Chapter 20

Propagation of RF 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, 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. More detailed discussions and the underlying mathematics of radio propagation physics can be found in the references listed at the end of this chapter.

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 20.1**. Electromagnetic waves result from the interaction of an electric and a magnetic field. An oscillating electric charge in a piece of wire, for example, creates an electric field and a corresponding magnetic field. The magnetic field in turn creates an electric field, which creates another magnetic field, and so on.

These two fields sustain themselves as a composite *electromagnetic wave*, which propagates itself into space. The electric and magnetic components are oriented at right angles to each other and 90° to the direction of travel. The polarization of a radio wave is usually designated the same as its electric field. This relationship can be visualized in **Fig 20.1**. 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.

Velocity

Radio waves, like all other electromagnetic radiation, travel nearly 300,000 km (186,400 mi) 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 of 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,

Table 20.1
The Electromagnetic Spectrum

Radiation	*Frequency*	*Wavelength*
X-ray	3×10^5 THz and higher	10 Å and shorter
Ultraviolet	800 THz - 3×10^5 THz	4000 - 10 Å
Visible light	400 THz - 800 THz	8000 - 4000 Å
Infrared	300 GHz - 400 THz	1 mm - 0.0008 mm
Radio	10 kHz - 300 GHz	30,000 km - 1 mm

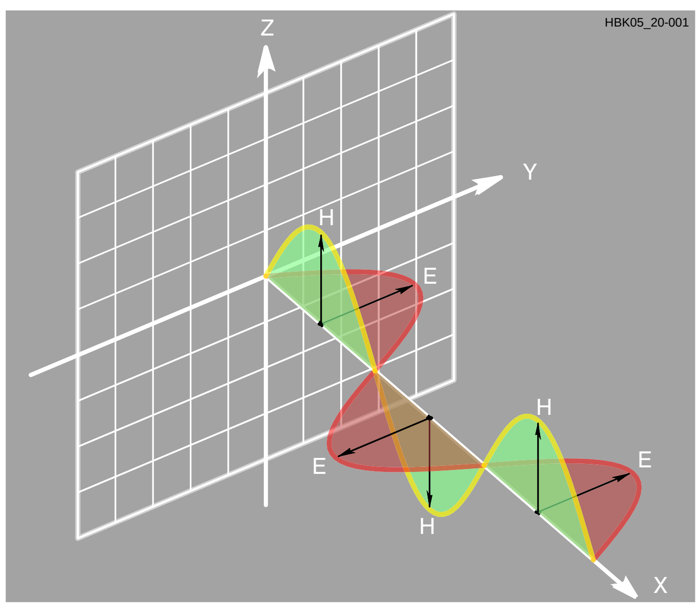

Fig 20.1—Electric and magnetic field components of the electromagnetic wave. The polarization of a radio wave is the same direction as the plane of its electric field.

whatever the medium. That relationship can be stated simply as:

$c = f \lambda$

where

c = speed in m/s
f = frequency in hertz
λ = wavelength in m

The *wavelength* (λ) of any radio frequency can be determined from this simple formula. In free space, where the speed is 3×10^8 m/s, the wavelength of a 30-MHz radio signal is thus 10 m. 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 m. This factor must be taken into consideration in antenna designs and other applications.

Wave Attenuation and Absorption

Radio waves weaken as they travel, whether in the near vacuum of cosmic space or within the Earth's atmosphere. *Free-space attenuation* results from the dispersal of radio energy from its source. See **Fig 20.2**. Attenuation grows rapidly with distance because signals weaken with the square of the distance traveled. If the distance between transmitter and receiver is increased from 1 km to 10 km (0.6 to 6 mi), the signal will be only one-hundredth as strong. 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 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.

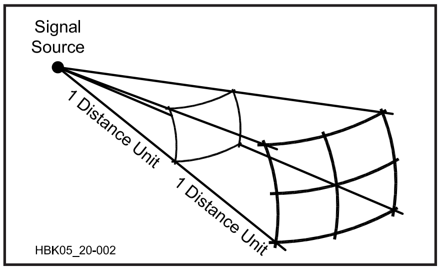

Fig 20.2—Radio energy disperses as the square of the distance from its source. For the change of one distance unit shown the signal is only one quarter as strong. Each spherical section has the same surface area.

Refraction

Electromagnetic waves travel in straight lines until they are deflected by something. Radio waves are *refracted*, or bent, slightly when traveling from one medium to another. 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 20.3**.

The amount of bending increases with the ratio of the *refractive indices* of the two media. Refractive index is simply the velocity of a radio wave in free space divided by its velocity in the medium. Radio waves are commonly refracted when they travel through different layers of the atmosphere, whether the highly charged ionospheric layers 100 km (60 mi) 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.

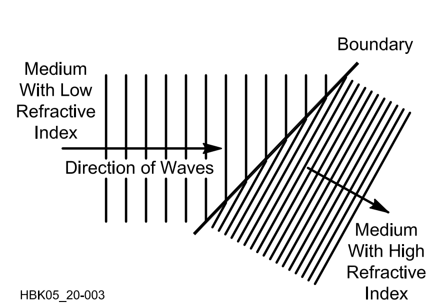

Fig 20.3—Radio waves are refracted as they pass at an angle between dissimilar media. The lines represent the crests of a moving wave front and the distance between them is the wavelength. The direction of the wave changes because one end of the wave slows down before the other as it crosses the boundary 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.

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.

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. Contrary to common sense notions, the best position for a reflector is not midway between two stations. Signal strength increases as the reflector approaches one end of the path, so the most effective reflectors are those closest to one station or the other.

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 mi), assuming the largest jets fly no higher than 12,000 m (40,000 ft), but actual airplane reflection contacts are likely to be considerably shorter.

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 20.4** depicts radio signals approaching an idealized knife-edge. The portion of the radio waves that strike the base of the knife-edge is entirely blocked, while that portion passing several wavelengths above the edge travel on relatively unaffected. It might seem at first glance that a knife-edge as large as a mountain, for example, would completely prevent radio signals from appearing on the other side but that is not quite true. Something quite unexpected happens to radio signals that pass just over a knife-edge.

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

The crest of a range of hills or mountains 50 to 100 wavelengths long can serve as a reasonable knife-edge diffractor at radio frequencies. Hillcrests that are clearly defined and free of trees, buildings and other clutter make the best 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.

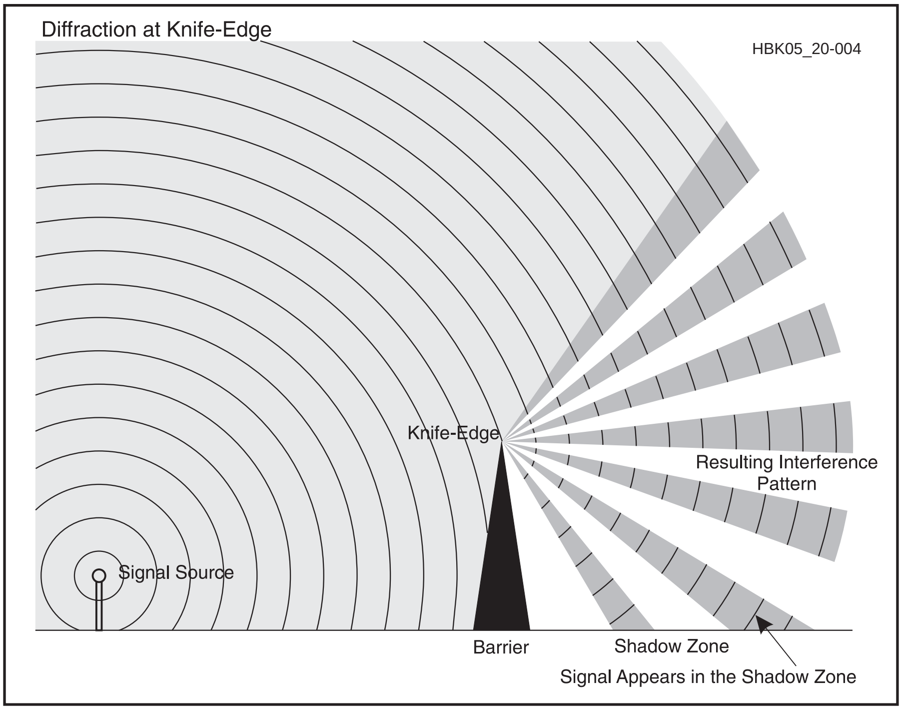

Fig 20.4—Radio, light and other waves are diffracted around the sharp edge of a solid object that is large in terms of wavelengths. Diffraction results from interference between waves right at the knife-edge and those that are passing above it. Some signals appear behind the knife-edge as a consequence of the interference pattern. Hills or mountains can serve as natural knife-edges at radio frequencies.

Ground Waves

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-m amateur bands, where practical ground-wave distances may extend beyond 200 km (120 mi). 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.

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 mi), 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

Propagation Summary, by Band

Medium Frequencies (300 kHz-3 MHz)

The only amateur medium-frequency band is situated just above the domestic AM broadcast band. Ground wave provides reliable communication out to 150 km (90 mi) during the day, when no other form of propagation is available. Long-distance paths are made at night via the F_2 layer.

1.8-2.0 MHz (160 m)

The top band, as it is sometimes called, suffers from extreme daytime D-layer absorption. Even at high radiation angles, virtually no signal can pass through to the F layer, so daytime communication is limited to ground-wave coverage. At night, the D layer quickly disappears and worldwide 160-m communication becomes possible via F_2-layer skip. Atmospheric and man-made noise limit propagation. Tropical and midlatitude 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 can often significantly reduce the amount of received noise while enhancing desired signals.

High Frequencies (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 m. 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, begin to be practical.

3.5-4.0 MHz (80 m)

The lowest HF band is similar to 160 m in many respects. Daytime absorption is significant, but not quite as extreme as at 1.8 MHz. High-angle signals may penetrate to the E and F layers. Daytime communication range is typically limited to 400 km (250 mi) by ground-wave and skywave propagation. 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-m DXer.

7.0-7.3 MHz (40 m)

The popular 40-m band has a clearly defined skip zone during the day. 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 mi). Ground-wave propagation is not important. At night, reliable worldwide communication via F_2 is common on the 40-m band.

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

10.1-10.15 MHz (30 m)

The 30-m 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 mi) 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 m adopts the characteristics of the daytime bands at 14 MHz and higher. The 30-m 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 m)

The 20-m band is traditionally regarded as the amateurs' primary long-haul DX favorite. Regardless of the 11-year solar cycle, 20 m can be depended on for at least a few hours of worldwide F_2 propagation during the day. During solar-maximum periods, 20 m 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 m tends to be very congested during the daylight hours.

18.068-18.168 MHz (17 m)

The 17-m band is similar to the 20-m 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 m 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 m will open to middle and equatorial latitudes, but only for short periods during midday on north-south paths.

21.0-21.45 MHz (15 m)

The 15-m 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 m is reliable for daytime F_2-layer DXing and will often stay open well into the night. During periods of moderate solar activity, 15 m is basically a daytime-only band, closing shortly after sunset. During solar minimum periods, 15 m may not open at all except for infrequent north-south transequatorial circuits. Sporadic E is observed occasionally in early summer and midwinter, although this is not common and the effects are not as pronounced as on the higher frequencies.

24.89-24.99 MHz (12 m)

This band offers propagation that combines the best of the 10- and 15-m bands. Although 12 m 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 m 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 m)

The 10-m band is well known for extreme variations in characteristics and variety of propagation modes. During solar maxima, long-distance F_2 propagation is so efficient that very low power can produce loud 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 m 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 mi) and multiple-hop opportunities of 4500 km (2800 mi) 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 spread-F provide the means of making contacts out to 2300 km (1400 mi) and farther, but these modes often go unnoticed at 28 MHz. Techniques similar to those used at VHF can be very effective on 10 m, 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 Frequencies (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 spread F (TE), are rarely observed at HF. Tropospheric propagation, which is not a factor at HF, becomes increasingly important above 50 MHz.

50-54 MHz (6 m)

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 mi) via tropospheric scatter, depending on terrain, power, receiver capabilities and antenna. Weak-signal troposcatter allows the best stations to make 500-km (310-mi) 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, 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 mi) when the MUF is just below 50 MHz. TE paths as long as 8000 km (5000 mi) 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-m band. Single-hop E-skip openings may last many hours for contacts from 600 to 2300-km (370 to 1400 mi), 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 m an exciting band. Maximum distances of about 2300 km (1400 mi) 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-m range to 4000 km (2500 mi) 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 m)

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 mi). 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 mi). Multiple-hop sporadic-E contacts greater than 3000 km (1900 mi) 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 weather plays an important propagation role. Weather-induced enhancements may extend the normal 300- to 600-km (190- to 370-mi) range of well-equipped stations to 800 km (500 mi) and more, especially during the summer and early fall. Tropospheric ducting extends this range to 2000 km (1200 mi) and farther over the continent and at least to 4000 km (2500 mi) 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-m 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

(continued on next page)

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 Frequencies (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 mi) 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 mi) and farther over land. The current 432-MHz terrestrial DX record of more than 4000 km (2500 mi) was accomplished by ducting over water.

902-928 MHz (33-cm) and Higher

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

Almost all extended-distance work in the UHF and microwave bands is accomplished with the aid of tropospheric enhancement. The frequencies above 902 MHz are very sensitive to changes in the weather. Tropospheric ducting occurs more frequently than in the VHF bands and the potential range is similar. At 1296 MHz, 2000-km (1200-mi) continental paths and 4000-km (2500-mi) paths between California and Hawaii have been spanned many times. Contacts of 1000 km (620 mi) have been made on all bands through 10 GHz in the US and over 1600 km (1000 mi) across the Mediterranean Sea. Well-equipped 903- and 1296-MHz stations can work reliably up to 300 km (190 mi), but normal working ranges generally shorten with increasing frequency.

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

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 mi). 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.

Structure of the Earth's Atmosphere

The atmosphere, which reaches to more than 600 km (370 mi) altitude, is divided into a number of regions, shown in **Fig 20.5**. The weather-producing *troposphere* lies between the surface and an average altitude of 10 km (6 mi). Between 10 and 50 km (6 and 30 mi) are the *stratosphere* and the imbedded *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 mi) is the *ionosphere*, notable for its effects on radio propagation. At these altitudes, atomic oxygen and nitrogen predominate under very low pressure. High-energy solar UV and X-ray radiation ionize these gases, 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 mi) and extends as far as 160,000 km (100,000 mi) 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. At about 3,200 and 16,000 km (2000 and 9900 mi), 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.

The Ionosphere

The ionosphere plays a basic role in long-distance communication in all the amateur bands from 1.8 MHz to 30 MHz. Ionospheric effects are less apparent in 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 during the early 1920s and used the letter E on his diagrams to designate the electric waves that were apparently reflected from it.

In 1924, Appleton discovered two additional layers in the ionosphere, as he and Robert Watson-Watt named this atmospheric region, and noted them with the letters D and F. Appleton was reluctant to alter this arbitrary nomenclature for fear of discovering yet other layers, so it has stuck to the present day. The basic physics of ionospheric propagation was largely worked out by the 1920s, yet both amateur and professional experimenters made further discoveries through the 1930s and 1940s. Sporadic E, aurora, meteor scatter and several types of field-aligned scattering were among additional ionospheric phenomena that required explanation.

Ionospheric Refraction

The refractive index of an ionospheric layer increases with the density of free-moving electrons. 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 20.6**.

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 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 6 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 20.7** depicts a simple ionogram.

The highest frequency that returns echoes at vertical incidence is known as the *vertical incidence* or *critical frequency*. The critical frequency is almost totally a function of ion density. The higher the ionization at a particular altitude, the higher becomes the critical frequency. Physicists are more apt to call this the *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.

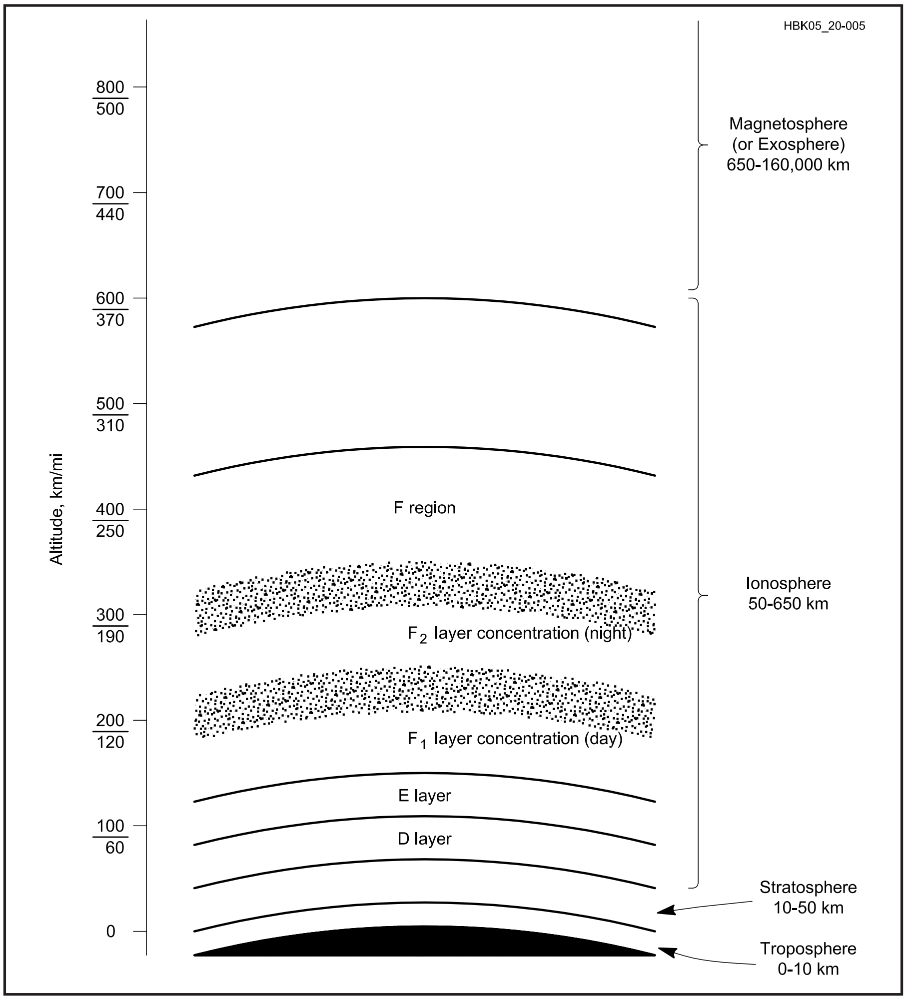

Fig 20.5—Regions of the ionosphere.

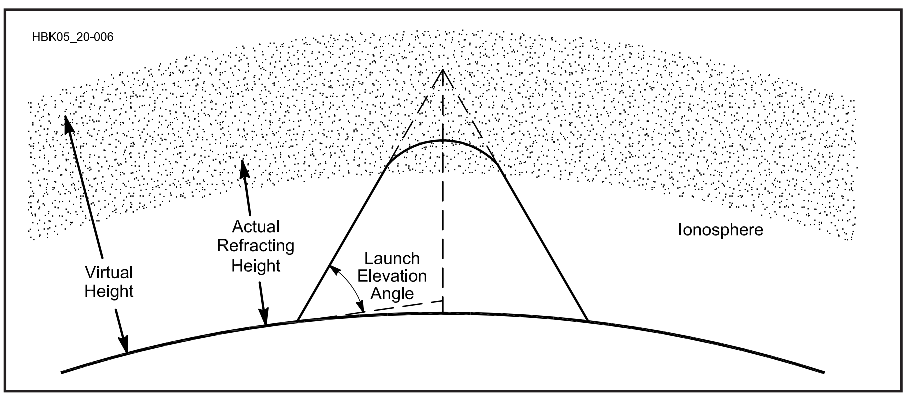

Fig 20.6—Gradual refraction in the ionosphere allows radio signals to be propagated long distances. It is often convenient to imagine the process as a reflection with an imaginary reflection point at some virtual height above the actual refracting region. The other figures in this chapter show ray paths as equivalent reflections, but you should keep in mind that the actual process is a gradual refraction.

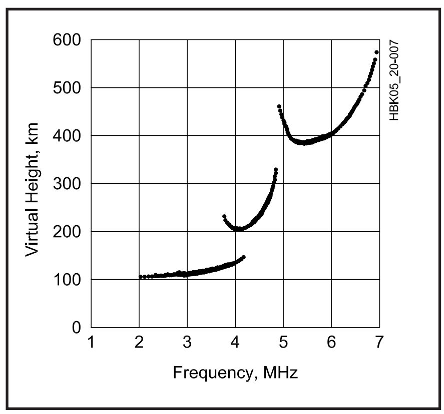

Fig 20.7—Simplified vertical incidence ionogram showing echoes returned from the E, F_1 and F_2 layers. The critical frequencies of each layer (4.1, 4.8 and 6.8 MHz) can be read directly from the ionogram scale.

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 20.8**.

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. 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 mi) for the F_2 layer and about 2300 km (1400 mi) for the E layer. See **Fig 20.9**.

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 limit of one-hop propagation, the MUF can be several times the critical frequency. See **Table 20.2**. The ratio between the MUF and the critical frequency is known as the *maximum usable frequency factor* (MUFF).

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 from one to the other through the required angle — that is, the frequency is below 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 at a lower frequency, or by ground wave if they are close enough. There is no skip zone at frequencies below the critical frequency.

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 (perhaps due to thunderstorms, local or distant) 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 communications modes that permit reduced receiver bandwidth or are less demanding of SNR — CW 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, in which case there is no frequency that supports communication on the particular path at that time.

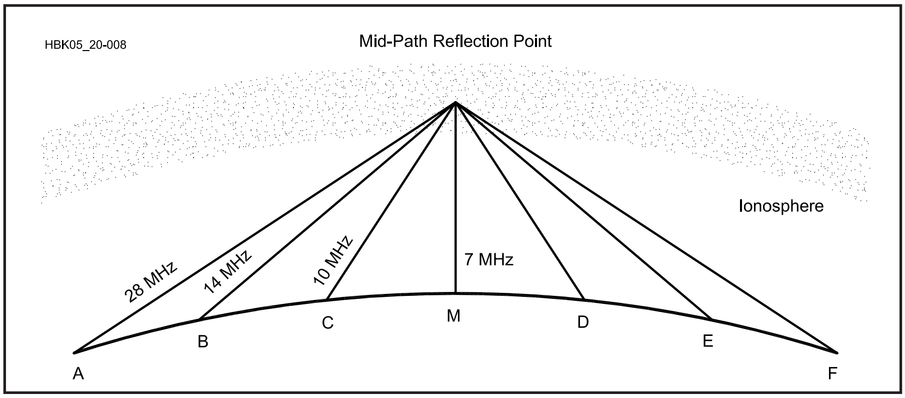

Fig 20.8—The relationships between critical frequency, maximum usable frequency (MUF) and skip zone can be visualized in this simplified, hypothetical case. The critical frequency is 7 MHz, allowing frequencies below this to be used for short-distance ionospheric communication by stations in the vicinity of point M. These stations cannot communicate by the ionosphere at 14 MHz. Stations at points B and E (and beyond) can communicate because signals at this frequency are refracted back to Earth 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.

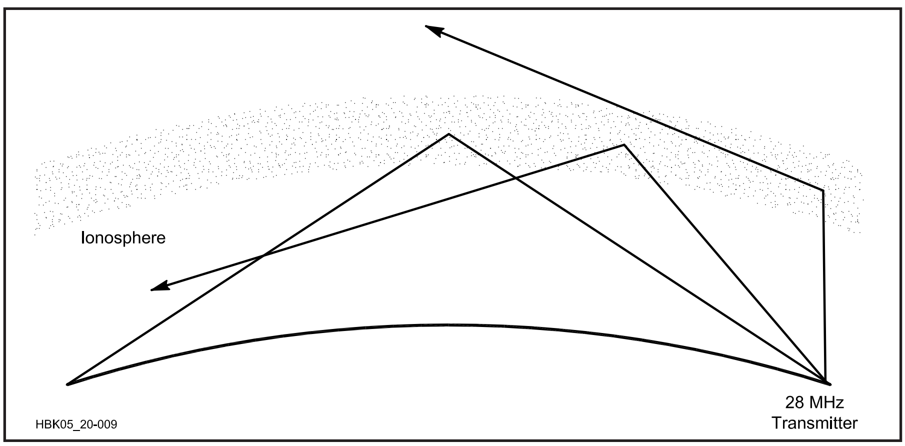

Fig 20.9—Signals at the MUF propagated at a low angle to the horizon provide the longest possible one-hop distances. In this example, 28-MHz signals entering the ionosphere at higher angles are not refracted enough to bring them back to Earth.

Table 20.2
Maximum Usable Frequency Factors (MUFF)

Layer	*Maximum Critical Frequency (MHz)*	*MUFF*	*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
D*	Not observed	—	None

* Daylight only

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 a 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.

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 an average sunspot number of over 200, the highest recorded to date. **Fig 20.10** shows average monthly sunspot numbers for the past four cycles.

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. 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 sunspot number varies from near zero during the solar-cycle minimum to over 200.

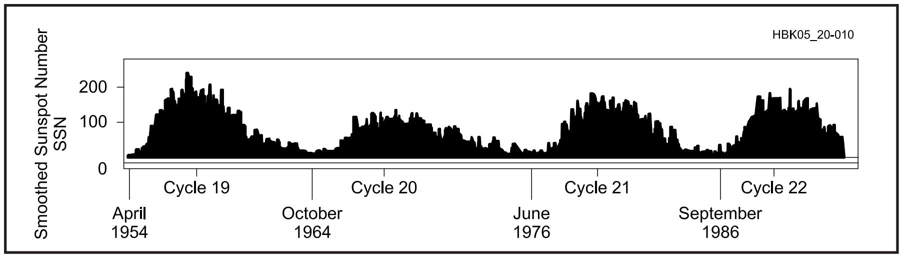

Fig 20.10—Average monthly sunspot numbers for Solar Cycles 19 to 22.

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. The 2800-MHz radio flux correlates well with the intensity of ionizing UV and X-ray radiation and provides a convenient alternative to sunspot numbers. It commonly varies on a scale of 60-300 and can be related to sunspot numbers, as shown in **Fig 20.11**. The Dominion Radio Astrophysical Observatory, Penticton, British Columbia, measures the 2800-MHz solar flux daily at local noon. (Prior to June 1991, the Algonquin Radio Observatory, Ontario, made the measurements.) Radio station WWV broadcasts the latest solar-flux index at 18 minutes after each hour; WWVH does the same at 45 minutes after the hour. The Penticton solar flux is employed in a wide variety of other applications. Daily, weekly, monthly and even 13-month smoothed average solar flux readings are commonly used in propagation predictions.

High flux values generally result in higher MUFs, but the actual procedures for predicting the MUF at any given hour and path are 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.

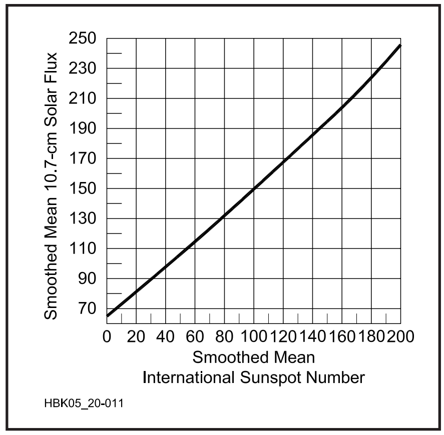

Fig 20.11—Approximate conversion between solar flux and sunspot number.

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. 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.

Solar-Ionospheric Disturbances

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 has to be considered pretty impressive!

There are two main types of solar eruptions, distinguished partly by where they originate on the sun: solar flares and coronal mass ejections. A *solar flare* erupts from the sun's surface, and its main effect is to launch out into space a wide spectrum of electromagnetic energy, although a big flare can also release matter into space, mainly in the form of energetic protons. 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.

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. The reality of how the sun operates is far more complex than initially expected. 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.

One surprise has been that a large CME can involve as much as half of the entire solar coronal region. Flares are far more limited spatially — they are launched from the area around active sunspot regions. At one time, scientists believed that 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.

While large flares can wreak disastrous effects on HF propagation, discussed further below, CMEs are the main causes of long-lasting magnetic storms here on Earth. Such storms can dramatically affect HF radio propagation — unfortunately, almost always in a negative fashion.

This is not to minimize the effects that a major solar flare can have on ionospheric propagation. After all, NASA rightly calls solar flares "the biggest explosions in the solar system." X-ray radiation from a large flare aimed towards Earth can cause an immediate increase in D- and E-layer ionization known as a *sudden ionospheric disturbance* (SID). Severe D-layer absorption may cause a short-term blackout of all HF communications on the sun-facing side of the Earth. Signals in the 2 to 30-MHz range may completely disappear. In extreme cases, nearly all background noise will be gone as well. SIDs may last up to an hour, after which ionospheric conditions temporarily return to normal.

Very energetic protons ejected during a large flare, and arriving in the vicinity of the Earth from several minutes to several hours after the flare, can penetrate deep into the ionosphere at the Earth's poles. This can produce intense ionization and consequent absorption of HF signals known as a *polar cap absorption* (PCA) event. A PCA event may last for days, dramatically affecting transpolar HF propagation.

When a CME occurs, whether or not it accompanies a solar flare, most of the time the electrons and protons ejected from the sun do not reach the Earth. This is because their trajectory takes them in another direction. If they do reach Earth, however, they do so 20 to 40 hours after the CME. As these charged particles sweep past, if their magnetic orientation is just right, they can distort the Earth's geomagnetic field, causing a *geomagnetic storm*. This results in acceleration of the particles to energy levels that permit them to penetrate into the ionosphere at the poles. This tremendous energy influx causes auroral displays at mid-latitudes and can disrupt HF communications for several hours or even much longer. Extraordinary radio noise and interference can accompany geomagnetic storms and associated auroras, especially at HF. Radio emissions from solar flares may be heard as sudden increases in noise on the VHF bands.

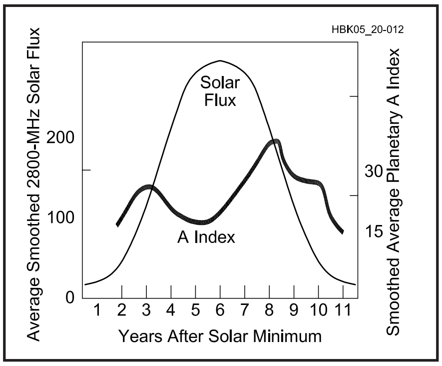

Fig 20.12—Geomagnetic activity (measured as the A-index) also follows an 11-year cycle. Average values over the past few cycles show that geomagnetic activity peaks before and after the peak of solar flux.

Table 20.3

Geomagnetic Storms

Typical Kp	*Description*	*Days per Solar Cycle*
9	Extreme	4
8	Severe	0
7	Strong	130
6	Moderate	360
5	Minor	900

Effects on *ionospheric storms* (another name for geomagnetic storms) at HF vary considerably. Communications may be temporarily blacked out during an SID, but ionospheric paths may be generally noisy, weakened or disrupted for several days. Transpolar signals at 14 MHz and higher may be considerably attenuated and take on a hollow multipath sound. The number of geomagnetic storms varies considerably from year to year, with peak geomagnetic activity following the peak of solar activity. See **Fig 20.12**.

Devices known as *magnetometers* monitor geomagnetic activity. 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 indexes. The *K index* provides an indication of magnetic activity on a finite scale of 0-9. Very quiet conditions are reported as 0 or 1, while geomagnetic storm levels begin at 4. See **Table 20.3** 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 *A index*, which corresponds roughly to the cumulative K index values. The A index commonly varies between 0 and 30 during quiet to active conditions, and up to 100 and higher during geomagnetic storms.

At 18 minutes past the hour, radio stations WWV and WWVH broadcast the latest solar flux number, the average planetary A-Index and the latest Boulder K-Index. In addition, they broadcast a descriptive account of the condition of the geomagnetic field and a forecast for the next three hours. 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 Boulder, Colorado. 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.

D-Layer Propagation

The *D layer* is the lowest region of the ionosphere, situated between 55 and 90 km

(30 and 60 mi). See **Fig 20.13**. It is ionized primarily by the strong ultraviolet emission of solar hydrogen and short X-rays, both of which penetrate through the upper atmosphere. 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 any radio signals.

Daytime D-Layer Absorption

Nevertheless, the D layer plays an important role in HF communications. During daylight hours, radio energy as high as 5 MHz is effectively absorbed by the D 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.

Nighttime D Layer

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.

D-Layer Ionospheric Forward Scatter

Radio signals in the 25-100 MHz range can be scattered by ionospheric irregularities, turbulence and stratification in the D and lower reaches of the E layers. Signals propagated by ionospheric forward scatter undergo very high losses, so signals are apt to be very weak. Typical scatter distances at 50 MHz are 800-1500 km (500-930 mi). This is not a common mode of propagation, but under certain conditions, ionospheric forward scatter can be very useful.

Ionospheric forward scatter is best during daylight hours from 10 AM to 2 PM local time, when the sun is highest in the sky and D-layer ionization peaks. It is worst at night. Scattering may be marginally more effective during the summer and during the solar cycle maximum due to somewhat higher D-layer ionization. The maximum path length of about 2000 km (1200 mi) is limited by the height of the scattering region, which is centered about 70 km (40 mi). Ionospheric scatter signals are typically weak, fluttery and near the noise level. Ionization from meteors sometimes temporarily raises signals well out of the noise for up to a few seconds at a time.

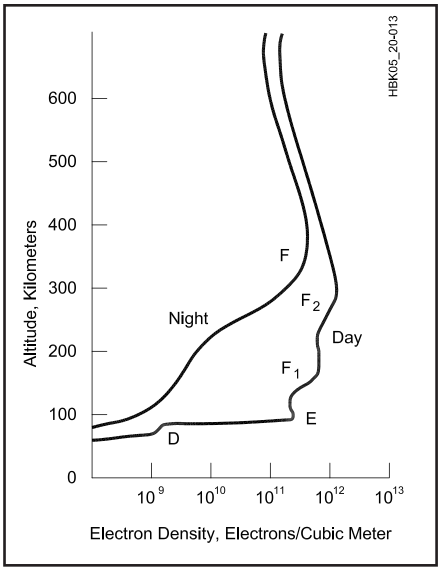

Fig 20.13—Typical electron densities for the various ionospheric regions.

This mode may find its greatest use when all other forms of propagation are absent, primarily because ionospheric scatter signals are so weak. For best results at 28 and 50 MHz, a 3-element Yagi or larger, several hundred watts of power and a sensitive receiver are required. The paths are direct. CW is preferred, although, under optimal conditions, ionospheric scatter signals may be consistent enough to support SSB communications. Scattering is not efficient below 25 MHz. The very best-equipped pairs of 144-MHz stations may also be able to complete ionospheric scatter contacts.

E-Layer Propagation

The *E layer* lies between 90 and 150 km (60 and 90 mi) altitude, but a narrower region centered at 95 to 120 km (60 to 70 mi) is more important for radio propagation. E-layer nitrogen and oxygen atoms are ionized by short UV and long X-ray radiation. 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 all but disappears.

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 a maximum MUF factor of about 4.8, suggests that single-hop E-layer skip might be useful between 5 and 20 MHz at distances up to 2300 km (1400 mi). 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 mi) 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 finds 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 aberrant forms of 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-m 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 mi). 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 mi) on the 10-m band and disappear entirely on 15 m. Unusual multiple-hop E_s has supported contacts up to 10,000 km (6200 mi) on 28 and 50 MHz and more than 3,000 km (1900 mi) 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 midlatitudes (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 is most likely to occur from 9 AM to noon local time and again early in the evening between 5 PM and 8 PM. Midlatitude E_s events may last only a few minutes to 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 midlatitude 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 mi) altitude and 10 to 100 km (6 to 60 mi) 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 mi), it is an indication 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 mi), should then be possible at 50 MHz. E-skip contacts as short as 700 km (435 mi) on 50 MHz, in turn, may indicate that 144-MHz contacts in the 2300-km (1400 mi) range can be completed. See **Fig 20.14**. Sporadic-E openings occur about a tenth as often at 144 MHz in comparison to 50 MHz and for much shorter periods.

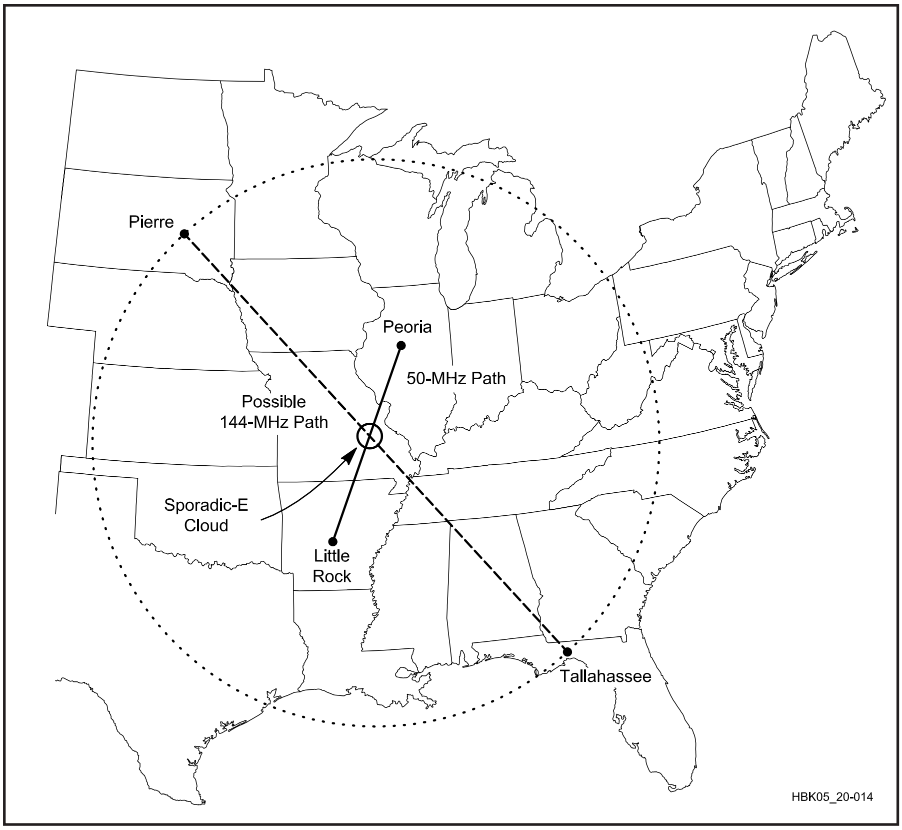

Fig 20.14—50 MHz sporadic-E contacts of 700 km (435 mi) or shorter (such as between Peoria and Little Rock) indicate that the MUF on longer paths is above 144 MHz. Using the same sporadic-E region reflecting point, 144-MHz contacts of 2200 km (1400 mi), such as between Pierre and Tallahassee, should be possible.

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 appear 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 mi).

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 mi) apart can be completed. See **Fig 20.15**. 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, high-energy particles flow into the ionosphere 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 midlatitudes. Auroral ionization in the E layer 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-m band late in the afternoon may become weak and watery. The 20-m 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, providing 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. Radio aurora activity is usually heard first in late afternoon and may reappear later in the evening. Auroras may be anticipated by following the A- and K-index 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 mi) 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.

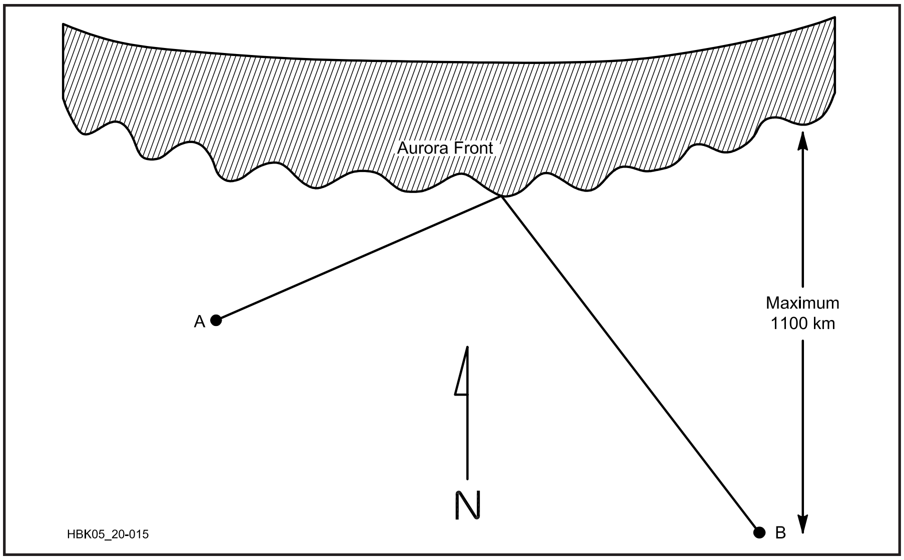

Fig 20.15—Point antennas generally north to make oblique long-distance contacts on 28 through 432 MHz via aurora scattering. Optimal antenna headings may shift considerably to the east or west depending on the location of the aurora.

Auroral E

Radio auroras may evolve into a propagation mode known as *auroral E* at 28, 50 and rarely 144 MHz. 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 mi), typical for E-layer modes, but 28- and 50-MHz auroral-E contacts of 5000 km (3100 mi) 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, although only one such contact has been reported.

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.

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-m 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. At least two other rare instances of 2-m auroral E have been reported.

Meteor Scatter

Contacts between 800 and 2300 km (500 and 1400 mi) can be made at 28 through 432 MHz via reflections from the ionized trails left by meteors as they travel through the ionosphere. The kinetic energy of meteors no larger than grains of rice are sufficient to ionize a column of air 20 km (12 mi) 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, the average rotational speed of the Earth in orbit. See **Fig 20.16**. 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.

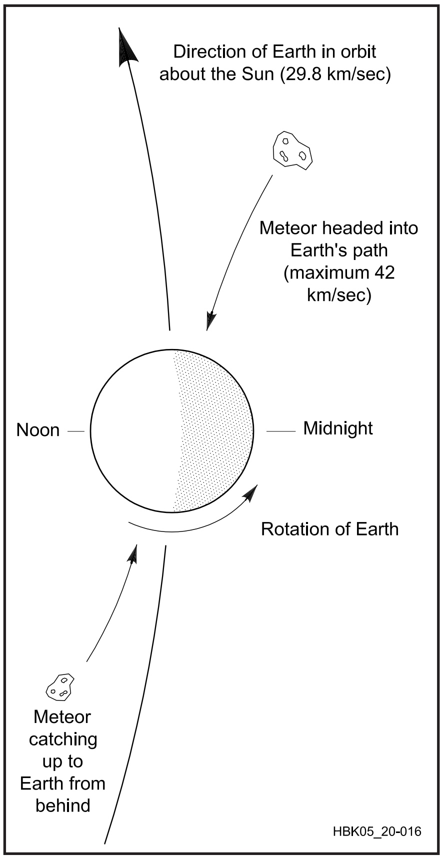

Fig 20.16—The relative velocity of meteors that meet the Earth head-on is increased by the rotational velocity of the Earth in orbit. Fast meteors strike the morning side of the Earth because their velocity adds to the Earth's rotational velocity, while the relative velocity of meteors that "catch up from behind" is reduced.

Meteor scatter opportunities are somewhat better during July and August 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 20.4**. A meteor shower occurs when the Earth passes through a relatively dense stream of particles, thought to be the remnants of a comet, that are also in orbit around the sun. The most-productive showers are relatively consistent from year to year, although several can produce great storms periodically.

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. Nonscheduled 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.

F-Layer Propagation

The region of the *F layers*, from 150 km (90 mi) to over 400 km (250 mi) 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 mi) and disappears at night. The F_2 layer extends above 250 km (160 mi), with a peak of ionization around 300 km (190 mi). At night, F-region ionization collapses into one broad layer at 300-400 km (190-250 mi) altitude. Ions recombine very slowly at these altitudes, because molecular density is relatively low. Maximum ionization levels change significantly with time of day, season and year of the solar cycle.

Table 20.4
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

F_1 Layer

The daytime F_1 layer is not important to HF communication. 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 mi), but these would be practically indistinguishable from F_2 skip.

F_2 and Nighttime F Layers

The F_2 layer forms between 250 and 400 km (160 and 250 mi) during the daytime and persists throughout the night as a single consolidated F region 50 km (30 mi) 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 UV solar radiation, which in turn follows closely 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 F_2 averages 330 km (210 mi), but varies between 200 and 400 km (120 and 250 mi). Maximum one-hop distance is about 4000 km (2500 mi).

Near-vertical incidence skywave propagation just below the critical frequency provides reliable coverage out to 200-300 km (120-190 mi) with no skip zone. It is most often observed on 7 MHz during the day.

The extraordinary high-angle *Pedersen Ray* can create effective single-hop paths of 5,000 to 12,000 km under certain conditions, but most operators will not be able to distinguish Pedersen-Ray paths from normal F-layer propagation. Pedersen-Ray paths are most evident over high-latitude east-west paths at frequencies near the MUF. They appear most often about noon local time at mid-path when the geomagnetic field is very quiet. Pedersen-Ray propagation may be responsible for 50 MHz paths between the US Northeast and Western Europe, for example, when ordinary MUF analysis could not explain the 5,000-km contacts. See **Fig 20.17E**.

In general, both F_2-layer ionization and MUF build rapidly at sunrise, usually reach a maximum in the afternoon, and then decrease to a minimum prior to 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 the Earth moving closer to the Sun and tilting. Wintertime 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 mi) 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 halfway around the Earth. Each hop involves additional attenuation and absorption, so the longest-distance signals tend to be the weakest. Even so, it is possible for signals to be propagated completely around the world and arrive back at their originating point. Multiple reflections within the F layer may bypass ground reflections altogether, creating what are known as *chordal hops*, with lower total attenuation. It takes a radio signal about 0.15 second to make a round-the-world trip.

Multihop paths can take on many different configurations, as shown in the examples of Fig 20.17. 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 multihop 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.

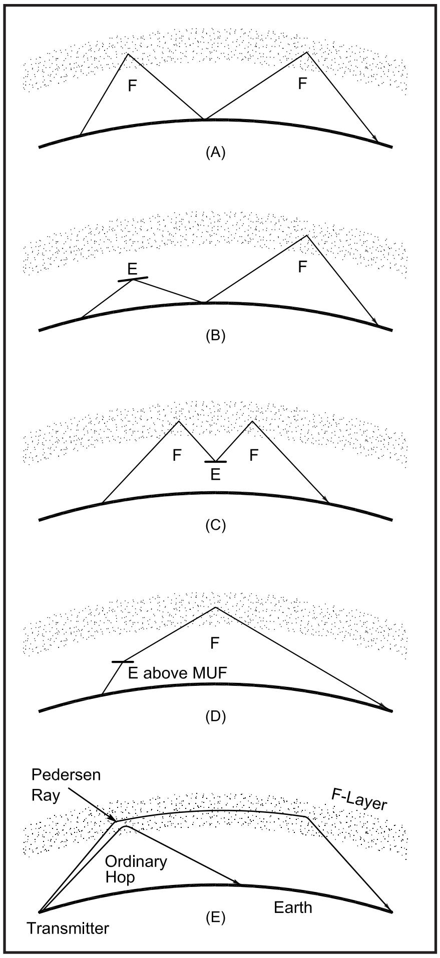

Fig 20.17—Multihop paths can take many different configurations, including a mixture of E- and F-layer hops. (A) Two F-layer hops. Five or more consecutive F-layer hops are possible. (B) An E-layer hookup to the F layer. (C) A top-side E-layer reflection can shorten the distance of two F-layer hops. (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 mi) or more. This is considerably further than the normal 4000-km (2500 mi) 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.

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 mi) — 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 mi) 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. There are times when the short path may be closed or disrupted by E-layer blanketing, 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 take into account the unusual ionospheric configuration along the twilight region between night and day. The gray line, as the twilight region is sometimes called, extends completely around the world. 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 the end of the day and sunset.

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.

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 20.18**. 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. *The ARRL Operating Manual* provides sunrise and sunset times over the entire year for several hundred worldwide locations. The position of the gray line on any date can also be plotted manually on a globe from these data.

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 mi) to the normal one-hop distance of 4000 km (2500 mi).

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 20.19**.

Sidescatter usually refers to a circuit that is oblique to the normal great-circle 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. US 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 density, such as between night and day, the path may take on a different geometry, as shown in **Fig 20.20**. 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.

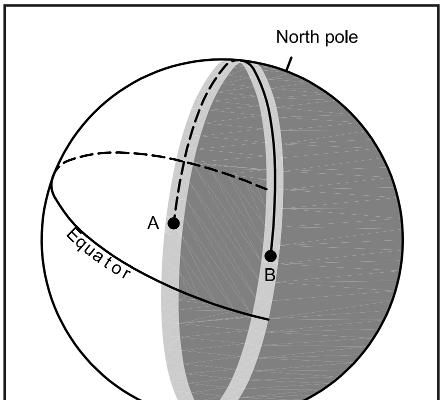

Fig 20.18—The gray line encircles the Earth, but the tilt at the equator to the poles varies over 46° with the seasons. Long-distance contacts can often be made halfway around the Earth along the gray line, even as low as 1.8 and 3.5 MHz. The strength of the signals, characteristic of gray-line propagation, 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, are involved.

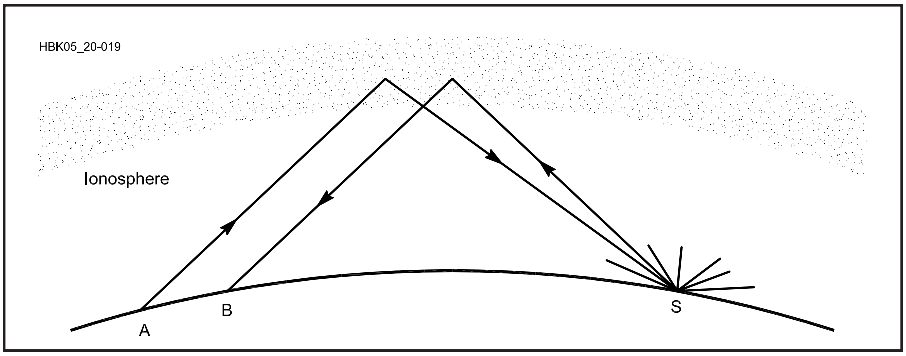

Fig 20.19—Schematic of a simple backscatter path. Stations A and B are too close to make contact via normal F-layer ionospheric refraction. Signals scattered back from a distant point on the Earth's surface (S), often the ocean, may be accessible to both and create a backscatter circuit.

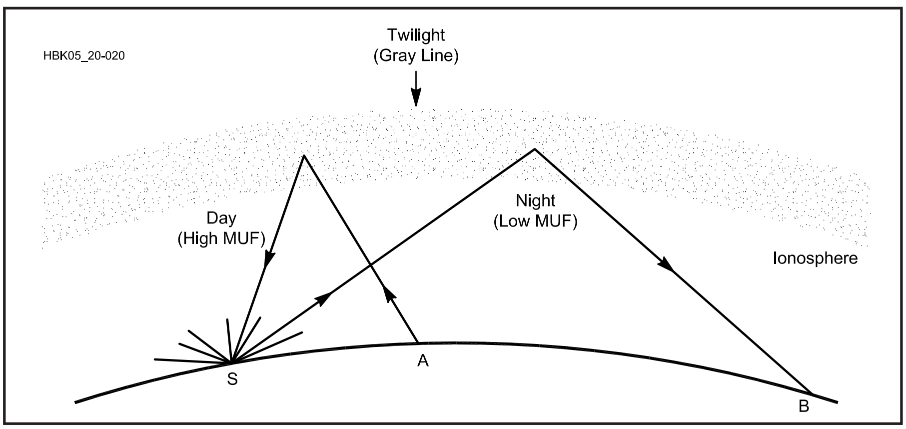

Fig 20.20—Backscatter path across the gray line. Stations A and B are too close to make contact via normal ionospheric refraction, but may hear each other's signals scattered from point S. Station A makes use of a high-angle refraction on the day side of the gray line, where the MUF is high. Station 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.

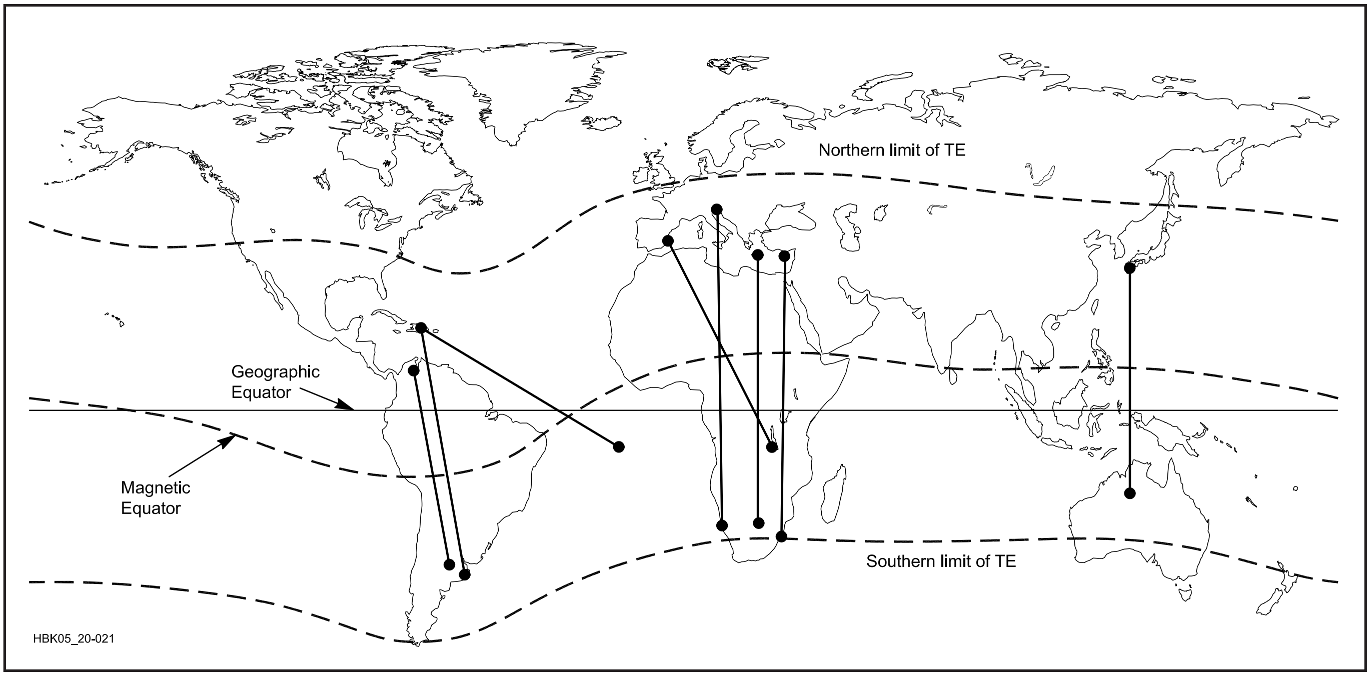

Fig 20.21—Transequatorial spread-F propagation takes place between stations equidistant across the geomagnetic equator. Distances up to 8000 km (5000 mi) are possible on 28 through 432 MHz. Note the geomagnetic equator is considerably south of the geographic equator in the Western Hemisphere.

Transequatorial Spread-F

Discovered in 1947, *transequatorial spread-F* (TE) supports propagation between 5000 and 8000 km (3100 and 5000 mi) across the 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. TE signals have been heard at 432 MHz, but so far, no two-way contacts have resulted.

Unfortunately for most continental US stations, the *geomagnetic equator* dips south of the geographic equator in the Western Hemisphere, as shown in **Fig 20.21**, 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 spread-F 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. Signals have a rough aurora-like note, sometimes termed *flutter fading*. High power and large antennas are not required to work TE, as VHF stations with 100 W and single long Yagis have been successful.

The best explanation of TE propagation suggests that the F_2 layer near the equator bulges and intensifies slightly, particularly during solar maxima. Irregular field-aligned ionization forms shortly after sunset in an area 100-200 km (60-120 mi) north and south of the geomagnetic equator and 500-3000 km (310-1900 mi) wide. For this reason, the mode is sometimes called *transequatorial field-aligned irregularities*. It moves west with the setting sun. The MUF may increase to twice its normal level 15° either side of the geomagnetic equator.

Field alignment of ionospheric irregularities favors refraction along magnetic field lines, that is north-south. VHF and UHF signals are refracted twice over the geomagnetic equator at angles that normally would be insufficient to bring the signals back toward Earth. See **Fig 20.22**. The geometry is such that two shallow reflections in the F_2 layer can create north-south terrestrial paths up to 8000 km (5000 mi).

Spread-F propagation also occurs over the polar regions, but because of low population densities, amateurs have rarely reported making use of it. Near the northern magnetic pole (located in extreme northeastern Canada), spread-F is a nearly permanent feature of winter. During summer, it appears most summer nights and at least half the time during the day. There is a greater probability of polar spread-F appearing during the equinox periods and during the solar cycle maximum. Field-alignment in the polar regions suggests that some form of backscatter signals, similar to aurora, would be most likely.

MUF PREDICTION

F-layer MUF prediction is key to forecasting HF communications paths at particular frequencies, dates and times, but

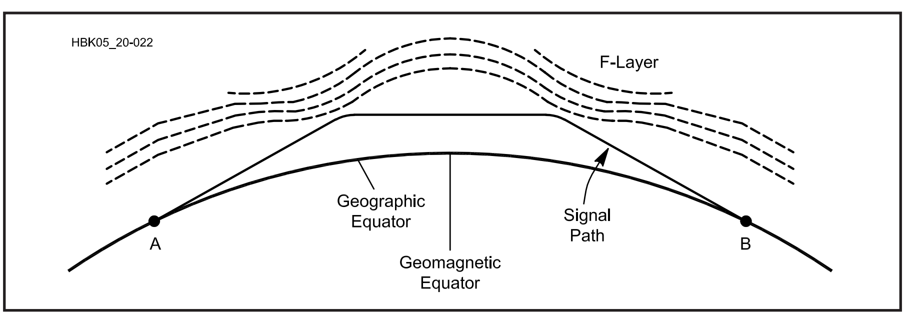

Fig 20.22—Cross-section of a transequatorial spread-F signal path, showing the effects of ionospheric bulging and a double refraction above the normal MUF.

forecasting is complicated by several variables. Solar radiation varies over the course of the day, season, year and solar cycle. 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.

MUF Forecasts

Long-range forecasts several months ahead, such as those formerly published in *QST* and other journals, provide only the most general form of prediction. A series of 48 charts on the members-only ARRLWeb site (**www.arrl.org/qst/propcharts/**), similar to **Fig 20.23**, 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 20.23 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 the calculated times when a band will open and close is reliable. You would use a long-range forecast to determine when you should start monitoring a band to see if propagation actually does occur that day, particularly at frequencies above 30 MHz.

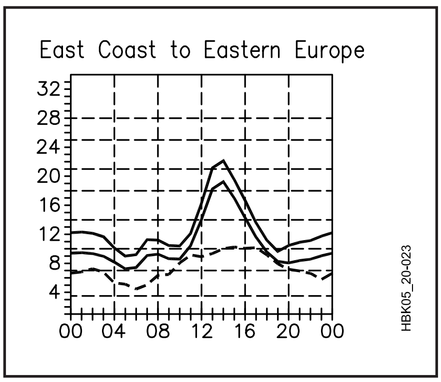

Fig 20.23—Propagation prediction chart for West Coast to Western Europe from the ARRLWeb members-only site for April 2001. An average 2800-MHz (10.7-cm) solar flux of 159 was assumed for the month. On 10% of the days, the highest frequency propagated is predicted to be at least as high as the uppermost 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.

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 also enhance short-term forecasts. Daily forecasts are even more reliable, because they are based on current solar and geophysical data, as well as warnings provided by observations of the sun in the visual to X-ray range.

The CD-ROM bundled with the 20th Edition of *The ARRL Antenna Book* contains even more detailed propagation-prediction tables from 150+ QTHs 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 WWW. Forecasts can also be made at home using one of several popular programs for personal computers, including *ASAPS*, *CAPMan*, *VOACAP*, *W6ELProp* and *WinCAP Wizard 2*.

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-m 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 20.5**) 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.

Table 20.5
Shortwave Broadcasting Bands

Frequency (MHz)	*Band (m)*
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

WWV and WWVH

The standard time stations WWV (Ft 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 is also available by telephoning the recorded message at 303-497-3235 or various Web sites, such as **dx.qsl.net/propagation/index.html**. 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.

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 designed by the Northern California DX Foundation, operating at 14.100, 18.110, 21.150, 24.930 and 28.200 MHz. Eleven beacons on five continents transmit in eighteen successive

Table 20.6
Popular Beacon Frequencies

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

one-minute intervals. More on this system, along with a longer list of HF, VHF and UHF beacons, can be found in *The ARRL Operating Manual*. Other interested groups publish updated lists of beacons with call sign, frequency, location, transmitter mode, power, and antenna. 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 20.6** provides the frequencies where beacons useful to HF propagation are most commonly placed.

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 the weather.

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.

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

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

where

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

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

Atmospheric Absorption

Atmospheric gases, most notably oxygen and water vapor, absorb radio signals, but neither is a significant factor below 10 GHz. Attenuation from rain becomes important at 3.3 GHz, where signals passing through 20 km (12 mi) of heavy showers incur an additional 0.2 dB loss. That same rain would impose 12 dB additional loss at 10 GHz and losses continue to increase with frequency. Heavy fog is similarly a problem only at 5.6 GHz and above. More detailed information about atmospheric absorption in the microwave bands can be found in the *ARRL UHF/Microwave Experimenter's Manual*.

Tropospheric Scatter

Contacts beyond the radio horizon out to a working distance of 100 to 500 km (60 to 310 mi), depending on frequency, equipment 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 wave-length sized gradients in the index of refraction of the

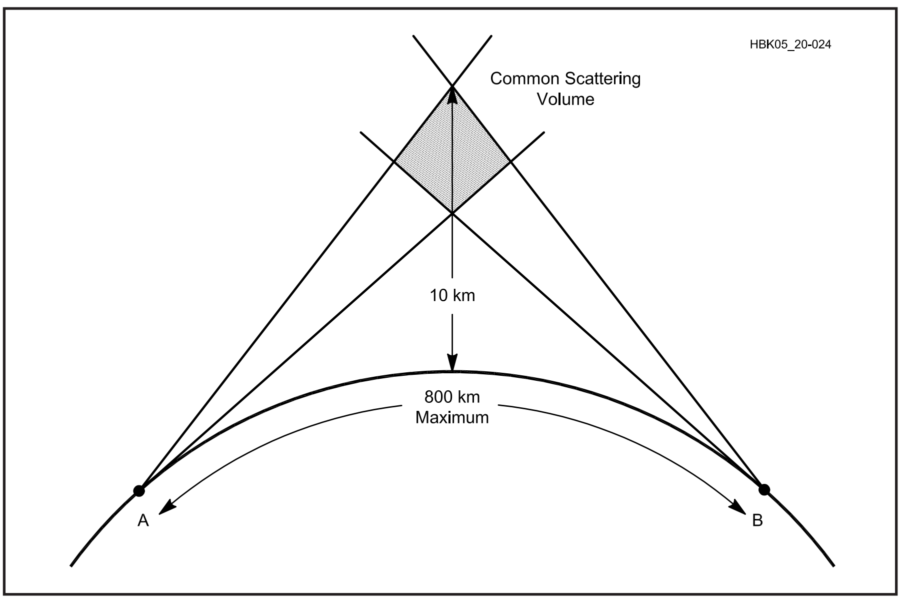

Fig 20.24—Tropospheric-scatter path geometry. The lower boundary of the common scattering volume is limited by the take-off angle of both stations. The upper boundary of 10 km (6 mi) altitude is the limit of efficient scattering in the troposphere. Signal strength increases with the scattering volume.

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 20.24**. The highest altitude for which scattering is efficient at amateur power levels is about 10 km (6 mi). An application of the distance-to-the-horizon formula yields 800 km (500 mi) as the limit for troposcatter paths, but typical maxima are more like 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

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 a 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.

It used to be possible to classify propagation-prediction programs by whether they were used primarily for heavy-duty, long-term forecasting — for planning a high-power shortwave broadcast station, for example — or for making a short-term forecast, perhaps to check out whether a band might be open today for a particular DXpedition. But with the increasing amount of computing power available nowadays, that distinction has blurred. What follows is some brief information about commercially available propagation-prediction programs for the IBM PC and compatible computers. See **Table 20.A**.

ASAPS Version 5

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/index.php**.

IONCAP, CAPMan 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.

CAPMan is a DOS-based version of *IONCAP* that is considerably more "user friendly" than the core program. *CAPMan* produces excellent graphs, some calibrated in S units if the user wishes. It incorporates amateur call signs to specify locations, making it comfortable for amateurs to use. *CAPMan* also allows the user to specify multiple antenna types for both transmitting and receiving. See: **www.taborsoft.com**/.

VOACAP is another version of *IONCAP*, 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 is now 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, CO. 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: **elbert.its.bldrdoc.gov/hf.html**.

W6ELProp, Version 1.0

In 2001, W6EL ported his well known DOS-based *MINIPROP PLUS* program into the Windows world. It uses the same Fricker-based computation engine as its predecessor. *W6ELProp* has a highly intuitive, ham-friendly user interface. It produces the same detailed output tables as its DOS counterpart, 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**.

WinCAP Wizard 2

Kangaroo Tabor Software sells the *CAPMan* program and is also the creator of the *Active Beacon Wizard* program included with the 19th and 20th Editions of *The ARRL Antenna Book*. They also sell a Windows-based "mini" version of *CAPMan*, called *WinCAP Wizard 2*. This range for rain scatter is as great as 600 km (370 mi), but the experience of amateurs in the microwave bands suggests that expected distances are less than 200 km (120 mi). 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.

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 mi) 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. Useful temperature inversions form between 250 and 2000 m (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.

uses the *CAPMan* computing engine but limits the number of input parameters to those most commonly used by amateurs. The outputs are customizable and include dynamic summary tables, sunrise/sunset tables and propagation maps.

PropLab Pro, Version 2

PropLab Pro by Solar Terrestrial Dispatch represents the high end of propagation-prediction programs. It is the only commercial program presently available that can do complete 3D ray tracing through the ionosphere, even taking complex geomagnetic effects into account. The number of computations is huge, especially in the full-blown 3D mode and operation can be slow and tedious. The user interface is also very complex and demanding, with a steep user-learning curve. However, it is fascinating to see exactly how a signal can bend off-azimuth or how it can split into the ordinary and extraordinary waves. See: **www.spacew.com/www/proplab.html**.

Table 20.A
Features and Attributes of Propagation Prediction Programs

	ASAPS V. 5	*VOACAP Windows*	*W6ELProp V. 1.00*	*CAPMan*	*WinCAP Wizard 2*	*PropLab Pro*
User Friendliness	Good	Good	Good	Good	Good	Poor
Operating System	Windows	Windows	Windows	DOS	Windows	DOS
Uses k index	No	No	Yes	Yes	Yes	Yes
User library of QTHs	Yes/Map	Yes	Yes	Yes	Yes	No
Bearings, distances	Yes	Yes	Yes	Yes	Yes	Yes
MUF calculation	Yes	Yes	Yes	Yes	Yes	Yes
LUF calculation	Yes	Yes	No	Yes	Yes	Yes
Wave angle calculation	Yes	Yes	Yes	Yes	Yes	Yes
Vary minimum wave angle	Yes	Yes	Yes	Yes	Yes	Yes
Path regions and hops	Yes	Yes	Yes	Yes	Yes	Yes
Multipath effects	Yes	Yes	No	Yes	Yes	Yes
Path probability	Yes	Yes	Yes	Yes	Yes	Yes
Signal strengths	Yes	Yes	Yes	Yes	Yes	Yes
S/N ratios	Yes	Yes	Yes	Yes	Yes	Yes
Long path calculation	Yes	Yes	Yes	Yes	Yes	Yes
Antenna selection	Yes	Yes	Indirectly	Yes	Isotropic	Yes
Vary antenna height	Yes	Yes	Indirectly	Yes	No	Yes
Vary ground characteristics	Yes	Yes	No	Yes	No	No
Vary transmit power	Yes	Yes	Indirectly	Yes	Yes	Yes
Graphic displays	Yes	Yes	Yes	Yes	Yes	2D/3D
UT-day graphs	Yes	Yes	Yes	Yes	Yes	Yes
Area Mapping	Yes	Yes	Yes	Yes	No	Yes
Documentation	Yes	On-line	Yes	Yes	Yes	Yes
Price class	$275 [1]	free [2]	free [3]	$89 [4]	$29.95 [4]	$150 [5]

Prices are for early 2004 and are subject to change.

[1]ASAPS: shipping and handling extra. See: **www.ips.gov.au/index.php**
[2]VOACAP available at: **elbert.its.bldrdoc.gov/hf.html**
[3]W6EL Prop, see: **www.qsl.net/w6elprop**
[4]CAPMan and WinCAP Wizard 2, see: **www.taborsoft.com/**
[5]PropLab Pro, see: **www.spacew.com/www/proplab.html**

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 20.25**.

The cooling process may continue through the evening and predawn hours, creating inversions that extend as high as 500 m (1500 ft). Deep radiation inversions are most common during clear, calm, summer evenings. 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 m (1500-10,000 ft) altitude, as shown in **Fig 20.26**. 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 20.27**.

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.

Semipermanent 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 mi) 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 mi) from Florida and the Carolinas to the West Indies, but its full potential has not been exploited. Other semipermanent highs lie in the Indian Ocean, the western Pacific and off the coast of western Africa.

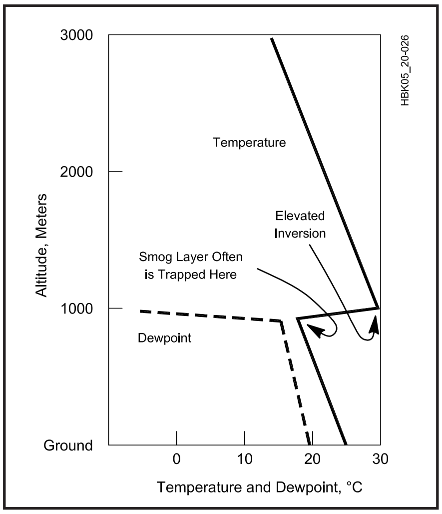

Fig 20.26—Temperature and humidity profile across an elevated duct at 1000-m altitude. Such inversions typically form in summertime high-pressure systems. Note the air is very dry in the inversion.

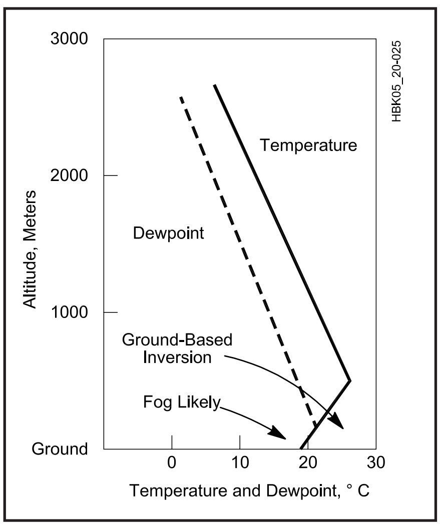

Fig 20.25—Temperature and dewpoint profile of an early-morning radiation inversion. Fog may form near the ground. The midday surface temperature would be at least 30°C.

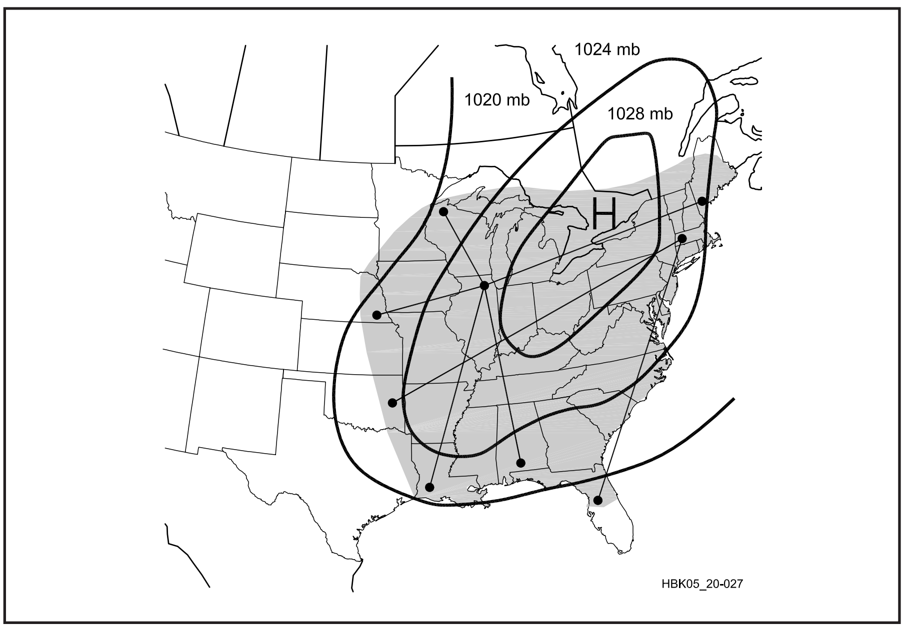

Fig 20.27—Surface weather map for September 13, 1993, shows that the eastern US was dominated by a sprawling high-pressure system. The shaded portion shows the area in which ducting conditions existed on 144 through 1286 MHz and higher.

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 20.28**, north-south radio paths 1500 km (930 mi) 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 m (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 mi) 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 20.29**. The warmer ocean air, in turn, travels at 200-300 m (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 mi) 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 mi) across the Mediterranean.

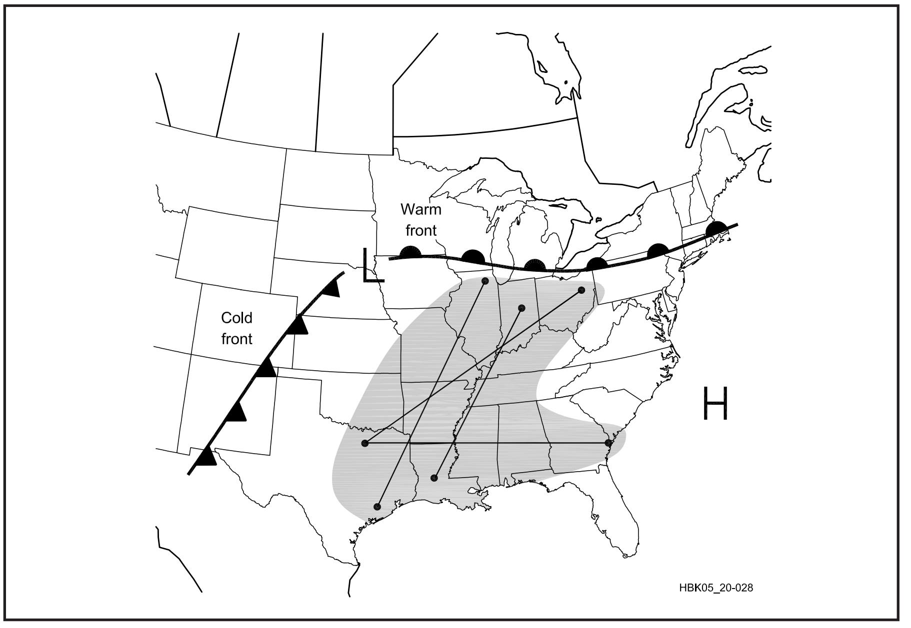

Fig 20.28—Surface weather map for June 2, 1980, with a typical spring wave cyclone over the southeastern quarter of the US. The shaded portion shows where ducting conditions existed.

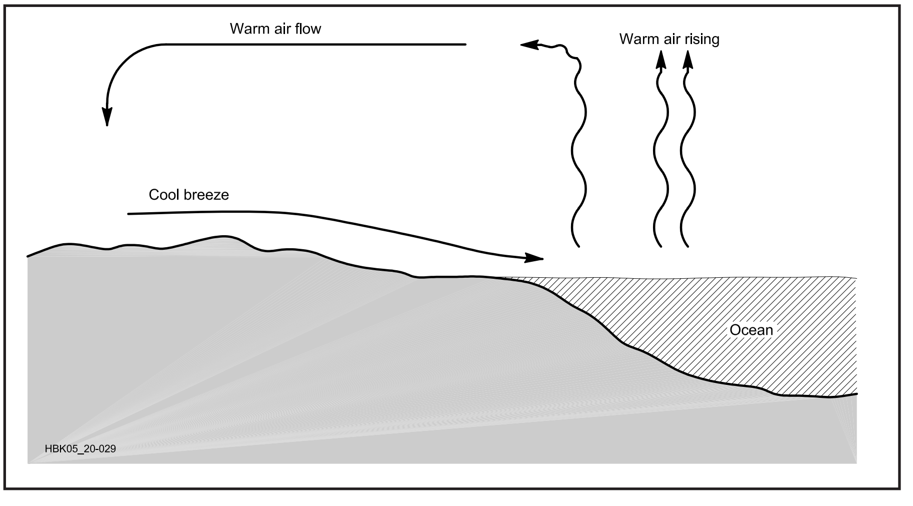

Fig 20.29—Land-breeze convection along a coast after sunset creates a temperature inversion over the land.

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 m (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 Fading

Tropospheric turbulence and small changes in the weather are responsible for most fading at VHF and higher. Local weather conditions, such as precipitation, warm air rising over cities and the effects of lakes and rivers, can all contribute to tropospheric instabilities that affect radio propagation. *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 ordinary tropospheric signal and that reflected by the airplane change with the airplane's movement.

EXTRATERRESTRIAL PROPAGATION

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. 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.

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. An additional 20 dB of path loss is incurred when polarization is shifted by 90°, an intolerable amount when signals are marginal.

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 one 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 and one with right-hand polarization.

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 of 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 chapter on **Space Communications**.

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 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 chapter on **Space Communications**.

NOISE AND PROPAGATION

Noise simply consists of unwanted radio signals that interfere 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 and cosmic. Interference from other transmitting stations on adjacent frequencies is not usually considered noise and may be controlled, to a some degree anyway, by careful station design.

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 **EMI/DFing** 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.

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.

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 raindrops, 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.

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.

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