and 472-479 kHz will be via short hops between the ionosphere and the D region, but with lower absorption than on 160 meters. Tempering this lower absorption are the lower antenna efficiencies and higher received noise levels. Thus these bands will be tough, but the Amateur Radio spirit will make the most of them.

19.9 Glossary of Radio Propagation Terms

A index — An open-ended linear index that corresponds roughly to the cumulative **K index** values (it's the daily average of the eight K indices after converting the K indices to a linear scale). The A index commonly varies between 0 and 30 during quiet to active conditions, and up to 100 and higher during geomagnetic storms.

Absorption — The dissipation of the energy of a radio wave as it travels through a medium such as the ionosphere.

Antipode — Locations directly opposite each other on a globe.

Atmosphere — The mass of air surrounding the Earth. Radio signals travel through the atmosphere and different conditions in the atmosphere (in conjunction with the signal's frequency) affect how those signals travel or propagate.

Aurora — A disturbance of the atmosphere at high latitudes resulting from an interaction between electrically charged particles from the magnetosphere and the magnetic field of the Earth. *Auroral propagation* occurs when HF through UHF signals are reflected from the aurora to reach another station.

Auroral E — Sporadic E in the auroral zone.

Backscatter — Single-hop signals that have been scattered by the Earth or the ocean at some distant point back toward the transmitting station.

Beacon station — A station that transmits continuously, allowing other stations to assess propagation to and from the location of the beacon station.

Coronal hole — A region on the Sun where the magnetic field is open to the interplanetary magnetic field (IMF) and ionized particles can escape into the solar wind.

Critical angle — The largest angle at which a radio wave of a specified frequency can be returned to Earth by the ionosphere.

Critical frequency — The highest frequency that returns echoes from the E and F regions at vertical incidence.

D region — The lowest region of the ionosphere. The D region (or layer) contributes very little to short-wave radio propagation. It absorbs energy from radio waves as they pass through it. This absorption has a significant effect on signals below about 7.5 MHz during daylight.

Diffraction — Bending of waves by an edge or corner.

E region — The second lowest ionospheric region, the E region (or layer) has its highest electron density during the day and falls to a much lower electron density during the night. Under certain conditions, it may refract radio waves enough to return them to Earth.

Earth-Moon-Earth (EME) or *Moonbounce* — A method of communicating with other stations by reflecting radio signals off the Moon's surface.

Electromagnetic wave — A wave of energy composed of an electric and magnetic field.

Equinoxes — One of two points in the orbit of the Earth around the Sun at which the Earth crosses a horizontal plane extending through the equator of the Sun. The vernal equinox marks the beginning of spring and the autumnal equinox marks the beginning of autumn.

Faraday rotation — A rotation of the polarization of radio waves when the waves travel through an ionized medium that is immersed in a magnetic field (for example, the Earth's ionosphere).

F region — A combination of the two highest ionospheric regions (or layers), the F_1 and F_2 regions. The F region refracts radio waves and returns them to Earth. Its height varies greatly depending on the time of day, season of the year and amount of sunspot activity.

Field-aligned irregularities (FAI) — A propagation mechanism observed at 50 and 144 MHz that occurs when irregularities in the distribution of free electrons in the ionosphere are aligned parallel to the Earth's magnetic field.

Free-space attenuation — The dissipation of the energy of a radio wave that results from the spherical spreading of radio energy from its source.

Gray-line — A special form of **long-path** propagation that takes into account the unusual ionospheric configuration along the twilight region between night and day.

Ground-wave propagation — The method by which radio waves travel along the Earth's surface.

High frequency (HF) — The term used for the frequency range between 3 MHz and 30 MHz. The amateur HF bands are where you are most likely to make long-distance (worldwide) contacts.

Ionosphere — A region of electrically charged (ionized) gases high in the atmosphere. The ionosphere bends radio waves as they travel through it, returning them to Earth. Also see **sky-wave propagation**.

K index — A geomagnetic-field measurement that is updated every three hours at various observatories around the world.

Changes in the K index can be used to indicate HF propagation conditions. Rising values generally indicate disturbed conditions while falling values indicate improving conditions.

Line-of-sight propagation — The term used to describe VHF and UHF propagation in a straight line directly from one station to another.

Long-path propagation — Propagation between two points on the Earth's surface that follows a path along the great circle between them, but in a direction opposite from the shortest distance between them.

Lowest usable frequency (LUF) — The frequency below the **maximum usable frequency** (MUF) at which ionospheric absorption and noise at the receiving location make the received signal-to-noise ratio too low to be usable.

M-factor — The ratio between the **maximum usable frequency** (MUF) and the critical frequency.

Maximum usable frequency (MUF) — The highest-frequency radio signal that will reach a particular destination using **sky-wave propagation**, or *skip*. The MUF may vary for radio signals sent to different destinations.

Meteor-scatter communication — A method of radio communication that uses the ionized trail of a meteor that burned up in the Earth's atmosphere to reflect, refract, or scatter radio signals back to Earth.

Microwave — Radio waves or signals with frequencies greater than 1000 MHz (1 GHz). This is not a strict definition, just a conventional way of referring to those frequencies.

Moonbounce — A common name for EME communication in which signals are bounced off the Moon before being received.

Multihop propagation — Long-distance radio propagation using several skips or hops between the Earth and the ionosphere.

Multipath — A fading effect caused by the transmitted signal traveling to the receiving station over more than one path.

Near Vertical Incidence Skywave (NVIS) propagation — A propagation mechanism that allows stations located within the **skip zone**, but too far apart for ground wave propagation, to maintain communications by going to a lower frequency.

Path loss — The total signal loss between transmitting and receiving stations relative to the total radiated signal energy.

Pedersen ray — A high-angle radio wave that penetrates deeper into the F region of the ionosphere, so the wave is bent less than a lower-angle wave, and thus for some distance parallels the Earth's surface in the F region, returning to Earth at a distance farther than normally expected for single-hop propagation.

Polarization — The orientation of the electrical-field of a radio wave. An antenna that is parallel to the surface of the Earth, such as a dipole, produces horizontally polarized waves. One that is perpendicular to the Earth's surface, such as a quarter-wave vertical, produces vertically polarized waves. An antenna that has both horizontal and vertical polarization is said to be circularly polarized.

Propagation — The process by which radio waves travel.

Radio frequency (RF) signals — RF signals are generally considered to be any electrical signals with a frequency higher than 20,000 Hz, up to 300 GHz.

Radio horizon — The position at which a direct wave radiated from an antenna becomes tangent to the surface of the Earth. Note that as the wave continues past the horizon, the wave gets higher and higher above the surface.

Radiation inversion — A weather condition that affects propagation at VHF and above. Radiation inversions form only over land after sunset as a result of progressive cooling of the air near the Earth's surface.

Rain scatter — A special case of tropospheric scatter practical in the 3.3 to 24 GHz range that is caused by scatter from raindrops.

Reflection — Signals that travel by **line-of-sight propagation** are reflected by large objects like buildings.

Refraction — Bending waves by changing the velocity of propagation. Radio waves refract as they travel through the ionosphere. If the radio waves refract enough they will return to Earth. This is the basis for long-distance communication on the HF bands.

Scattering — Radio wave propagation by means of multiple reflections in the layers of the atmosphere or from an obstruction. Scatter propagation also occurs in the ionosphere when there is not enough ionization for refraction or reflection, but enough to send weak electromagnetic waves off into varied directions.

Scintillation fading — Fading that occurs when a signal arrives at the receiver by two or more different paths simultaneously, causing addition or partial cancellation depending on the relative phases and amplitudes of the paths.

Selective fading — A variation of radio-wave intensity that changes over small frequency changes. It may be caused by changes in the medium through which the wave is traveling or changes in transmission path, among other things.

Short path — The shorter of the two great circle paths between two stations.

Skip — Propagation by means of ionospheric reflection. Traversing the distance to the ionosphere and back to the ground is called a *hop*.

Skip zone — A ring-shaped area of poor radio communication, too distant for ground waves and too close for sky waves.

Sky-wave propagation — The method by which radio waves travel through the ionosphere and back to Earth. Sometimes called *skip*, sky-wave propagation has a far greater range than **line-of-sight** and **ground-wave propagation**.

Solar cycle — The approximate 11-year period of variation in solar activity.

Solar flare — An eruption on the surface of the Sun that launches a wide spectrum of electromagnetic energy into space, disrupting communications on Earth. A large flare can also release relativistic protons that cause additional absorption in the polar cap.

Solar wind — Electrically charged particles emitted by the Sun and traveling through space. Variations in the solar wind may have a sudden impact on radio communications when they arrive at the atmosphere of the Earth.

Sporadic E — A form of enhanced radio-wave propagation that occurs when radio signals are reflected from small, dense ionization patches in the E region of the ionosphere. Sporadic E is observed on the 15, 10, 6 and 2 meter bands, and occasionally on the 1.25 meter band.

Sunspot cycle — The number of **sunspots** increases and decreases in a somewhat predictable cycle that lasts about 11 years.

Sunspots — Dark spots on the surface of the Sun. When there are few sunspots, long-distance radio propagation is poor on the higher-frequency bands. When there are many sunspots, long-distance HF propagation improves.

Temperature inversion — A condition in the atmosphere in which a region of cool air is trapped beneath warmer air.

Transequatorial propagation — A form of F layer ionospheric propagation, in which signals of higher frequency than the expected MUF are propagated across the Earth's magnetic equator.

Troposphere — The region in Earth's atmosphere just above the Earth's surface and below the ionosphere.

Tropospheric bending — When radio waves are bent in the troposphere, they return to Earth farther away than the visible horizon.

Tropospheric ducting — A type of VHF propagation that can occur when warm air overruns cold air (a temperature inversion).

Tropospheric scatter — A method of radio communication at VHF and above that takes advantage of scattering in the **troposphere** to allow contacts beyond the radio horizon out to a working distance of 100 to 500 km (60 to 310 miles), depending on frequency.

Ultra high frequency (UHF) — The term used for the frequency range between 300 MHz and 3000 MHz (3 GHz). Technician licensees have full privileges on all Amateur UHF bands.

Very high frequency (VHF) — The term used for the frequency range between 30 MHz and 300 MHz. Technician licensees have full privileges on all Amateur VHF bands.

Visible horizon — The most distant point one can see by line of sight.

WWV/WWVH — Radio stations run by the US NIST (National Institute of Standards and Technology) to provide accurate time and frequencies.

19.10 References and Bibliography

A. Barter, G8ATD, ed., *International Microwave Handbook*, 2nd edition (Potters Bar: RSGB, 2008). Includes a chapter on microwave propagation.

A. Barter, G8ATD, ed., *VHF/UHF Handbook*, 2nd edition (Potters Bar: RSGB, 2008). Includes a chapter on VHF/UHF propagation.

B. R. Bean and E. J. Dutton, *Radio Meteorology* (New York: Dover, 1968).

K. Davies, *Ionospheric Radio* (London: Peter Peregrinus, 1989). Excellent though highly technical text on propagation.

R. D. Hunsucker, J.K. Hargreaves, *The High Latitude Ionosphere and Its Effect on Radio Propagation* (Cambridge University Press, 2003). Highly technical, but with an excellent chapter on fundamental physics of the ionosphere.

G. Jacobs, T. Cohen, R. Rose, *The New Shortwave Propagation Handbook*, *CQ* Communications, Inc. (Hicksville, NY: CQ Communications, 1995).

C. Luetzelschwab, K9LA, **http://myplace. frontiercom/~k9la**. Many articles about the ionosphere and propagation as they relate to 160 meters, HF, VHF, contesting and more.

L. F. McNamara, *Radio Amateur's Guide to the Ionosphere* (Malabar, Florida: Krieger Publishing Company, 1994). Excellent, quite-readable text on HF propagation.

A. Mehrotra, *Cellular Radio Performance Engineering* (Artech House, 1994). See Chapter 4 "Propagation" and the introduction to Chapter 3 "Cellular Environment." Diversity reception techniques are covered in Chapter 8.

D. Straw, N6BV, "What's the Deal About 'NVIS'?," *QST*, Dec 2005.

J. A. White, VA7JW, and K. Tapping, "The Penticton Solar Flux receiver," *QST*, Feb 2013, pp 39-45.