Chapter 23

Radio Wave Propagation

Because radio communication is carried on by means of electromagnetic waves traveling through the Earth's atmosphere, it is important to understand the nature of these waves and their behavior in the propagation medium. Most antennas will radiate the power applied to them efficiently, but no antenna can do all things equally well, under all circumstances. Whether you design and build your own antennas, or buy them and have them put up by a professional, you'll need propagation know-how for best results, both during the planning stages and while operating your station.

For station planning, this chapter contains detailed new information on elevation angles from transmitting locations throughout the world to important areas throughout the world. With this information in hand, you can design your own antenna installation for optimum capabilities possible within your budget. See the CD-ROM in back of this book.

The Nature of Radio Waves

You probably have some familiarity with the concept of electric and magnetic fields. A radio wave is a combination of both, with the energy divided equally between them. If the wave could originate at a point source in free space, it would spread out in an ever-growing sphere, with the source at the center. No antenna can be designed to do this, but the theoretical *isotropic antenna* is useful in explaining and measuring the performance of practical antennas we *can* build. It is, in fact, the basis for any discussion or evaluation of antenna performance.

Our theoretical spheres of radiated energy would expand very rapidly at the same speed as the propagation of light, approximately 186,000 miles or 300,000,000 meters per second. These values are close enough for practical purposes, and are used elsewhere in this book. If one wishes to be more precise, light propagates in a vacuum at the speed of 299.7925 meters per microsecond, and slightly slower in air.

The path of a *ray* traced from its source to any point on a spherical surface is considered to be a straight line—a radius of the sphere. An observer on the surface of the sphere would think of it as being flat, just as the Earth seems flat to us. A radio wave far enough from its source to appear flat is called a *plane wave*. From here on, we will be discussing primarily plane waves.

It helps to understand the radiation of electromagnetic energy if we visualize a plane wave as being made up of electric and magnetic forces, as shown in **Fig 1**. The nature of wave propagation is such that the electric and magnetic lines of force are always perpendicular. The plane containing the sets of crossed lines represents the wave front. The direction of travel is always perpendicular to the wave front; *forward* or *backward* is determined by the relative directions of the electric and magnetic forces.

The speed of travel of a wave through anything but a vacuum is always less than 300,000,000 meters per second. How much less depends on the medium. If it is air, the reduction in propagation speed can be ignored in most discussions of propagation at frequencies below 30 MHz. In the VHF range and higher, temperature and moisture content of the medium have increasing effects on the communication range, as will be discussed later. In solid insulating materials the speed is considerably less. In distilled water (a good insulator) the speed is $1/9$ that in free space. In good conductors the speed is so low that the opposing fields set up by the wave front occupy practically the same space as the wave itself, and thus cancel it out. This is the reason for "skin effect" in conductors at high frequencies, making metal enclosures good shields for electrical circuits working at radio frequencies.

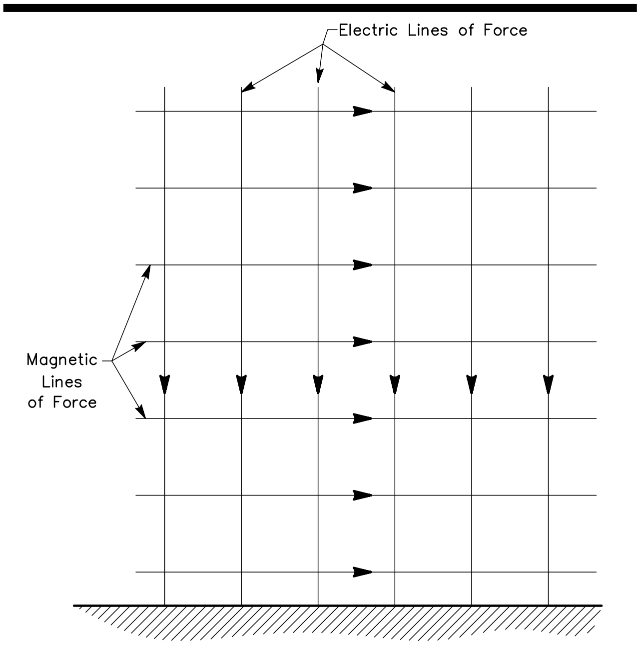

Fig 1—Representation of the magnetic and electric fields of a vertically polarized plane wave traveling along the ground. The arrows indicate instantaneous directions of the fields for a wave traveling perpendicularly out of the page toward the reader. Reversal of the direction of one set of lines reverses the direction of travel. There is no change in direction when both sets are reversed. Such a dual reversal occurs in fact once each half cycle.

Phase and Wavelength

Because the velocity of wave propagation is so great, we tend to ignore it. Only $^1/_7$ of a second is needed for a radio wave to travel around the world—but in working with antennas the *time* factor is extremely important. The wave concept evolved because an alternating current flowing in a wire (antenna) sets up moving electric and magnetic fields. We can hardly discuss antenna theory or performance at all without involving travel time, consciously or otherwise.

Waves used in radio communication may have frequencies from about 10,000 to several billion Hz. Suppose the frequency is 30 MHz. One cycle, or period, is completed in 1/30,000,000 second. The wave is traveling at 300,000,000 meters per second, so it will move only 10 meters during the time that the current is going through one complete period of alternation. The electromagnetic field 10 meters away from the antenna is caused by the current that was flowing one period earlier in time. The field 20 meters away is caused by the current that was flowing two periods earlier, and so on.

If each period of the current is simply a repetition of the one before it, the currents at corresponding instants in each period will be identical. The fields caused by those currents will also be identical. As the fields move outward from the antenna they become more thinly spread over larger and larger surfaces. Their amplitudes decrease with distance from the antenna but they do not lose their identity with respect to the instant of the period at which they were generated. They are, and they remain, *in phase*. In the example above, at intervals of 10 meters measured outward from the antenna, the phase of the waves at any given instant is identical.

From this information we can define both *wave front* and *wavelength*. Consider the wave front as an imaginary surface. On every part of this surface, the wave is in the same phase. The wavelength is the distance between two wave fronts having the same phase at any given instant. This distance must be measured perpendicular to the wave fronts along the line that represents the direction of travel. The abbreviation for wavelength is the Greek letter lambda, λ, which is used throughout this book.

The wavelength will be in the same length units as the velocity when the frequency is expressed in the same time units as the velocity. For waves traveling in free space (and near enough for waves traveling through air) the wavelength is

$$\lambda_{\text{meters}} = \frac{299.7925}{F(\text{MHz})} \qquad \text{(Eq 1)}$$

There will be few pages in this book where phase, wavelength and frequency do not come into the discussion. It is essential to have a clear understanding of their meaning in order to understand the design, installation, adjustment or use of antennas, matching systems or transmission lines in detail. In essence, *phase* means *time*. When something goes through periodic variations, as an alternating current does, corresponding instants in succeeding periods are *in phase*.

The points A, B and C in **Fig 2** are all in phase. They are corresponding instants in the current flow, at 1-λ intervals. This is a conventional view of a sine-wave alternating current, with time progressing to the right. It also represents a *snapshot* of the intensity of the traveling fields, if distance is substituted for time in the horizontal axis. The distance between A and B or between B and C is one wavelength. The field-intensity distribution follows the sine curve, in both amplitude and polarity, corresponding exactly to the time variations in the current that produced the fields. Remember that this is an *instantaneous* picture—the wave moves outward, much as a wave created by a rock thrown into water does.

Polarization

A wave like that in Fig 1 is said to be *polarized* in the direction of the electric lines of force. The polarization here is vertical, because the electric lines are perpendicular to the surface of the Earth. It is one of the laws of electromagnetics that electric lines touching the surface of a perfect conductor must do so perpendicularly, or else they would have to generate infinite currents in the conductor, an obvious impossibility. Most ground is a rather good conductor at frequencies below about 10 MHz, so waves at these

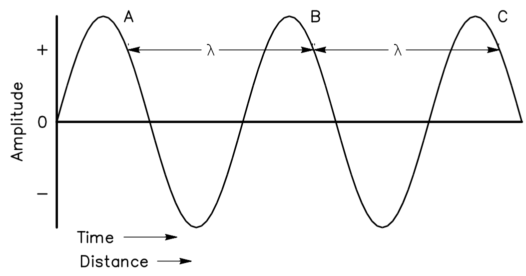

Fig 2—The instantaneous amplitude of both fields (electric and magnetic) varies sinusoidally with time as shown in this graph. Since the fields travel at constant velocity, the graph also represents the instantaneous distribution of field intensity along the wave path. The distance between two points of equal phase such as A-B and B-C is the length of the wave.

frequencies, traveling close to good ground, are mainly vertically polarized. Over partially conducting ground there may be a forward tilt to the wave front; the tilt in the electric lines of force increases as the energy loss in the ground becomes greater.

Waves traveling in contact with the surface of the Earth, called *surface waves*, are of little practical use in amateur communication. This is because as the frequency is raised, the distance over which they will travel without excessive energy loss becomes smaller and smaller. The surface wave is most useful at low frequencies and through the standard AM broadcast band. The surface wave will be covered later. At high frequencies a wave reaching a receiving antenna has had little contact with the ground, and its polarization is not necessarily vertical.

If the electric lines of force are horizontal, the wave is said to be *horizontally polarized*. Horizontally and vertically polarized waves may be classified generally under *linear polarization*. Linear polarization can be anything between horizontal and vertical. In free space, "horizontal" and "vertical" have no meaning, since the reference of the seemingly horizontal surface of the Earth has been lost.

In many cases the polarization of waves is not fixed, but rotates continually, somewhat at random. When this occurs the wave is said to be *elliptically polarized*. A gradual shift in polarization in a medium is known as *Faraday rotation*. For space communication, circular polarization is commonly used to overcome the effects of Faraday rotation. A circularly polarized wave rotates its polarization through 360° as it travels a distance of one wavelength in the propagation medium. The direction of rotation as viewed from the transmitting antenna defines the direction of circularity—right-hand (clockwise) or left-hand (counterclockwise). Linear and circular polarization may be considered as special cases of elliptical polarization.

Field Intensity

The energy from a propagated wave decreases with distance from the source. This decrease in strength is caused by the spreading of the wave energy over ever-larger spheres as the distance from the source increases.

A measurement of the strength of the wave at a distance from the transmitting antenna is its *field intensity*, which is synonymous with *field strength*. The strength of a wave is measured as the voltage between two points lying on an electric line of force in the plane of the wave front. The standard of measure for field intensity is the voltage developed in a wire that is 1 meter long, expressed as volts per meter. (If the wire were 2 meters long, the voltage developed would be divided by two to determine the field strength in volts per meter.)

The voltage in a wave is usually low, so the measurement is made in millivolts or microvolts per meter. The voltage goes through time variations like those of the current that caused the wave. It is measured like any other ac voltage—in terms of the effective value or, sometimes, the peak value. It is fortunate that in amateur work it is not necessary to measure actual field strength, as the equipment required is elaborate. We need to know only if an adjustment has been beneficial, so relative measurements are satisfactory. These can be made easily with home-built equipment.

Wave Attenuation

In free space, the field intensity of the wave varies inversely with the distance from the source, once you are in the radiating far field of the antenna. If the field strength at 1 mile from the source is 100 millivolts per meter, it will be 50 millivolts per meter at 2 miles, and so on. The relationship between field intensity and power density is similar to that for voltage and power in ordinary circuits. They are related by the impedance of free space, which is approximately 377 Ω. A field intensity of 1 volt per meter is therefore equivalent to a power density of

$$P = \frac{E^2}{Z} = \frac{1\,(\text{volt/m})^2}{377\,\Omega} = 2.65\ \text{mW/m}^2 \qquad \text{(Eq 2)}$$

Because of the relationship between voltage and power, the power density therefore varies with the square root of the field intensity, or inversely with the *square* of the distance. If the power density at 1 mile is 4 mW per square meter, then at a distance of 2 miles it will be 1 mW per square meter.

It is important to remember this so-called *spreading loss* when antenna performance is being considered. Gain can come only from narrowing the radiation pattern of an antenna, which concentrates the radiated energy in the desired direction. There is no "antenna magic" by which the total energy radiated can be increased.

In practice, attenuation of the wave energy may be much greater than the inverse-distance law would indicate. The wave does not travel in a vacuum, and the receiving antenna seldom is situated so there is a clear line of sight.

The Earth is spherical and the waves do not penetrate its surface appreciably, so communication beyond visual distances must be by some means that will bend the waves around the curvature of the Earth. These means involve additional energy losses that increase the path attenuation with distance, above that for the theoretical spreading loss in a vacuum.

Bending of Radio Waves

Radio waves and light waves are both propagated as electromagnetic energy. Their major difference is in wavelength, since radio-reflecting surfaces are usually much smaller in terms of wavelength than those for light. In material of a given electrical conductivity, long waves penetrate deeper than short ones, and so require a thicker mass for good reflection. Thin metal however is a good reflector of even long-wavelength radio waves. With poorer conductors, such as the Earth's crust, long waves may penetrate quite a few feet below the surface.

Reflection occurs at any boundary between materials of differing dielectric constant. Familiar examples with light are reflections from water surfaces and window panes. Both water and glass are transparent for light, but their dielectric constants are very different from that of air. Light waves, being very short, seem to bounce off both surfaces. Radio waves, being much longer, are practically unaffected by glass, but their behavior upon encountering water may vary, depending on the purity of that medium. Distilled water is a good insulator; salt water is a relatively good conductor.

Depending on their wavelength (and thus their frequency), radio waves may be reflected by buildings, trees, vehicles, the ground, water, ionized layers in the upper atmosphere, or at boundaries between air masses having different temperatures and moisture content. Ionospheric and atmospheric conditions are important in practically all communication beyond purely local ranges.

Refraction is the bending of a ray as it passes from one medium to another at an angle. The appearance of bending of a straight stick, where it enters water at an angle, is an example of light refraction known to us all. The degree of bending of radio waves at boundaries between air masses increases with the radio frequency. There is slight atmospheric bending in our HF bands. It becomes noticeable at 28 MHz, more so at 50 MHz, and it is much more of a factor in the higher VHF range and in UHF and microwave propagation.

Diffraction of light over a solid wall prevents total darkness on the far side from the light source. This is caused largely by the spreading of waves around the top of the wall, due to the interference of one part of the beam with another. The dielectric constant of the surface of the obstruction may affect what happens to our radio waves when they encounter terrestrial obstructions—but the radio *shadow area* is never totally dark. See Chapter 3, The Effects of Ground, for more information on diffraction.

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

GROUND WAVES

As we have already seen, radio waves are affected in many ways by the media through which they travel. This has led to some confusion of terms in earlier literature concerning wave propagation. Waves travel close to the ground in several ways, some of which involve relatively little contact with the ground itself. The term *ground wave* has had several meanings in antenna literature, but it has come to be applied to any wave that stays close to the Earth, reaching the receiving point without leaving the Earth's lower atmosphere. This distinguishes the ground wave from a *sky wave*, which utilizes the ionosphere for propagation between the transmitting and receiving antennas.

The ground wave could be traveling in actual contact with the ground, as in Fig 1, where it is called the *surface wave*. Or it could travel directly between the transmitting and receiving antennas, when they are high enough so they can "see" each other—this is commonly called the *direct wave*. The ground wave also travels between the transmitting and receiving antennas by reflections or diffractions off intervening terrain between them. The ground-influenced wave may interact with the direct wave to create a vector-summed resultant at the receiver antenna.

In the generic term ground wave, we also will include ones that are made to follow the Earth's curvature by bending in the Earth's lower atmosphere, or *troposphere*, usually no more than a few miles above the ground. Often called *tropospheric bending*, this propagation mode is a major factor in amateur communications above 50 MHz.

THE SURFACE WAVE

The surface wave travels in contact with the Earth's surface. It can provide coverage up to about 100 miles in the standard AM broadcast band during the daytime, but attenuation is high. As can be seen from **Fig 3**, the attenuation increases with frequency. The surface wave is of little value in amateur communication, except possibly at 1.8 MHz. Vertically polarized antennas must be used, which tends to limit amateur surface-wave communication to where large vertical systems can be erected.

THE SPACE WAVE

Propagation between two antennas situated within line of sight of each other is shown in **Fig 4**. Energy traveling directly between the antennas is attenuated to about the same degree as in free space. Unless the antennas are very high or

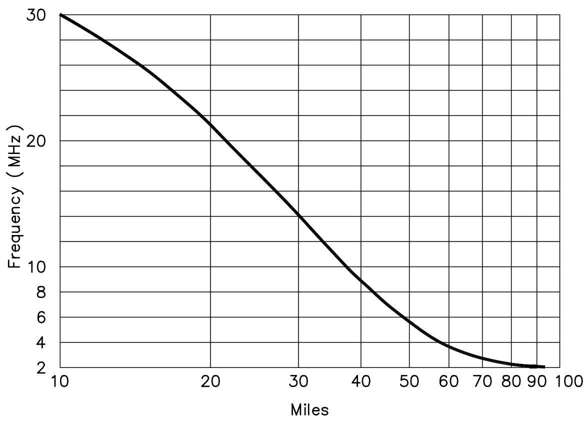

Fig 3—Typical HF ground-wave range as a function of frequency.

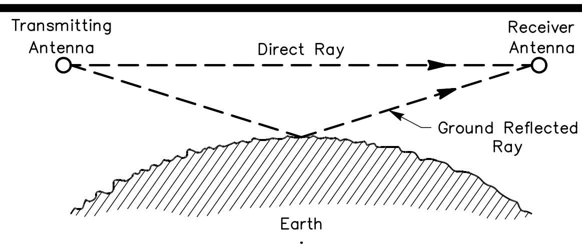

Fig 4—The ray traveling directly from the transmitting antenna to the receiving antenna combines with a ray reflected from the ground to form the space wave. For a horizontally polarized signal a reflection as shown here reverses the phase of the ground-reflected ray.

quite close together, an appreciable portion of the energy is reflected from the ground. This reflected wave combines with direct radiation to affect the actual signal received.

In most communication between two stations on the ground, the angle at which the wave strikes the ground will be small. For a horizontally polarized signal, such a reflection reverses the phase of the wave. If the distances traveled by both parts of the wave were the same, the two parts would arrive out of phase, and would therefore cancel each other. The ground-reflected ray in Fig 4 must travel a little further, so the phase difference between the two depends on the lengths of the paths, measured in wavelengths. The wavelength in use is important in determining the useful signal strength in this type of communication.

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

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

As with most propagation explanations, the space-wave picture presented here is simplified, and practical considerations dictate modifications. There is always some energy loss when the wave is reflected from the ground. Further, the phase of the ground-reflected wave is not shifted exactly 180°, so the waves never cancel completely. At UHF, ground-reflection losses can be greatly reduced or eliminated by using highly directive antennas. By confining the antenna pattern to something approaching a flashlight beam, nearly all the energy is in the direct wave. The resulting energy loss is low enough that microwave relays, for example, can operate with moderate power levels over hundreds or even thousands of miles. Thus we see that, while the space wave is inconsequential below about 20 MHz, it can be a prime asset in the VHF realm and higher.

VHF/UHF PROPAGATION BEYOND LINE OF SIGHT

From Fig 4 it appears that use of the space wave depends on direct line of sight between the antennas of the communicating stations. This is not literally true, although that belief was common in the early days of amateur communication on frequencies above 30 MHz. When equipment became available that operated more efficiently and after antenna techniques were improved, it soon became clear that VHF waves were actually being bent or scattered in several ways, permitting reliable communication beyond visual distances between the two stations. This was found true even with low power and simple antennas. The average communication range can be approximated by assuming the waves travel in straight lines, but with the Earth's radius increased by one-third. The distance to the *radio horizon* is then given as

$$D_{miles} = 1.415\sqrt{H_{feet}} \qquad \text{(Eq 3)}$$

or

$$D_{km} = 4.124\sqrt{H_{meters}} \qquad \text{(Eq 4)}$$

where H is the height of the transmitting antenna, as shown in **Fig 5**. The formula assumes that the Earth is smooth out to the horizon, so any obstructions along the path must be taken into consideration. For an elevated receiving antenna the communication distance is equal to D + D1, that is, the sum of the distances to the horizon of both

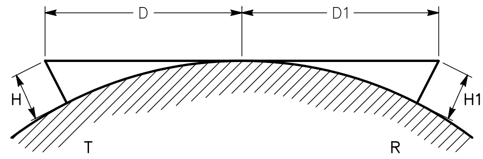

Fig 5—The distance D to the horizon from an antenna of height H is given by equations in the text. The maximum line-of-sight distance between two elevated antennas is equal to the sum of their distances to the horizon as indicated here.

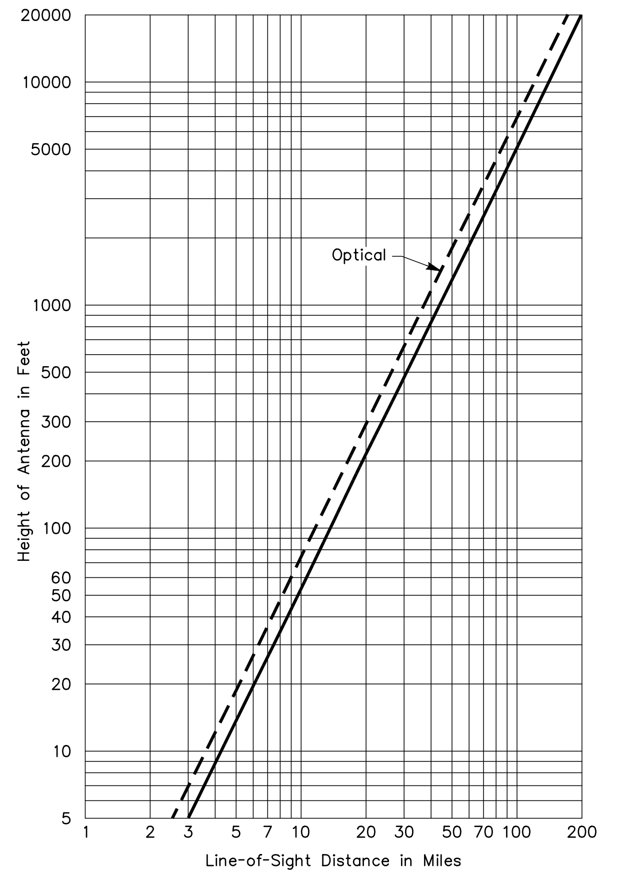

Fig 6—Distance to the horizon from an antenna of given height. The solid curve includes the effect of atmospheric retraction. The optical line-of-sight distance is given by the broken curve.

antennas. Radio horizon distances are given in graphic form in **Fig 6**. Two stations on a flat plain, one with its antenna 60 feet above ground and the other 40 feet, could be up to about 20 miles apart for strong-signal line-of-sight communication (11 + 9 mi). The terrain is almost never completely flat, however, and variations along the way may add to or subtract from the distance for reliable communication. Remember that energy is absorbed, reflected or scattered in many ways in nearly all communication situations. The formula or the chart will be a good guide for estimating the potential radius of coverage for a VHF FM repeater, assuming the users are mobile or portable with simple, omnidirectional antennas. Coverage with optimum home-station equipment, high-gain directional arrays, and SSB or CW is quite a different matter. A much more detailed method for estimating coverage on frequencies above 50 MHz is given later in this chapter.

For maximum use of the ordinary space wave it is important to have the antenna as high as possible above nearby buildings, trees, wires and surrounding terrain. A hill that rises above the rest of the countryside is a good location for an amateur station of any kind, and particularly so for extensive coverage on the frequencies above 50 MHz. The highest point on such an eminence is not necessarily the best location for the antenna. In the example shown in **Fig 7**, the hilltop would be a good site in all directions. But if maximum performance to the right is the objective, a point just below the crest might do better. This would involve a trade-off with reduced coverage in the opposite direction. Conversely, an antenna situated on the left side, lower down the hill, might do well to the left, but almost certainly would be inferior in performance to the right.

Selection of a home site for its radio potential is a complex business, at best. A VHF enthusiast dreams of the highest hill. The DX-minded HF ham may be more attracted by a dry spot near a salt marsh. A wide saltwater horizon, especially from a high cliff, just smells of DX. In shopping for ham radio real estate, a mobile or portable rig for the frequencies you're most interested in can provide useful clues.

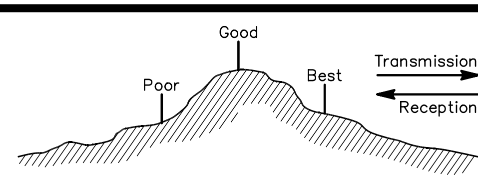

Fig 7—Propagation conditions are generally best when the antenna is located slightly below the top of a hill on the side facing the distant station. Communication is poor when there is a sharp rise immediately in front of the antenna in the direction of communication.

ANTENNA POLARIZATION

If effective communication over long distances were the only consideration, we might be concerned mainly with radiation of energy at the lowest possible angle above the horizon. However, being engaged in a residential avocation often imposes practical restrictions on our antenna projects. As an example, our 1.8 and 3.5-MHz bands are used primarily for short-distance communication because they serve that purpose with antennas that are not difficult or expensive to put up. Out to a few hundred miles, simple wire antennas for these bands do well, even though their radiation is mostly at high angles above the horizon. Vertical systems might be better for long-distance use, but they require extensive ground systems for good performance.

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

High-gain antennas are almost always used at 50 MHz and higher frequencies, and most of them are horizontal. The principal exception is mobile communication with FM through repeaters, discussed in Chapter 17, Repeater Antenna Systems. The height question is answered easily for VHF enthusiasts—the higher the better.

The theoretical and practical effects of height above ground at HF are treated in detail in Chapter 3, The Effects of Ground. Note that it is the height in *wavelengths* that is important—a good reason to think in the metric system, rather than in feet and inches.

In working locally on any amateur frequency band, best results will be obtained with the same polarization at both stations, except on rare occasions when polarization shift is caused by terrain obstructions or reflections from buildings. Where such a shift is observed, mostly above 100 MHz or so, horizontal polarization tends to work better than vertical. This condition is found primarily on short paths, so it is not too important. Polarization shift may occur on long paths where tropospheric bending is a factor, but here the effect tends to be random. Long-distance communication by way of the ionosphere produces random polarization effects, so polarization matching is of little or no importance. This is fortunate for the HF mobile enthusiast, who will find that even his short, inductively loaded whips work very well at all distances other than local.

Because it responds to all plane polarizations equally, circular polarization may pay off on circuits where the arriving polarization is random, but it exacts a 3-dB penalty when used with a single-plane polarization of any kind. Circular systems find greatest use in work with orbiting satellites. It should be remembered that "horizontal" and "vertical" are meaningless terms in space, where the plane-Earth reference is lost.

Polarization Factors Above 50 MHz

In most VHF communication over short distances, the polarization of the space wave tends to remain constant. Polarization discrimination is high, usually in excess of 20 dB, so the same polarization should be used at both ends of the circuit. Horizontal, vertical and circular polarization all have certain advantages above 50 MHz, so there has never been complete standardization on any one of them.

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

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

In communication over the Earth-Moon-Earth (EME) route the polarization picture is blurred, as might be expected with such a diverse medium. If the moon were a flat target, we could expect a 180° phase shift from the moon reflection process. But it is not flat. This plus the moon's *libration* (its slow oscillation, as viewed from the Earth), and the fact that waves must travel both ways through the Earth's entire atmosphere and magnetic field, provide other variables that confuse the phase and polarization issue. Building a huge array that will track the moon, and give gains in excess of 20 dB, is enough of a task that most EME enthusiasts tend to take their chances with phase and polarization problems. Where rotation of the element plane has been tried it has helped to stabilize signal levels, but it is not widely employed.

PROPAGATION OF VHF WAVES

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

Tropospheric scatter is always with us. Its effects are often hidden, masked by more effective propagation modes on the lower frequencies. But beginning in the VHF range, scatter from the lower atmosphere extends the reliable range markedly if we make use of it. Called *troposcatter*, this is what produces that nearly flat portion of the curves that will be described later (in the section where you can compute reliable VHF coverage range). With a decent station, you can consistently make troposcatter contacts out to 300 miles out on the VHF and even UHF bands, especially if you don't mind weak signals and something less than 99% reliability. As long ago as the early 1950s, VHF enthusiasts found that VHF contests could be won with high power, big antennas and a good ear for signals deep in the noise. They still can.

Ionospheric scatter works much the same as the tropo version, except that the scattering medium is higher up, mainly the E region of the ionosphere but with some help from the D and F layers too. Ionospheric scatter is useful mainly above the MUF, so its useful frequency range depends on geography, time of day, season, and the state of the Sun. With near maximum legal power, good antennas and quiet locations, ionospheric scatter can fill in the skip zone with marginally readable signals scattered from ionized trails of meteors, small areas of random ionization, cosmic dust, satellites and whatever may come into the antenna patterns at 50 to 150 miles or so above the Earth. It's mostly an E-layer business, so it works all E-layer distances. Good antennas and keen ears help.

Transequatorial propagation (TE) was an amateur 50-MHz discovery in the years 1946-1947. Amateurs of all continents observed it almost simultaneously on three separate north-south paths. These amateurs tried to communicate at 50 MHz, even though the predicted MUF was around 40 MHz for the favorable daylight hours. The first success came at night, when the MUF was thought to be even lower. A remarkable research program inaugurated by amateurs in Europe, Cyprus, Zimbabwe and South Africa eventually provided technically sound theories to explain the then-unknown mode.

It has been known for years that the MUF is higher and less seasonally variable on transequatorial circuits, but the full extent of the difference was not learned until amateur work brought it to light. As will be explained in a later section in more detail, the ionosphere over equatorial regions is higher, thicker and more dense than elsewhere. Because of its more constant exposure to solar radiation, the equatorial belt has high nighttime-MUF possibilities. TE can often work marginally at 144 MHz, and even at 432 MHz on occasion. The potential MUF varies with solar activity, but not to the extent that conventional F-layer propagation does. It is a late-in-the-day mode, taking over about when normal F-layer propagation goes out.

The TE range is usually within about 4000 km (2500 miles) either side of the geomagnetic equator. The Earth's magnetic axis is tilted with respect to the geographical axis, so the TE belt appears as a curving band on conventional flat maps of the world. See **Fig 8**. As a result, TE has a different latitude coverage in the Americas from that from Europe to Africa. The TE belt just reaches into the southern continental US. Stations in Puerto Rico, Mexico and even the northern parts of South America encounter the mode more often than those in favorable US areas. It is no accident that TE was discovered as a result of 50-MHz work in Mexico City and Buenos Aires.

Within its optimum regions of the world, the TE mode extends the usefulness of the 50-MHz band far beyond that of conventional F-layer propagation, since the practical TE MUF runs around 1.5 times that of normal F_2. Both its seasonal and diurnal characteristics are extensions of what is considered normal for 50-MHz propagation. In that part of the Americas south of about 20° North latitude, the existence of TE affects the whole character of band usage, especially in years of high solar activity.

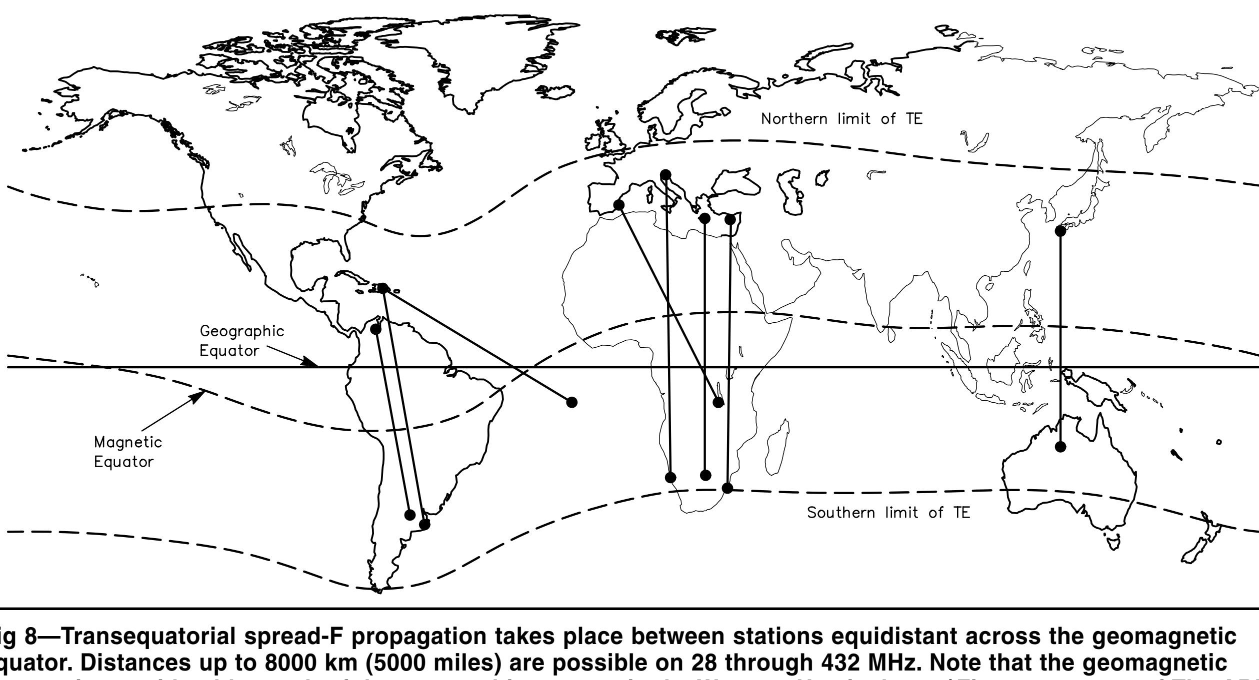

Fig 8—Transequatorial spread-F propagation takes place between stations equidistant across the geomagnetic equator. Distances up to 8000 km (5000 miles) are possible on 28 through 432 MHz. Note that the geomagnetic equator is considerably south of the geographic equator in the Western Hemisphere. (*Figure courtesy of The ARRL Handbook*.)

Weather Effects on VHF/UHF Tropospheric Propagation

Changes in the dielectric constant of the medium can affect propagation. Varied weather patterns over most of the Earth's surface can give rise to boundaries between air masses of very different temperature and humidity characteristics. These boundaries can be anything from local anomalies to air-circulation patterns of continental proportions.

Under stable weather conditions, large air masses can retain their characteristics for hours or even days at a time. See **Fig 9**. Stratified warm dry air over cool moist air, flowing slowly across the Great Lakes region to the Atlantic Seaboard, can provide the medium for east-west communication on 144 MHz and higher amateur frequencies over as much as 1200 miles. More common, however, are communication distances of 400 to 600 miles under such conditions.

A similar inversion along the Atlantic Seaboard as a result of a tropical storm air-circulation pattern may bring VHF and UHF openings extending from the Maritime Provinces of Canada to the Carolinas. Propagation across the Gulf of Mexico, sometimes with very high signal levels, enlivens the VHF scene in coastal areas from Florida to Texas. The California coast, from below the San Francisco Bay Area to Mexico, is blessed with a similar propagation aid during the warmer months. Tropical storms moving west, across the Pacific below the Hawaiian Islands, may provide a transpacific long-distance VHF medium. Amateurs first exploited this on 144, 220 and 432 MHz, in 1957. It has been used fairly often in the summer months since, although not yearly.

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

There is a diurnal effect in temperate climates. At sunrise the air aloft is warmed more rapidly than that near the Earth's surface, and as the Sun goes lower late in the day the upper air is kept warm, while the ground cools. In fair, calm weather such sunrise and sunset temperature inversions can improve signal strength over paths beyond line of sight as much as 20 dB over levels prevailing during the hours of high sun. The diurnal inversion may also extend the operating range for a given strength by some 20 to 50%. If you would be happy with a new VHF antenna, try it first around sunrise!

There are other short-range effects of local atmospheric and topographical conditions. Known as *subsidence*, the flow of cool air down into the bottom of a valley, leaving warm air aloft, is a familiar summer-evening pleasure. The daily inshore-offshore wind shift along a seacoast in summer sets up daily inversions that make coastal areas highly favored as VHF sites. Ask any jealous 144-MHz operator who lives more than a few miles inland.

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

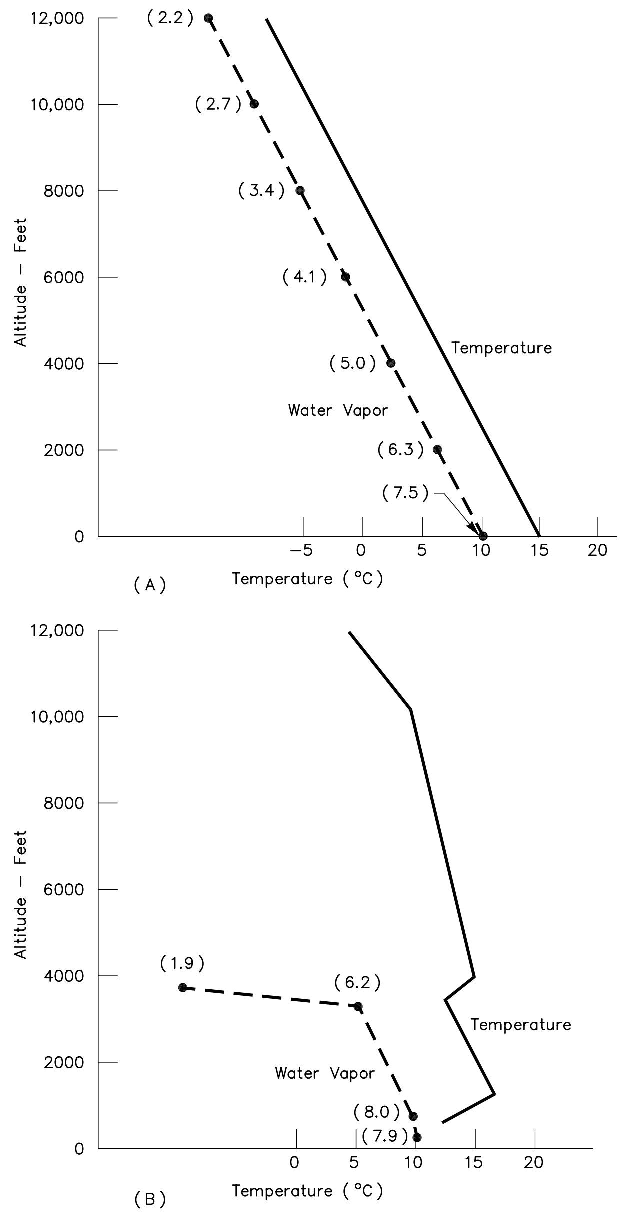

Fig 9—Upper air conditions that produce extended-range communication on the VHF bands. At the top is shown the US Standard Atmosphere temperature curve. The humidity curve (dotted) is what would result if the relative humidity were 70%, from ground level to 12,000 feet elevation. There is only slight refraction under this standard condition. At the bottom is shown a sounding that is typical of marked refraction of VHF waves. Figures in parentheses are the "mixing ratio" —grams of water vapor per kilogram of dry air. Note the sharp break in both curves at about 3500 feet.

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

Tropospheric Ducting

Tropospheric propagation of VHF and UHF waves can influence signal levels at all distances from purely local to something beyond 4000 km (2500 miles). The outer limits are not well known. At the risk of over simplification, we will divide the modes into two classes—extended local and long distance. This concept must be modified depending on the frequency under consideration, but in the VHF range the extended-local effect gives way to a form of propagation much like that of microwaves in a waveguide, called *ducting*. The transition distance is ordinarily somewhere around 200 miles. The difference lies in whether the atmospheric condition producing the bending is localized or continental in scope. Remember, we're concerned here with frequencies in the VHF range, and perhaps up to 500 MHz. At 10 GHz, for example, the scale is much smaller.

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

Amateurs have played a major part in the discovery and eventual explanation of tropospheric propagation. In recent years they have shown that, contrary to beliefs widely held in earlier times, long-distance communication using tropospheric modes is possible to some degree on all amateur frequencies from 50 to at least 10,000 MHz.

RELIABLE VHF COVERAGE

In the preceding sections we discussed means by which amateur bands above 50 MHz may be used intermittently for communication far beyond the visual horizon. In emphasizing distance we should not neglect a prime asset of the VHF band: reliable communication over relatively short distances. The VHF region is far less subject to disruption of local communication than are frequencies below 30 MHz. Since much amateur communication is essentially local in nature, our VHF assignments can carry a great load, and such use of the VHF bands helps solve interference problems on lower frequencies.

Because of age-old ideas, misconceptions about the coverage obtainable in our VHF bands persist. This reflects the thoughts that VHF waves travel only in straight lines, except when the DX modes described above happen to be present. However, let us survey the picture in the light of modern wave-propagation knowledge and see what the bands above 50 MHz are good for on a day-to-day basis, ignoring the anomalies that may result in extensions of normal coverage.

It is possible to predict with fair accuracy how far you should be able to work consistently on any VHF or UHF band, provided a few simple facts are known. The factors affecting operating range can be reduced to graph form, as described in this section. The information was originally published in November 1961 *QST* by D. W. Bray, K2LMG (see the Bibliography at the end of this chapter).

To estimate your station's capabilities, two basic numbers must be determined: station gain and path loss. Station gain is made up of seven factors: receiver sensitivity, transmitted power, receiving antenna gain, receiving antenna height gain, transmitting antenna gain, transmitting antenna height gain and required signal-to-noise ratio. This looks complicated but it really boils down to an easily made evaluation of receiver, transmitter, and antenna performance. The other number, path loss, is readily determined from the nomogram, **Fig 10**. This gives path loss over smooth Earth, for 99% reliability.

For 50 MHz, lay a straightedge from the distance between stations (left side) to the appropriate distance at the right side. For 1296 MHz, use the full scale, right center. For 144, 222 and 432, use the dot in the circle, square or triangle, respectively. Example: At 300 miles the path loss for 144 MHz is 214 dB.

To be meaningful, the losses determined from this nomograph are necessarily greater than simple free-space path losses. As described in an earlier section, communication beyond line-of-sight distances involves propagation modes that increase the path attenuation with distance.

VHF/UHF Station Gain

The largest of the eight factors involved in station design is receiver sensitivity. This is obtainable from **Fig 11**, if you know the approximate receiver noise figure and transmission-line loss. If you can't measure noise figure, assume 3 dB for 50 MHz, 5 for 144 or 222, 8 for 432 and 10 for 1296 MHz, if you know your equipment is working moderately well. These noise figures are well on the conservative side for modern solid-state receivers.

Line loss can be taken from information in Chapter 24 for the line in use, if the antenna system is fed properly. Lay a straightedge between the appropriate points at either side of Fig 11, to find effective receiver sensitivity in decibels below 1 watt (dBW). Use the narrowest bandwidth that is practical for the emission intended, with the receiver you will be using. For CW, an average value for effective work

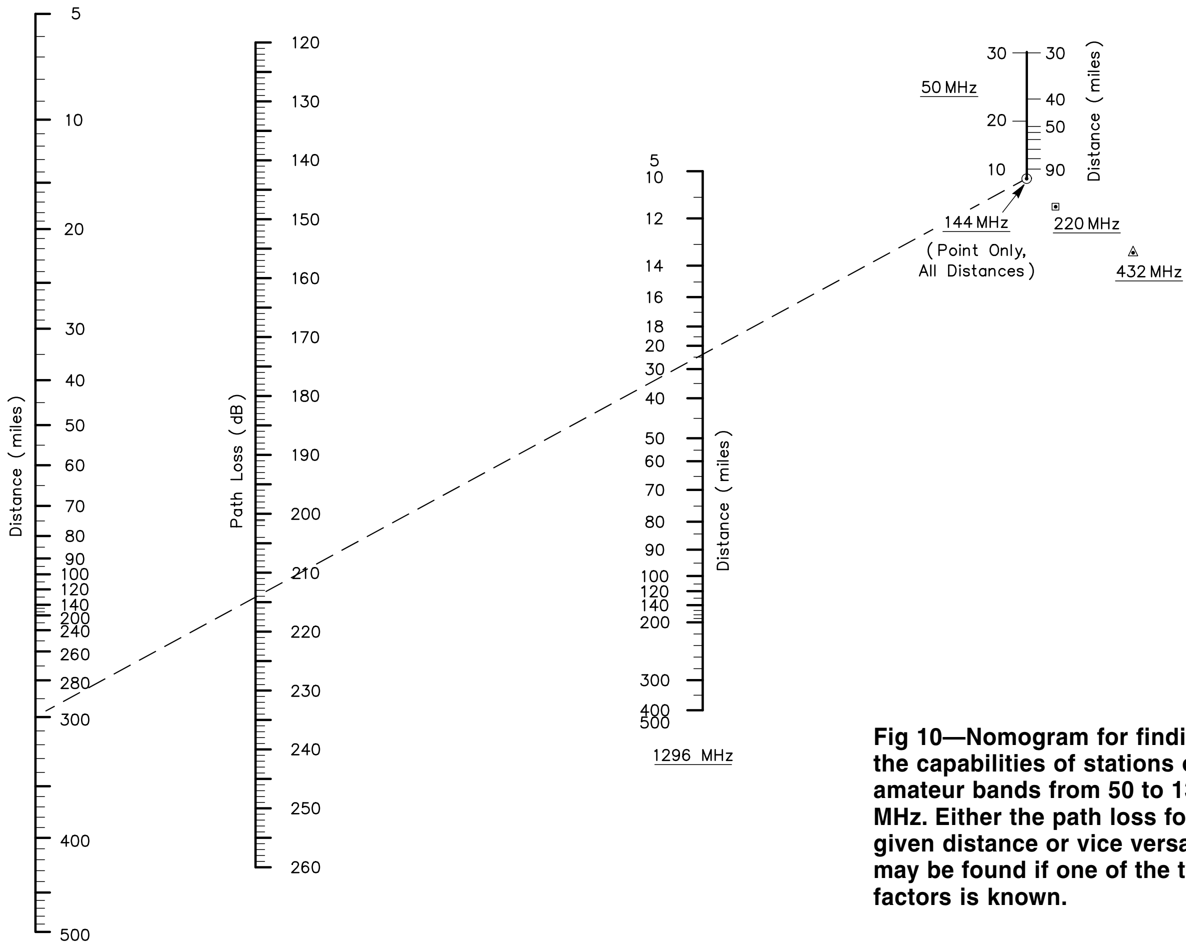

Fig 10—Nomogram for finding the capabilities of stations on amateur bands from 50 to 1300 MHz. Either the path loss for a given distance or vice versa may be found if one of the two factors is known.

is about 500 Hz. Phone bandwidth can be taken from the receiver instruction manual, but it usually falls between 2.1 to 2.7 kHz.

Antenna gain is next in importance. Gains of amateur antennas are often exaggerated. For well-designed Yagis the gain (over isotropic) run close to 10 times the boom length in wavelengths. (Example: A 24-foot Yagi on 144 MHz is 3.6 wavelengths long; 3.6 x 10 = 36, and $10 \log_{10} 36 =$ 15.5 dBi in free space.) Add 3 dB for stacking, where used properly. Add 4 dB more for ground reflection gain. This varies in amateur work, but averages out near this figure.

We have one more plus factor—antenna height gain, obtained from **Fig 12**. Note that this is greatest for short distances. The left edge of the horizontal center scale is for 0 to 10 miles, the right edge for 100 to 500 miles. Height gain for 10 to 30 feet is assumed to be zero. For 50 feet the height gain is 4 dB at 10 miles, 3 dB at 50 miles, and 2 dB at 100 miles. At 80 feet the height gains are roughly 8, 6 and 4 dB for these distances. Beyond 100 miles the height gain is nearly uniform for a given height, regardless of distance.

Transmitter power output must be stated in decibels above 1 watt. If you have 500 W output, add 10 log (500/1), or 27 dB, to your station gain. The transmission-line loss must be subtracted from the station gain. So must the required signal-to-noise ratio. The information is based on CW work, so the additional signal needed for other modes must be subtracted. Use a figure of 3 dB for SSB. Fading losses must be accounted for also. It has been shown that for distances beyond 100 miles, the signal will vary plus or minus about 7 dB from the average level, so 7 dB must be subtracted from the station gain for high reliability. For distances under 100 miles, fading diminishes almost linearly with distance. For 50 miles, use –3.5 dB for fading.

What It All Means

Add all the plus and minus factors to get the station gain. Use the final value to find the distance over which you can expect to work reliably from the nomogram, Fig 10. Or work it the other way around: Find the path loss for the distance you want to cover from the nomogram and then figure out what station changes will be needed to overcome it.

The significance of all this becomes more obvious when we see path loss plotted against frequency for the various bands, as in **Fig 13**. At the left this is done for 50% reliability. At the right is the same information for 99% reliability.

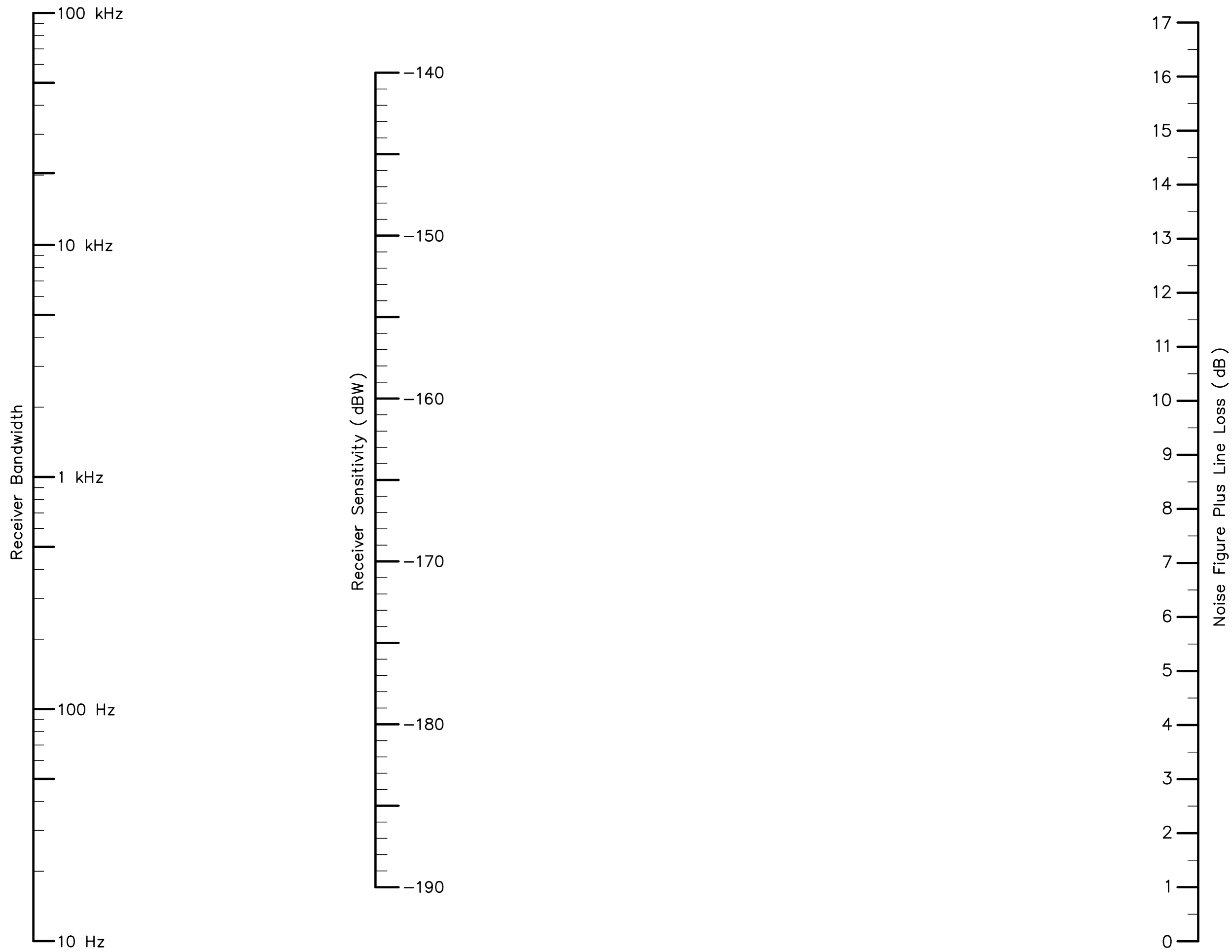

Fig 11—Nomogram for finding effective receiver sensitivity.

For near-perfect reliability, a path loss of 195 dB (easily encountered at 50 or 144 MHz) is involved in 100-mile communication. But look at the 50% reliability curve: The same path loss takes us out to well over 250 miles. Few amateurs demand near-perfect reliability. By choosing our times, and by accepting the necessity for some repeats or occasional loss of signal, we can maintain communication out to distances far beyond those usually covered by VHF stations.

Working out a few typical amateur VHF station setups with these curves will show why an understanding of these factors is important to any user of the VHF spectrum. Note that path loss rises very steeply in the first 100 miles or so. This is no news to VHF operators; locals are very strong, but stations 50 or 75 miles away are much weaker. What happens beyond 100 miles is not so well known to many of us.

From the curves of Fig 13, we see that path loss levels off markedly at what is the approximate limit of working range for average VHF stations using wideband modulation modes. Work out the station gain for a 50-W station with an average receiver and antenna, and you'll find that it comes out around 180 dB. This means you'd have about a 100-mile working radius in average terrain, for good but not perfect reliability. Another 10 dB may extend the range to as much as 250 miles. Just changing from AM phone to SSB and CW makes a major improvement in daily coverage on the VHF bands.

A bigger antenna, a higher one if your present beam is not at least 50 feet up, an increase in power to 500 W from 50 W, an improvement in receiver noise figure if it is presently poor—any of these things can make a big improvement in reliable coverage. Achieve all of them, and you will have very likely tripled your sphere of influence, thanks to that hump in the path-loss curves. This goes a long way toward explaining why using a 10-W packaged station with a small antenna, fun though it may be, does not begin to show what the VHF bands are really good for.

Terrain at VHF/UHF

The coverage figures derived from the above procedure are for average terrain. What of stations in mountainous country? Although an open horizon is generally desirable for the VHF station site, mountain country should not be

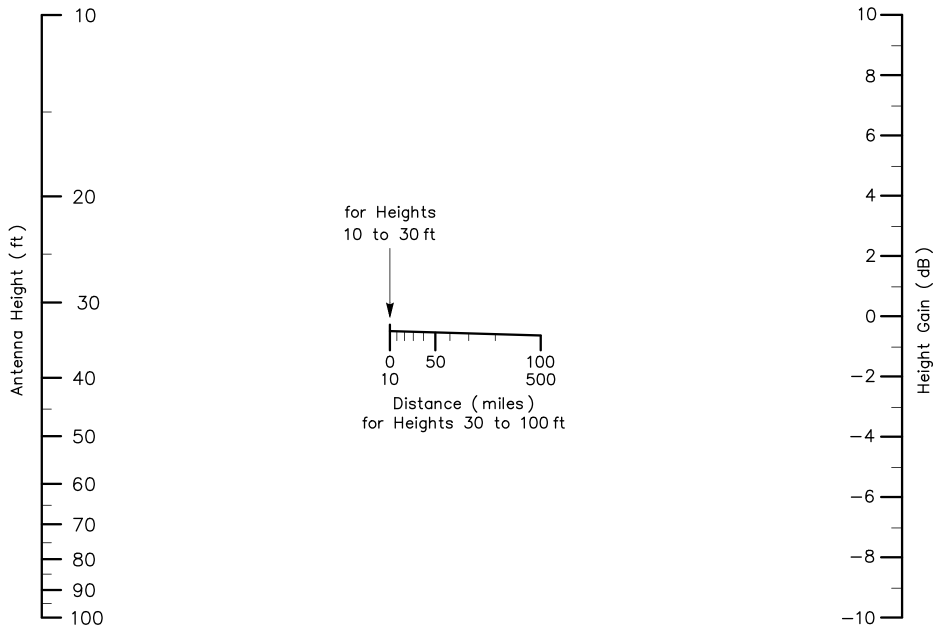

Fig 12—Nomogram for determining antenna-height gain.

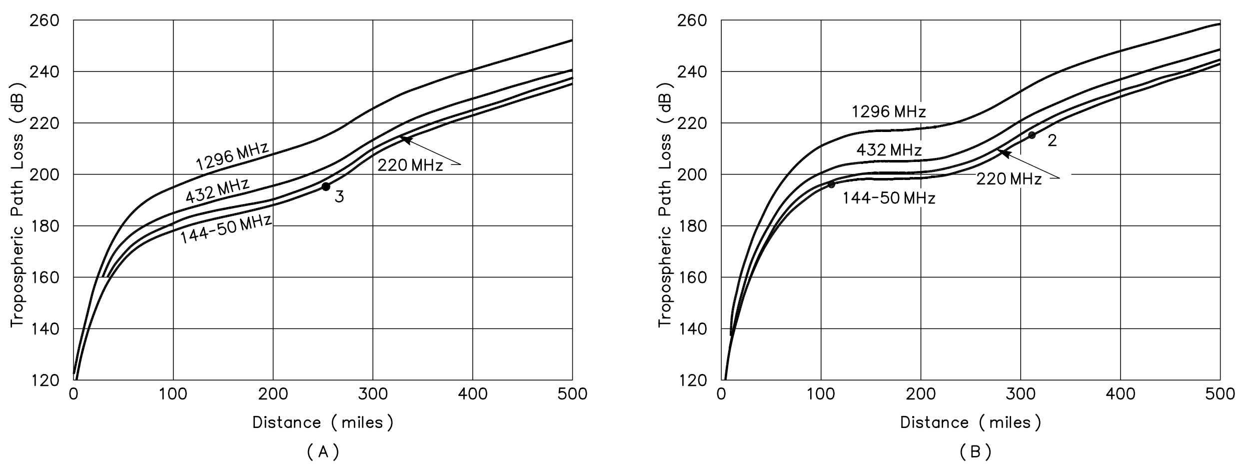

Fig 13—Path loss versus distance for amateur frequencies above 50 MHz. At A are curves for 50% of the time; at B, for 99%. The curves at A are more representative of Amateur Radio requirements.

considered hopeless. Help for the valley dweller often lies in the optical phenomenon known as *knife-edge diffraction*. A flashlight beam pointed at the edge of a partition does not cut off sharply at the partition edge, but is diffracted around it, partially illuminating the shadow area. A similar effect is observed with VHF waves passing over ridges; there is a shadow effect, but not a complete blackout. If the signal is strong where it strikes the mountain range, it will be heard well in the bottom of a valley on the far side. (See Chapter 3, The Effects of Ground, for a more thorough discussion of the theory of diffraction.)

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

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

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

AURORAL PROPAGATION

The Earth has a *magnetosphere* or magnetic field surrounding it. NASA scientists have described the magnetosphere as a sort of protective "bubble" around the Earth that shields us from the solar wind. Under normal circumstances, there are lots of electrons and protons moving in our magnetosphere, traveling along magnetic lines of force that trap them and keep them in place, neither bombarding the earth nor escaping into outer space.

Sudden bursts of activity on the Sun are sometimes accompanied by the ejection of charged particles, often from so-called Coronal Mass Ejections (CME) because they originate from the Sun's outer coronal region. These charged particles can interact with the magnetosphere, compressing and distorting it. If the orientation of the magnetic field contained in a large blast of solar wind or in a CME is aligned opposite to that of the Earth's magnetic field, the magnetic bubble can partially collapse and the particles normally trapped there can be deposited into the Earth's atmosphere along magnetic lines near the North or South poles. This produces a visible or radio *aurora*. An aurora is visible if the time of entry is after dark.

The visible aurora is, in effect, fluorescence at E-layer height—a curtain of ions capable of refracting radio waves in the frequency range above about 20 MHz. D-region absorption increases on lower frequencies during auroras. The exact frequency ranges depend on many factors: time, season, position with relation to the Earth's auroral regions, and the level of solar activity at the time, to name a few.

The auroral effect on VHF waves is another amateur discovery, this one dating back to the 1930s. The discovery came coincidentally with improved transmitting and receiving techniques then. The returning signal is diffused in frequency by the diversity of the auroral curtain as a refracting (scattering) medium. The result is a modulation of a CW signal, from just a slight burbling sound to what is best described as a "keyed roar." Before SSB took over in VHF work, voice was all but useless for auroral paths. A sideband signal suffers, too, but its narrower bandwidth helps to retain some degree of understandability. Distortion induced by a given set of auroral conditions increases with the frequency in use. 50-MHz signals are much more intelligible than those on 144 MHz on the same path at the same time. On 144 MHz, CW is almost mandatory for effective auroral communication.

The number of auroras that can be expected per year varies with the geomagnetic latitude. Drawn with respect to the Earth's magnetic poles instead of the geographical ones, these latitude lines in the US tilt upward to the northwest. For example, Portland, Oregon, is 2° farther north (geographic latitude) than Portland, Maine. The Maine city's geomagnetic latitude line crosses the Canadian border before it gets as far west as its Oregon namesake. In terms of auroras intense enough to produce VHF propagation results, Portland, Maine, is likely to see about 10 times as many per year. Oregon's auroral prospects are more like those of southern New Jersey or central Pennsylvania.

The antenna requirements for auroral work are mixed. High gain helps, but the area of the aurora yielding the best returns sometimes varies rapidly, so sharp directivity can be a disadvantage. So could a very low radiation angle, or a beam pattern very sharp in the vertical plane. Experience indicates that few amateur antennas are sharp enough in either plane to present a real handicap. The beam heading for maximum signal can change, however, so a bit of scanning in azimuth may turn up some interesting results. A very large array, such as is commonly used for moonbounce (with azimuth-elevation control), should be worthwhile.

The incidence of auroras, their average intensity, and their geographical distribution as to visual sightings and VHF propagation effects all vary to some extent with solar activity. There is some indication that the peak period for auroras lags the sunspot-cycle peak by a year or two. Like sporadic E, an unusual auroral opening can come at any season. There is a marked diurnal swing in the number of auroras. Favored times are late afternoon and early evening, late evening through early morning, and early afternoon, in about that order. Major auroras often start in early afternoon and carry through to early morning the next day.

HF Sky-Wave Propagation

As described earlier, the term *ground wave* is commonly applied to propagation that is confined to the Earth's lower atmosphere. Now we will use the term *sky wave* to describe modes of propagation that use the Earth's ionosphere. First, however, we must examine how the Earth's ionosphere is affected by the Sun.

THE ROLE OF THE SUN

Everything that happens in radio propagation, as with all life on Earth, is the result of radiation from the Sun. The variable nature of radio propagation here on Earth reflects the ever-changing intensity of ultraviolet and X-ray radiation, the primary ionizing agents in solar energy. Every day, solar nuclear reactions are turning hydrogen into helium, releasing an unimaginable blast of energy into space in the process. The total power radiated by the Sun is estimated at 4×10^{23} kW—that is, the number four followed by 23 zeroes. At its surface, the Sun creates about 60 *megawatts* per square meter. That is a very potent transmitter!

The Solar Wind

The Sun is constantly ejecting material from its surface in all directions into space, making up the so-called *solar wind*. Under relatively quiet solar conditions the solar wind blows around 200 miles per second—675,000 miles per hour—taking away about two million tons of solar material each second from the Sun. You needn't worry—the Sun is not going to shrivel up anytime soon. It's big enough that it will take many billions of years before that happens.

A 675,000 mile/hour wind sounds like a pretty stiff breeze, doesn't it? Lucky for us, the density of the material in the solar wind is very small by the time it has been spread out into interplanetary space. Scientists calculate that the density of the particles in the solar wind is less than that of the best vacuum they've ever achieved on Earth. Despite the low density of the material in the solar wind, the effect on the Earth, especially its magnetic field, is very significant.

Before the advent of sophisticated satellite sensors, the Earth's magnetic field was considered to be fairly simple, modeled as if the Earth were a large bar magnet. The axis of this hypothetical bar magnet is oriented about 11° away from the geographic north-south pole. We now know that the solar wind alters the shape of the Earth's magnetic field significantly, compressing it on the side facing the Sun and elongating it on the other side—in the same manner as the tail of a comet is stretched out radially in its orientation from the Sun. In fact, the solar wind is also responsible for the shape of a comet's tail.

Partly because of the very nature of the nuclear reactions going on at the Sun itself, but also because of variations in the speed and direction of the solar wind, the interactions between the Sun and our Earth are incredibly complex. Even scientists who have studied the subject for years do not completely understand everything that happens on the Sun. Later in this chapter, we'll investigate the effects of the solar wind when conditions on the Sun are *not* "quiet." As far as amateur HF skywave propagation is concerned, the results of disturbed conditions on the Sun are not generally beneficial.

Sunspots

The most readily observed characteristic of the Sun, other than its blinding brilliance, is its tendency to have grayish black blemishes, seemingly at random times and at random places, on its fiery surface. (See **Fig 14**.) There are written records of naked-eye sightings of *sunspots* in the Orient back to more than 2000 years ago. As far as is known, the first indication that sunspots were recognized as part of the Sun was the result of observations by Galileo in the early 1600s, not long after he developed one of the first practical telescopes.

Galileo also developed the projection method for observing the Sun safely, but probably not before he had suffered severe eye damage by trying to look at the Sun di-

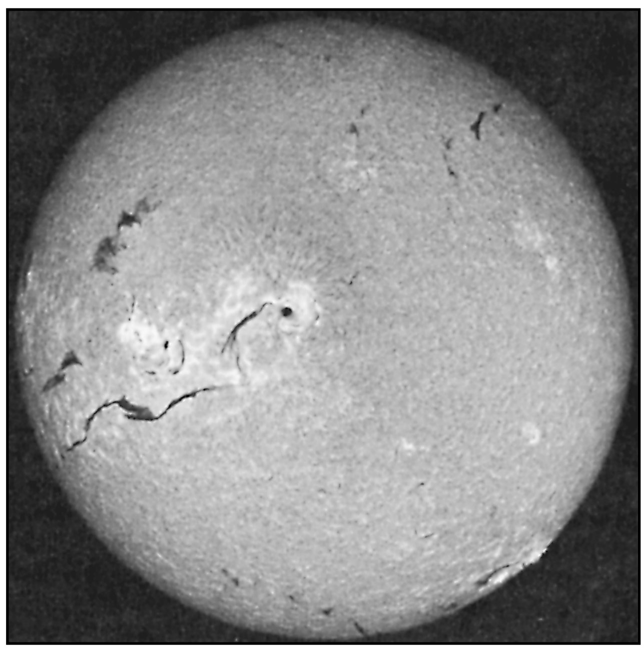

Fig 14—Much more than sunspots can be seen when the sun is viewed through selective optical filters. This photo was taken through a hydrogen-alpha filter that passes a narrow light segment at 6562 angstroms. The bright patches are active areas around and often between sunspots. Dark irregular lines are filaments of activity having no central core. Faint magnetic field lines are visible around a large sunspot group near the disc center. (*Photo courtesy of Sacramento Peak Observatory, Sunspot, New Mexico*).

rectly. (He was blind in his last years.) His drawings of sunspots, indicating their variable nature and position, are the earliest such record known to have been made. His reward for this brilliant work was immediate condemnation by church authorities of the time, which probably set back progress in learning more about the Sun for generations.

The systematic study of solar activity began about 1750, so a fairly reliable record of sunspot numbers goes back that far. (There are some gaps in the early data.) The record shows clearly that the Sun is always in a state of change. It never looks exactly the same from one day to the next. The most obvious daily change is the movement of visible activity centers (sunspots or groups thereof) across the solar disc, from east to west, at a constant rate. This movement was soon found to be the result of the rotation of the Sun, at a rate of approximately four weeks for a complete round. The average is about 27.5 days, the Sun's *synodic* rotation speed, viewed from the perspective of the Earth, which is also moving around the Sun in the same direction as the Sun's rotation.

Sunspot Numbers

Since the earliest days of systematic observation, our traditional measure of solar activity has been based on a count of sunspots. In these hundreds of years we have learned that the average number of spots goes up and down in cycles very roughly approximating a sine wave. In 1848, a method was introduced for the daily measurement of sunspot numbers. That method, which is still used today, was devised by the Swiss astronomer Johann Rudolph Wolf. The observer counts the total number of spots visible on the face of the Sun and the number of groups into which they are clustered, because neither quantity alone provides a satisfactory measure of sunspot activity. The observer's sunspot number for that day is computed by multiplying the number of groups he sees by 10, and then adding to this value the number of individual spots. Where possible, sunspot data collected prior to 1848 have been converted to this system.

As can readily be understood, results from one observer to another can vary greatly, since measurement depends on the capability of the equipment in use and on the stability of the Earth's atmosphere at the time of observation, as well as on the experience of the observer. A number of observatories around the world cooperate in measuring solar activity. A weighted average of the data is used to determine the *International Sunspot Number* or ISN for each day. (Amateur astronomers can approximate the determination of ISN values by multiplying their values by a correction factor determined empirically.)

A major step forward was made with the development of various methods for observing narrow portions of the Sun's spectrum. Narrowband light filters that can be used with any good telescope perform a visual function very similar to the aural function of a sharp filter added to a communications receiver. This enables the observer to see the actual area of the Sun doing the radiating of the ionizing energy, in addition to the sunspots, which are more a by-product than a cause. The photo of Fig 14 was made through such a filter. Studies of the ionosphere with instrumented probes, and later with satellites, manned and unmanned, have added greatly to our knowledge of the effects of the Sun on radio communication.

Daily sunspot counts are recorded, and monthly and yearly averages determined. The averages are used to see trends and observe patterns. Sunspot records were formerly kept in Zurich, Switzerland, and the values were known as *Zurich Sunspot Numbers*. They were also known as Wolf sunspot numbers. The official international sunspot numbers are now compiled at the Sunspot Index Data Center in Bruxelles, Belgium.

The yearly means (averages) of sunspot numbers from 1700 through 2002 are plotted in **Fig 15**. The cyclic nature of solar activity becomes readily apparent from this graph. The duration of the cycles varies from 9.0 to 12.7 years, but averages approximately 11.1 years, usually referred to as the 11-year solar cycle. The first complete cycle to be observed systematically began in 1755, and is numbered Cycle 1. Solar cycle numbers thereafter are consecutive. Cycle 23 began in October, 1996.

The "Quiet" Sun

For more than 60 years it has been well known that radio propagation phenomena vary with the number and size of sunspots, and also with the position of sunspots on the surface of the Sun. There are daily and seasonal variations in the Earth's ionized layers resulting from changes in the amount of ultraviolet light received from the Sun. The 11-year sunspot cycle affects propagation conditions because there is a direct correlation between sunspot activity and ionization.

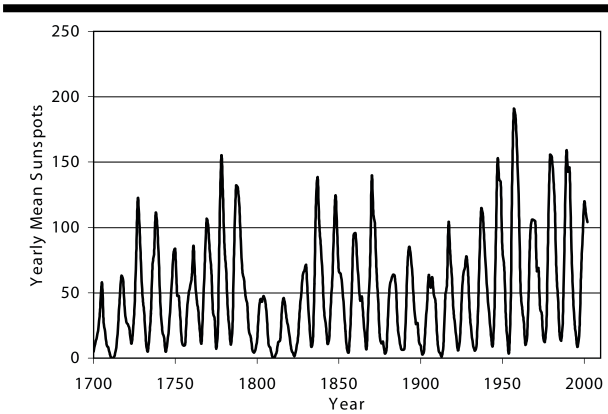

Fig 15—Yearly means of smoothed sunspot numbers from data for 1700 through 2002. This plot clearly shows that sunspot activity takes place in cycles of approximately 11 years duration. There is also a longer-term periodicity in this plot, the Gleissberg 88-year cycle. Cycle 1, the first complete cycle to be examined by systematic observation, began in 1755.

Activity on the surface of the Sun is changing continually. In this section we want to describe the activity of the so-called *quiet Sun*, meaning those times when the Sun is not doing anything more spectacular than acting like a "normal" thermonuclear ball of flaming gases. The Sun and its effects on Earthly propagation can be described in *statistical* terms—that's what the 11-year solar cycle does. You may experience vastly different conditions on any particular day compared to what a long-term average would suggest.

An analogy may be in order here. Have you ever gazed into a relatively calm campfire and been surprised when suddenly a flaming ember or a large spark was ejected in your direction? The Sun can also do unexpected and sometimes very dramatic things. Disturbances of propagation conditions here on Earth are caused by disturbed conditions on the Sun. More on this later.

Individual sunspots may vary in size and appearance, or even disappear totally, within a single day. In general, larger active areas persist through several rotations of the Sun. Some active areas have been identified over periods up to about a year. Because of these continual changes in solar activity, there are continual changes in the state of the Earth's ionosphere and resulting changes in propagation conditions. A short-term burst of solar activity may trigger unusual propagation conditions here on Earth lasting for less than an hour.

Smoothed Sunspot Numbers (SSN)

Sunspot data are averaged or smoothed to remove the effects of short-term changes. The sunspot values used most often for correlating propagation conditions are *Smoothed Sunspot Numbers* (SSN), often called 12-month running average values. Data for 13 consecutive months are required to determine a smoothed sunspot number.

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

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

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

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

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

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

Solar Flux

Since the late 1940s an additional method of determining solar activity has been put to use—the measurement of *solar radio flux*. The quiet Sun emits radio energy across a broad frequency spectrum, with a slowly varying intensity. Solar flux is a measure of energy received per unit time, per unit area, per unit frequency interval. These radio fluxes, which originate from atmospheric layers high in the Sun's chromosphere and low in its corona, change gradually from day to day, in response to the activity causing sunspots. Thus, there is a degree of correlation between solar flux values and sunspot numbers.

One solar flux unit equals 10^{-22} joules per second per square meter per hertz. Solar flux values are measured daily at 2800 MHz (10.7 cm) at The Dominion Radio Astrophysical Observatory, Penticton, British Columbia, where daily data have been collected since 1991. (Prior to June 1991, the Algonquin Radio Observatory, Ontario, made the measurements.) Measurements are also made at other observatories around the world, at several frequencies. With some variation, the daily measured flux values increase with increasing frequency of measurement, to at least 15.4 GHz. The daily 2800 MHz Penticton value is sent to Boulder, Colorado, where it is incorporated into WWV propagation bulletins (see later section). Daily solar flux information can be of some value in determining current propagation conditions, as sunspot numbers on a given day do not relate directly to maximum usable frequency. Solar flux values are much more reliable for this purpose, when it is averaged over time, as will be discussed later in the section on computer-prediction programs.

Correlating Sunspot Numbers and Solar Flux Values

Based on historical data, an exact mathematical relationship does not exist to correlate sunspot data and solar flux values. Comparing daily values yields almost no correlation. Comparing monthly mean values (often called monthly averages) produces a degree of correlation, but the spread in data is still significant. This is indicated in **Fig 16**, a scatter diagram plot of monthly mean sunspot numbers versus the monthly means of solar flux values adjusted to one astronomical unit. (This adjustment applies a correction for differences in distance between the Sun and the Earth at different times of the year.)

A closer correlation exists when smoothed (12-month running average) sunspot numbers are compared with smoothed (12-month running average) solar flux values adjusted to one astronomical unit. A scatter diagram for smoothed data appears in **Fig 17**. Note how the plot points establish a better defined pattern in Fig 17. The correlation is still no better than a few percent, for records indicate a given smoothed sunspot number does not always correspond with the same smoothed solar flux value, and vice versa.

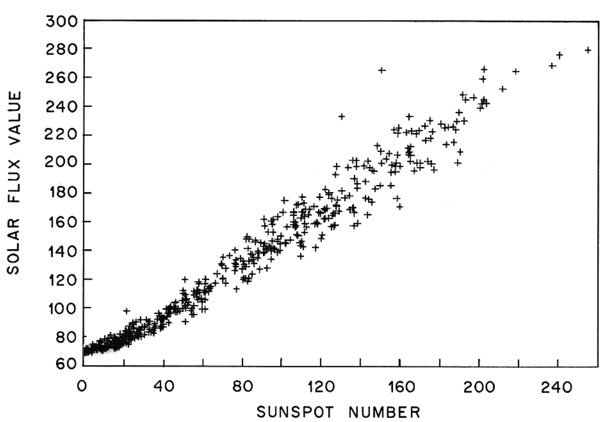

Fig 16—Scatter diagram or X-Y plot of monthly mean sunspot numbers and monthly mean 2800MHz solar flux values. Data values are from February 1947 through February 1987. Each "+" mark represents the intersection of data for a given month. If the correlation between sunspot number and flux values were consistent, all the marks would align to form a smooth curve.

Table 1 illustrates some of the inconsistencies that exist in the historical data. Smoothed or 12-month running average values are shown.

Even though there is no precise mathematical relationship between sunspot numbers and solar flux values, it is helpful to have some way to convert from one to the other. The primary reason is that sunspot numbers are valuable as a long-term link with the past, but the great usefulness of solar flux values are their immediacy, and their direct bearing on our field of interest. (Remember, a smoothed sunspot number will not be calculated until six months after the fact.)

The following mathematical approximation has been derived to convert a smoothed sunspot number to a solar flux value.

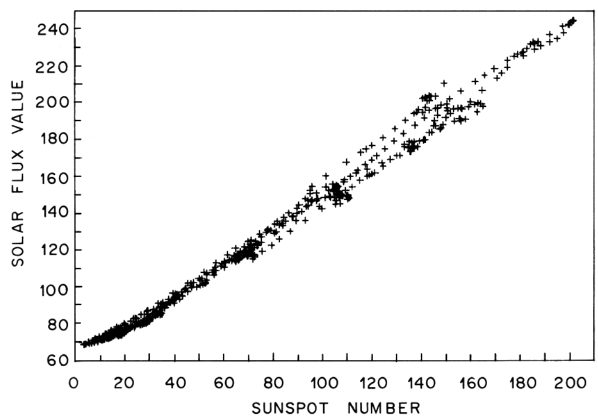

Fig 17—Scatter diagram of smoothed, or 12-month running averages, sunspot numbers versus 2800MHz solar flux values. The correlation of smoothed values is better than for monthly means, shown in Fig 16.

Table 1

Selected Historical Data Showing Inconsistent Correlation Between Sunspot Number and Solar Flux

Month	*Smoothed Sunspot Number*	*Smoothed Solar Flux Value*
May 1953	17.4	75.6
Sept 1965	17.4	78.5
Jul 1985	17.4	74.7
Jun 1969	106.1	151.4
Jul 1969	105.9	151.4
Dec 1982	94.6	151.4
Aug 1948	141.1	180.5
Oct 1959	141.1	192.3
Apr 1979	141.1	180.4
Aug 1981	141.1	203.3

$$F = 63.75 + 0.728\,S + 0.00089\,S^2 \quad \text{(Eq 5)}$$

where

F = solar flux number

S = smoothed sunspot number

A graphic representation of this equation is given in **Fig 18**. Use this chart to make conversions graphically, rather than by calculations. With the graph, solar flux and sunspot number conversions can be made either way. The equation has been found to yield errors as great as 10% when historical data was examined. (Look at the August 1981 data in Table 1.) Therefore, conversions should be rounded to the nearest whole number, as additional decimal places are unwarranted. To make conversions from flux to sunspot number, the following approximation may be used.

$$S = 33.52\sqrt{85.12 + F} - 408.99 \quad \text{(Eq 6)}$$

THE IONOSPHERE

There will be inevitable "gray areas" in our discussion of the Earth's atmosphere and the changes wrought in it by the Sun and by associated changes in the Earth's magnetic field. This is not a story that can be told in neat equations, or values carried out to a satisfying number of decimal places. The story must be told, and understood—with its well-known limitations—if we are to put up good antennas and make them serve us well.

Thus far in this chapter we have been concerned with what might be called our "above-ground living space"—that portion of the total atmosphere wherein we can survive without artificial breathing aids, or up to about 6 km (4 miles). The boundary area is a broad one, but life (and radio propagation) undergo basic changes beyond this zone. Somewhat farther out, but still technically within the Earth's atmosphere, the role of the Sun in the wave-propagation picture is a dominant one.

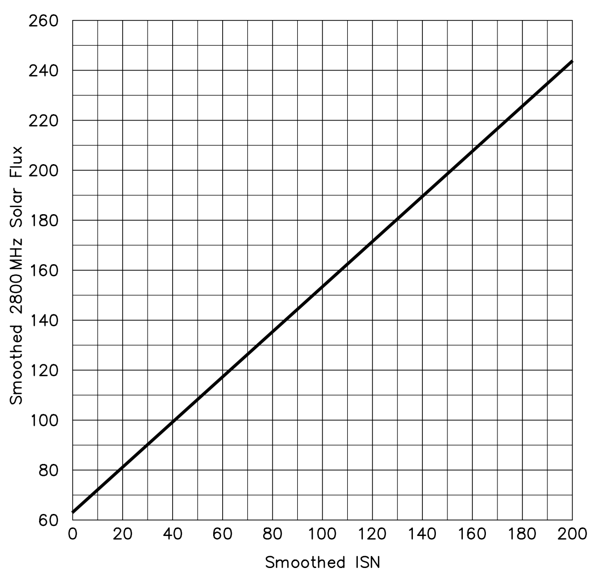

Fig 18—Chart for conversions between smoothed International Sunspot Numbers and smoothed 2800MHz solar flux. This curve is based on the mathematical approximation given in the text.

This is the *ionosphere*—a region where the air pressure is so low that free electrons and ions can move about for some time without getting close enough to recombine into neutral atoms. A radio wave entering this rarefied atmosphere, a region of relatively many free electrons, is affected in the same way as in entering a medium of different dielectric constant—its direction of travel is altered.

Ultraviolet (UV) radiation from the Sun is the primary cause of ionization in the outer regions of the atmosphere, the ones most important for HF propagation. However, there are other forms of solar radiation as well, including both hard and soft x-rays, gamma rays and extreme ultraviolet (EUV). The radiated energy breaks up, or *photoionizes*, atoms and molecules of atmospheric gases into electrons and positively charged ions. The degree of ionization does not increase uniformly with distance from the Earth's surface. Instead there are relatively dense regions (layers) of ionization, each quite thick and more or less parallel to the Earth's surface, at fairly well-defined intervals outward from about 40 to 300 km (25 to 200 miles). These distinct layers are formed due to complex photochemical reactions of the various types of solar radiation with oxygen, ozone, nitrogen and nitrous oxide in the rarefied upper atmosphere.

Ionization is not constant within each layer, but tapers off gradually on either side of the maximum at the center of the layer. The total ionizing energy from the Sun reaching a given point, at a given time, is never constant, so the height and intensity of the ionization in the various regions will also vary. Thus, the practical effect on long-distance communication is an almost continuous variation in signal level, related to the time of day, the season of the year, the distance between the Earth and the Sun, and both short-term and long-term variations in solar activity. It would seem from all this that only the very wise or the very foolish would attempt to predict radio propagation conditions, but it is now possible to do so with a fair chance of success. It is possible to plan antenna designs, particularly the choosing of antenna heights, to exploit known propagation characteristics.

Ionospheric Layer Characteristics

The lowest known ionized region, called the *D layer* (or the *D region*), lies between 60 and 92 km (37 to 57 miles) above the Earth. In this relatively low and dense part of the atmosphere, atoms broken up into ions by sunlight recombine quickly, so the ionization level is directly related to sunlight. It begins at sunrise, peaks at local noon and disappears at sundown. When electrons in this dense medium are set in motion by a passing wave, collisions between particles are so frequent that a major portion of their energy may be used up as heat, as the electrons and disassociated ions recombine.

The probability of collisions depends on the distance an electron travels under the influence of the wave—in other words, on the wavelength. Thus, our 1.8- and 3.5-MHz bands, having the longest wavelengths, suffer the highest daytime absorption loss as they travel through the D layer, particularly for waves that enter the medium at the lowest angles. At times of high solar activity (peak years of the solar cycle) even waves entering the D layer vertically suffer almost total energy absorption around midday, making these bands almost useless for communication over appreciable distances during the hours of high sun. They "go dead" quickly in the morning, but come alive again the same way in late afternoon. The diurnal (daytime) D-layer effect is less at 7 MHz (though still marked), slight at 14 MHz and inconsequential on higher amateur frequencies.

The D region is ineffective in bending HF waves back to Earth, so its role in long-distance communication by amateurs is largely a negative one. It is the principal reason why our frequencies up through the 7-MHz band are useful mainly for short-distance communication during the high-sun hours.

The lowest portion of the ionosphere useful for long-distance communication by amateurs is the *E layer* (also known as the *E region*) about 100 to 115 km (62 to 71 miles) above the Earth. In the E layer, at intermediate atmospheric density, ionization varies with the Sun angle above the horizon, but solar ultraviolet radiation is not the sole ionizing agent. Solar X-rays and meteors entering this portion of the Earth's atmosphere also play a part. Ionization increases rapidly after sunrise, reaches maximum around noon local time, and drops off quickly after sundown. The minimum is after midnight, local time. As with the D layer, the E layer absorbs wave energy in the lower-frequency amateur bands when the Sun angle is high, around mid-day. The other varied effects of E-region ionization will be discussed later.

Most of our long-distance communication capability stems from the tenuous outer reaches of the Earth's atmosphere known as the *F layer*. At heights above 100 miles, ions and electrons recombine more slowly, so the observable effects of the Sun develop more slowly. Also, the region holds its ability to reflect wave energy back to Earth well into the night. The *maximum usable frequency* (MUF) for F-layer propagation on east-west paths thus peaks just after noon at the midpoint, and the minimum occurs after midnight. We'll examine the subject of MUF in more detail later.

Judging what the F layer is doing is by no means that simple, however. The layer height may be from 160 to more than 500 km (100 to over 310 miles), depending on the season of the year, the latitudes, the time of day and, most capricious of all, what the Sun has been doing in the last few minutes and in perhaps the last three days before the attempt is made. The MUF between Eastern US and Europe, for example, has been anything from 7 to 70 MHz, depending on the conditions mentioned above, plus the point in the long-term solar-activity cycle at which the check is made.

During a summer day the F layer may split into two layers. The lower and weaker F_1 *layer*, about 160 km (100 miles) up, has only a minor role, acting more like the E than the F_2 *layer*. At night the F_1 region disappears and the F_2 region height drops somewhat.

Propagation information tailored to amateur needs is transmitted in all information bulletin periods by the ARRL Headquarters station, W1AW. Finally, solar and geomagnetic field data, transmitted hourly and updated eight times daily, are given in brief bulletins carried by the US Time Standard stations, WWV and WWVH, and also on Internet Web sites. But more on these services later.

Bending in the Ionosphere

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

Two extremes are thus possible. If the intensity of the ionization is sufficient and the frequency is low enough, even a wave entering the layer perpendicularly will be reflected back to Earth. Conversely, if the frequency is high enough or the ionization decreases to a low-enough density, a condition is reached where the wave angle is not affected enough by the ionosphere to cause a useful portion of the wave energy to return to the Earth. The frequency at which this occurs is called the vertical-incidence *critical frequency*. Each region in the ionosphere has a critical frequency associated with it, and this critical frequency will change depending on the date, time and state of the 11-year solar cycle.

Fig 19 shows a simplified graph of the electron density (in electrons per cubic meter) versus height in the ionosphere (in km) for a particular set of daytime and nighttime conditions. Free electrons are what return the signals you launch into the ionosphere back down to the Earth at some distance from your transmitter—The more free electrons in the ionosphere, the better propagation will be, particularly at higher frequencies.

Electron-density profiles are extremely complicated and vary greatly from one location to the next, depending on a bewildering variety of factors. Of course, this sheer variability makes it all the more interesting and challenging for hams to work each other on ionospheric HF paths!

The following discussion about sounding the ionosphere provides some background information about the scientific instruments used to decipher the highly intricate mechanisms behind ionospheric HF propagation.

SOUNDING THE IONOSPHERE

For many years scientists have *sounded* the ionosphere to determine its communication potential at various elevation angles and frequencies. The word "sound" stems from

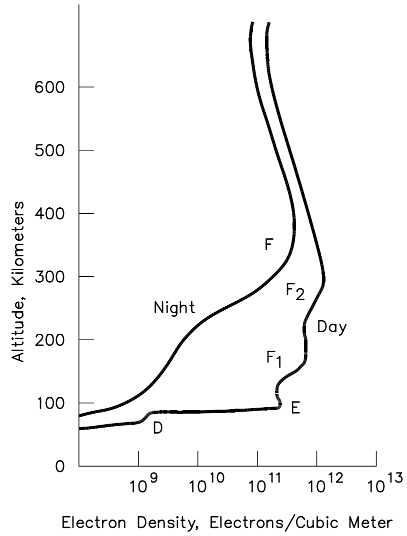

Fig 19—Typical electron densities for nighttime and daytime conditions in the various ionospheric regions.

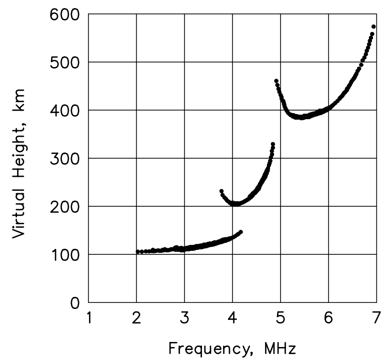

Fig 20—Very simplified ionogram from a vertical-incidence sounder. The lowest trace is for the E region; the middle for the F_1 and the upper trace for the F_2 region.

an old idea—one that has nothing to do with the audio waves that we can hear as "sounds." Long ago, sailors sounded the depths beneath their boats by dropping weighted ropes, calibrated in fathoms, into the water. In a similar fashion, the instrument used to probe the height of the ionosphere is called an *ionosonde*, or ionospheric sounder. It measures distances to various layers by launching a calibrated electronic signal directly up into the ionosphere.

Radar uses the same techniques as ionospheric sounding to detect targets such as airplanes. An ionosonde sends precisely timed pulses into the ionosphere over a range of MF and HF frequencies. The time of reception of an echo reflected from a region in the ionosphere is compared to the time of transmission. The time difference is multiplied by the speed of light to give the apparent distance that the wave has traveled from the transmitter to the ionosphere and back to the receiver. (It is an *apparent* or *virtual distance* because the speed of a wave slows very slightly in the ionosphere, just as the speed of propagation through any medium other than a vacuum slows down because of that medium.)

Another type of ionosonde sweeps the frequency of transmission, from low to high. This is called an "FM-CW," or more colorfully, a "chirp" sounder. Since a received echo takes time to travel from the transmitter up to the reflection point and then back again to the receiver, the echo will be at a lower frequency than the still-moving frequency of the transmitter. The frequency difference is an indication of the height of the echo's reflection off the various ionospheric layers.

Vertical-Incidence Sounders

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

Fig 20 shows a highly simplified ionogram for a typical vertical-incidence sounder. The echos at the lowest height at the left-hand side of the plot show that the E region is about 100 km high. The F_1 region shown in the middle of the plot varies from about 200 to 330 km in this example, and the F_2 region ranges from just under 400 km to almost 600 km in height. You can see that the F_1 and F_2 ionospheric regions take a "U" shape, indicating that the electron density varies throughout the layer. In this example, the peak in electron density is at a virtual height of the F_2 region of about 390 km, the lowest point in the F_2 curve.

Scientists can derive a lot of information from a vertical-incidence ionogram, including the critical frequencies for each region, where raising the frequency any higher causes the signals to disappear into space. In Fig 20, the E-region critical frequency (abbreviated f_oE) is about 4.1 MHz. The F_1-region critical frequency (abbreviated f_oF_1) is 4.8 MHz. The F2-region critical frequency (abbreviated f_oF_2) is this simplified diagram is 6.8 MHz.

The observant reader may well be wondering what the subscripted "o" in the abbreviations f_oE, f_oF_1 and f_oF_2 mean. The abbreviation "o" means "ordinary." When an electromagnetic wave is launched into the ionosphere, the Earth's magnetic field splits the wave into two independent waves—the "ordinary" (o) and the "extraordinary" (x) components. The ordinary wave reaches the same height in the ionosphere whether the Earth's magnetic field is present or not, and hence is called "ordinary." The extraordinary wave, however, is greatly affected by the presence of the Earth's magnetic field, in a very complex fashion.

Fig 21 shows an example of an actual ionogram from the vertical Lowell Digisonde at Millstone Hill in Massa-

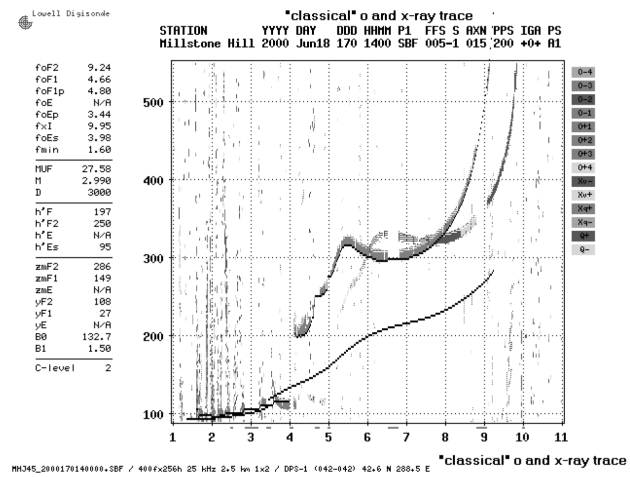

Fig 21—Actual vertical-incidence ionogram from the Lowell Digisonde, owned and operated at Millstone Hill in Massachusetts by MIT. The ordinary (o) and extraordinary (x) traces are shown for heights greater than about 300 km. At the upper left are listed the computer-determined ionospheric parameters, such as f_oF_2 of 9.24 MHz and f_oF_1 at 4.66 MHz.

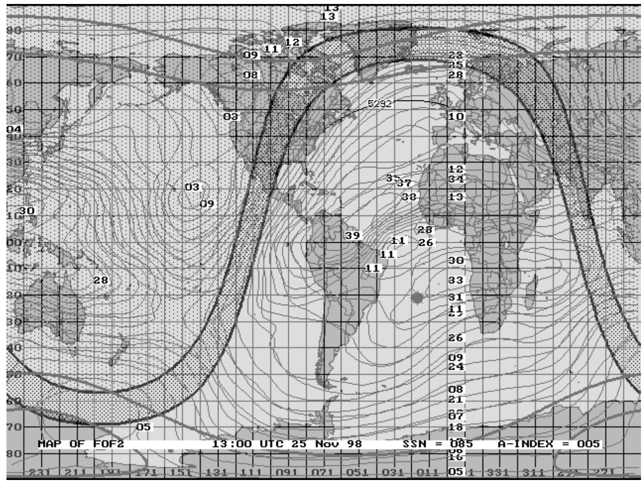

Fig 22—Computer simulation of the f_oF_2 contours for 25 November 1998, for an SSN of 85 and a quiet planetary A_p index of 5. Note the two regions of high f_oF_2 values off the upper and lower west coast of Africa. These are the "equatorial anomalies," regions of high electronic density in the F_2 region that often allow chordal-hop north-south propagation. See also Fig 8. (*PropLab Pro simulation, courtesy of Solar Terrestrial Dispatch*.)

chusetts, owned and operated by the Massachusetts Institute of Technology. This ionogram was made on June 18, 2000, and shows the conditions during a period of very high solar activity. The black-and-white rendition in Fig 21 of the actual color ionogram unfortunately loses some information. However, you can still see that a real ionogram is a lot more complicated looking than the simple simulated one in Fig 20.

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

Compared to the simplified ionogram in Fig 20, Fig 21 shows another trace that appears on the plot from about 5.3 to 9.8 MHz, a trace shifted to the right of the darker ordinary trace. This second trace is the extraordinary (x) wave mentioned above. Since the x and o waves are created by the Earth's magnetic field, the difference in the ordinary and extraordinary traces is about $^1/_2$ the *gyro frequency*, the frequency at which an electron will spiral down a particular magnetic field line. The electron gyro frequency is different at various places around the Earth, being related to the Earth's complicated and changing magnetic field. The extraordinary trace always has a higher critical frequency than the ordinary trace on a vertical-incidence ionogram, and it is considerably weaker than the ordinary trace, especially at frequencies below about 4 MHz because of heavy absorption.

The Big Picture Overhead

There are about 150 vertical-incidence ionosondes around the world. Ionosondes are located on land, even on a number of islands. There are gaps in sounder coverage, however, mainly over large expanses of open ocean. The compilation of all available vertical-incidence data from the worldwide network of ionospheric sounders results in global f_oF_2 maps, such as the map shown in **Fig 22**, a simulation from the highly sophisticated *PropLab Pro* computer program.

This simulation is for 1300 UTC, several hours after East Coast sunrise on Nov 25, 1998, with a high level of solar activity of 85 and a planetary A_p index of 5, indicating calm geomagnetic conditions. The contours of f_oF_2 peak over the ocean off the west coast of Africa at 38 MHz. Over the southern part of Africa, f_oF_2 peaks at 33 MHz.

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

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

Oblique-Angle Ionospheric Sounding

A more elaborate form of ionospheric sounder is the *oblique ionosonde*. Unlike a vertical-incidence ionospheric sounder, which sends its signals directly overhead, an oblique sounder transmits its pulses obliquely through the ionosphere, recording echos at a receiver located some distance from the transmitter. The transmitter and distant receiver are precisely coordinated in GPS-derived time in modern oblique sounders.

Interpretation of ionograms produced by oblique sounders is considerably more difficult than for vertically incident ones. An oblique ionosonde purposely transmits over a continuous range of elevation angles simultaneously and hence cannot give explicit information about each elevation angle it launches. **Fig 23** shows a typical HF oblique-sounder ionogram for the path from Hawaii to California in March of 1973, during a period of medium-level sunspot activity. The y-axis is calibrated in time delay, in milliseconds. Longer distances involve longer time delays between the start of a transmitted pulse and the reception of the echo. The x-axis in this ionogram is the frequency, just like a vertical-incidence ionogram. Note that the frequency range for this plot extends to 32 MHz, while vertical-incidence ionograms usually don't sweep higher than about 12 MHz.

Six possible modes are shown in this ionogram: $1F_2$, $2F_2$, $3F_2$, $4F_2$ and $5F_2$. These involve multiple modes of propagation (commonly called *hops*) between the ionosphere and reflections from the Earth. For example, at an operating frequency of 14 MHz, there are three modes open during the mid-morning: $2F_2$, $3F_2$ and $4F_2$. We'll discuss multiple hops later in more detail.

The lowest mode, $1F_2$ in Fig 23, employs a single F_2 hop to cover the 3900-km long path from Hawaii to California, but it is only open on 28-MHz. (Note that 3900 km is close to the maximum possible single-hop length for the F_2 region. We'll look at this in more detail later too.) In general, each mode that involves more than a single hop is weaker than a single hop. For example, you can see that the received $5F_2$ echo is weak and broken up because of the accumulation of losses at each ground-level reflection in its five hops, with absorption in the ionosphere all along its complicated path to the receiver.

The trace labeled "FOT" is the *frequency of optimum traffic*, considered the most reliable frequency for communications on this particular circuit and date/time. In this example, the FOT would be near the 21-MHz amateur band.

Another interesting point in Fig 23 is labeled "High Angle Ray." This refers to the Pedersen ray. Before we go into more details about the Pedersen high-angle wave, we need to examine how launch angles affect the way waves are propagated through the ionosphere.

Fig 24 shows a highly simplified situation, with a single ionospheric layer and a smooth Earth. This illustrates several important facts about antenna design for long-distance communication. In Fig 24, Wave #1 is launched at the lowest elevation angle (that is, most nearly horizontal to the horizon). Wave #1 manages to travel from the transmitter to the receiving location at point C in a single hop.

Wave #2 is launched at a higher elevation angle than Wave #1, and penetrates further into the ionospheric layer before it is refracted enough to return to Earth. The ground distance covered from the transmitter to point B is less for

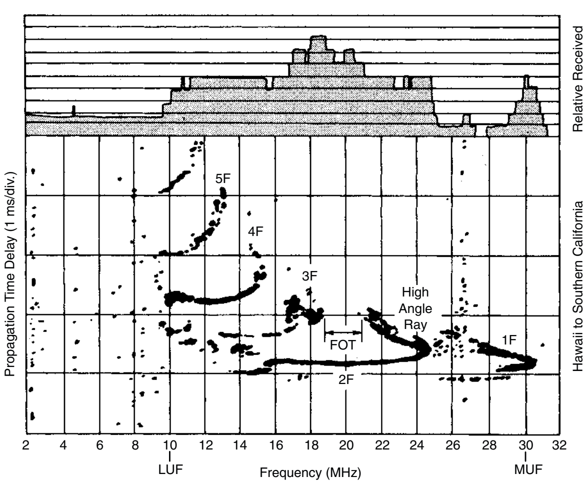

Fig 23—HF oblique-sounder ionogram. This is a typical chirpsounder measurement on a 2500-mile path from Hawaii to southern California during midmorning in March at a medium level of solar activity. Six possible modes (hops) are shown. The "FOT" is the frequency of optimum traffic, considered most reliable for this path/time.

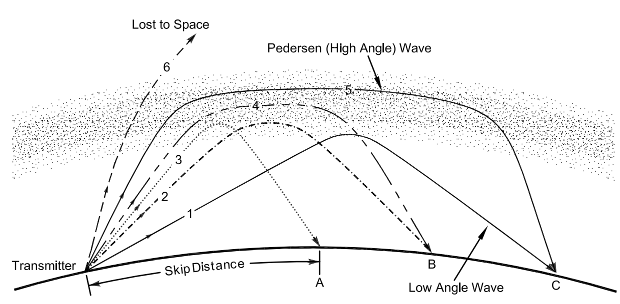

Fig 24—Very simplified smooth-Earth/ionosphere diagram showing how the ground range from transmitter to receiver can vary as the elevation angle is gradually raised. The Pedersen wave, launched at a relatively high angle, has the same ground range as the low-angle wave #1, but is weaker because it travels for a long distance in the ionosphere.

Wave #2 than for lower-angle Wave #1. Wave #3 is launched at a still-higher elevation angle. Like Wave #2 before it, Wave #3 penetrates further into the ionosphere and covers less ground downrange than #2.

Now, we see something very interesting happening for Wave #4, whose launch elevation angle is still higher than #3. Wave #4 penetrates even higher into the ionosphere than #3, reaching the highest level of ionization in our theoretical ionospheric layer, where it is finally refracted sufficiently to bend down to Earth. Wave #4 manages to arrive at the same point B as Wave #2, which was launched at a much lower elevation angle.

In other words, in the sequence from #1 to #3 we have been continually *increasing* the elevation launch angle and the ground range covered from the transmitter to the return of the signal back to Earth has been continually *decreasing*. However, starting with Wave #4, the ground range starts to *increase* with increased elevation angle. A further increase in the elevation angle causes Wave #5 to travel for an even longer distance through the ionosphere, exiting finally at point C, the same ground distance as lowest-angle Wave #1.

Finally, increasing the elevation angle even further results in Wave #6 being lost to outer space because the ionization in the layer is insufficient to bend the wave back to Earth. In other words, Wave #6 has exceeded the *critical angle* for this hypothetical ionospheric layer and this frequency of operation.

Both Waves #4 and #5 in Fig 24 are called "high-angle" or Pedersen waves. Because Wave #5 has traveled a greater distance through the ionosphere, it is always weaker than Wave #1, the one launched at the lowest elevation angle. Pedersen waves are usually not very stable, since small changes in elevation angle can result in large changes in the ground range that these high-angle waves cover.

SKIP DISTANCE

Fig 24 shows that we can communicate with the point on the Earth labeled "A" (where Wave #3 arrives), but not any closer to our transmitter site. When the critical angle is less than 90° (that is, directly overhead) there will always be a region around the transmitting site where an ionospherically propagated signal cannot be heard, or is heard weakly. This area lies between the outer limit of the ground-wave range and the inner edge of energy return from the ionosphere. It is called the *skip zone*, and the distance between the originating site and the beginning of the ionospheric return is called the skip distance. This terminology should not to be confused with ham jargon such as "the skip is in," referring to the fact that a band is open for sky-wave propagation.

The signal may often be heard to some extent within the skip zone, through various forms of scattering (discussed in detail later), but it will ordinarily be marginal in strength. When the skip distance is short, both ground-wave and sky-wave signals may be received near the transmitter. In such instances the sky wave frequently is stronger than the ground wave, even as close as a few miles from the transmitter. The ionosphere is an efficient communication medium under favorable conditions. Comparatively, the ground wave is not.

If the radio wave leaves the Earth at a radiation angle of zero degrees, just at the horizon, the maximum distance that may be reached under usual ionospheric conditions in the F_2 region is about 4000 km (2500 miles).

MULTI-HOP PROPAGATION

As mentioned previously in the discussion about Fig 23, the Earth itself can act as a reflector for radio waves, resulting a multiple hops. Thus, a radio signal can be reflected from the reception point on the Earth back into the ionosphere, reaching the Earth a second time at a still more-distant point. This effect is illustrated in **Fig 25**, where a single ionospheric layer is depicted, although this time we show both the layer and the Earth beneath it as curved rather than flat. The wave identified as "Critical Angle" travels from the transmitter via the ionosphere to point A, in the center of the drawing, where it is reflected upwards and travels through the ionosphere to point B, at the right. This shows a two-hop signal.

As in the simplified case in Fig 24, the distance at which a ray eventually reaches the Earth depends on the launch elevation angle at which it left the transmitting antenna. You have some control of the launch angle by adjusting the height of the antennas you use, as described in Chapter 3, The Effects of Ground.

The information in Fig 25 is greatly simplified. On actual communication paths the picture is complicated by many factors. One is that the transmitted energy spreads over a considerable area after it leaves the antenna. Even with an antenna array having the sharpest practical beam pattern, there is what might be described as a *cone of radiation* centered on

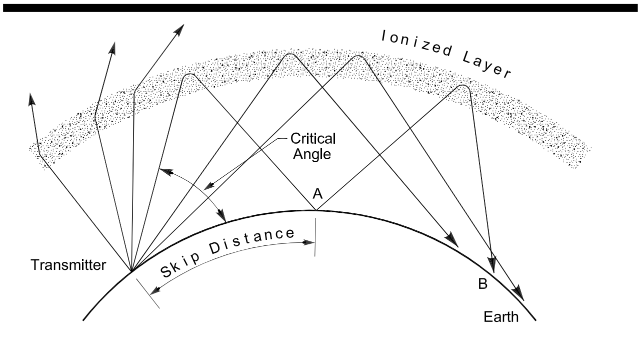

Fig 25—Behavior of waves encountering a simple curved ionospheric layer over a curved Earth. Rays entering the ionized region at angles above the critical angle are not bent enough to be returned to Earth, and are lost to space. Waves entering at angles below the critical angle reach the Earth at increasingly greater distances as the launch angle approaches the horizontal. The maximum distance that may normally be covered in a single hop is 4000 km. Greater distances are covered with multiple hops.

the wave lines (rays) shown in the drawing. The reflection/refraction in the ionosphere is also highly variable, and is the cause of considerable spreading and scattering.

Under some conditions it is possible for as many as four or five signal hops to occur over a radio path, as illustrated by the oblique ionogram in Fig 23. But no more than two or three hops is the norm. In this way, HF communication can be conducted over thousands of miles.

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

Assuming that both waves do reach point B in Fig 25, the low-angle wave will contain more energy at point B. This wave passes through the lower layers just twice, compared to the higher-angle route, which must pass through these layers four times, plus encountering an Earth reflection. Measurements indicate that although there can be great variation in the relative strengths of the two signals—the one-hop signal will generally be from 7 to 10 dB stronger. The nature of the terrain at the mid-path reflection point for the two-hop wave, the angle at which the wave is reflected from the Earth, and the condition of the ionosphere in the vicinity of all the refraction points are the primary factors in determining the signal-strength ratio.

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

Non-Hopping Propagation Modes

Present propagation theory holds that for communication distances of many thousands of kilometers, signals do not always hop in relatively short increments from ionosphere-to-Earth-to-ionosphere and so forth along the entire path. Instead, the wave is thought to propagate *inside* the ionosphere throughout some portion of the path length, tending to be *ducted* in the ionized layer.

As was shown in Fig 24, the high-angle Pedersen ray can also penetrate an ionospheric layer farther than lower-angle rays. In the less-densely ionized upper edge of the layer, the amount of refraction is less, nearly equaling the curvature of the layer itself as it encircles the Earth.

Non-hopping theory of long-distance propagation is further supported by studies of travel times for signals that go completely around the world. The time required is significantly less than would be necessary to hop between the Earth and the ionosphere 10 or more times while circling the Earth.

Propagation between two points thousands of kilometers apart may in fact consist of a combination of ducting and hopping. It may involve combinations of refractions from the E layer and the F layer. Despite all the complex factors involved, most long-distance propagation can be seen to follow certain general rules. Thus, much commercial and military point-to-point communication over long distances employs antennas designed to make maximum use of known radiation angles and layer heights, even on paths where multihop propagation is assumed.

In amateur work, however, we usually try for the lowest practical radiation angle, hoping to keep reflection losses to a minimum. Years of amateur experience have shown this to be a decided advantage under all usual conditions.

The geometry of propagation by means of the F_2 layer limits our maximum distance along the Earth's surface to about 4000 km (2500 miles) for a single hop. For higher radiation angles, this same distance may require two or more hops (with higher reflection loss). And fewer hops are better, in most cases. If you have a nearby neighbor who consistently outperforms you on the longer paths, a radiation angle difference in his favor is probably the reason.

MAXIMUM USABLE FREQUENCY

The vertical-incidence critical frequency is the *maximum usable frequency* for local sky-wave high-angle communication. It is also useful in the selection of optimum working frequencies and the determination of the maximum usable frequency for distant points at a given time. The abbreviation "MUF" for maximum usable frequency will be used hereafter.

In geographic middle latitudes, the vertical-incident critical frequency ranges between about 1 and 4 MHz for the E layer, and between 2 and 13 MHz for the F_2 layer. The lowest figures are for nighttime conditions in the lowest years of the solar cycle. The highest are for the daytime hours in the years of high solar activity. These are average figures. Critical frequencies have reached as high as 20 MHz briefly during exceptionally high solar activity in the middle latitudes. As was pointed out earlier in Fig 22, f_oF_2 levels approaching 40 MHz are possible at low latitudes.

While vertical-incidence critical frequencies are interesting from a scientific point of view, hams are far more concerned about how we can exploit propagation conditions to communicate, preferably at long distances. The MUF for a 4000-km (2500 miles) distance is about 3.5 times the vertical-incidence critical f_oF_2 frequency existing at the path midpoint. For one-hop signals, if a uniform ionosphere is assumed, the MUF decreases with shorter distances along the path. This is true because the higher-frequency waves must be launched at higher elevation angles for shorter ranges, and at these launch angles they are not bent sufficiently to reach the Earth. Thus, a lower frequency (where more bending occurs) must be used.

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

Therefore, the MUF cannot be expressed broadly as a single frequency, even for any given location at a particular time. The ionosphere is never uniform, and in fact at a given time and for a fixed distance, the MUF changes significantly with changes in compass direction for almost any point on the Earth. Under usual conditions, the MUF will always be highest in the direction toward the Sun—to the east in the morning, to the south at noon (from northern latitudes), and to the west in the afternoon and evening.

For the strongest signals at the greatest distance, especially where the limited power levels of the Amateur Radio Service are concerned, it is important to work fairly near the MUF. It is at these frequencies where signals suffer the least loss. The MUFs can be estimated with sufficient accuracy by using the prediction charts that appear on the ARRL Web site (**www.arrl.org/qst/propcharts/**) or by using a computer prediction program. The CD-ROM bundled in the back of this book contains detailed and summary tables for more than 175 transmitting locations around the world. (See section on "What HF Bands Are Open—Where and When?" later in this chapter.)

MUFs can also be observed, with the use of a continuous coverage communications receiver. Frequencies up to the MUFs are in round-the-clock use today. When you "run out of signals" while tuning upward in frequency from your favorite ham band, you have a pretty good clue as to which band is going to work well, right then. Of course, it helps to know the direction to the transmitters whose signals you are hearing. Shortwave broadcasters know what frequencies to use, and you can hear them anywhere, if conditions are good. Time-and-frequency stations are also excellent indicators, since they operate around the clock. See **Table 2**. WWV is also a reliable source of propagation data, hourly, as discussed in more detail later in this chapter.

The value of working near the MUF is two-fold. Under undisturbed conditions, the absorption loss decreases proportional to the square of a change in frequency. For example, the absorption loss is four times higher at 14 MHz than it is at 28 MHz. Perhaps more important, the hop distance is considerably greater as the MUF is approached. A transcontinental contact is thus much more likely to be made on a single hop on 28 MHz than on 14 MHz, so the higher frequency will give the stronger signal most of the time. The strong-signal reputation of the 28-MHz band is founded on this fact.

LOWEST USABLE FREQUENCY

There is also a lower limit to the range of frequencies that provide useful communication between two given points by way of the ionosphere. *Lowest usable frequency* is abbreviated LUF. If it were possible to start near the MUF and work gradually lower in frequency, the signal would decrease in strength and eventually would disappear into the ever-present "background noise." This happens because signal absorption increases proportional to the square of the lowering of the frequency. The frequency nearest the point where reception became unusable would be the LUF. It is not likely that you would want to work at the LUF, although reception could be improved if the station could increase power by a considerable amount, or if larger antennas could be used at both ends of the path.

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

Frequently, the *window* between the LUF and the MUF for two fixed points is very narrow, and there may be no amateur frequencies available inside the window. On occasion the LUF may be higher than the MUF between two points. This means that, for the highest possible frequency that will propagate through the ionosphere for that path, the absorption is so great as to make even that frequency unusable. Under these conditions it is impossible to establish amateur sky-wave communication between those two points, no matter what frequency is used. (It would normally be possible, however, to communicate between either point and

Table 2
Time and Frequency Stations Useful for Propagation Monitoring

Call	Frequency (MHz)	Location
WWV	2.5, 5, 10, 15, 20	Ft Collins, Colorado
WWVH	Same as WWV but no 20	Kekaha, Kauai, Hawaii
CHU	3.330, 7.335, 14.670	Ottawa, Ontario, Canada
RID	5.004, 10.004, 15.004	Irkutsk, USSR*
RWM	4.996, 9.996, 14.996	Novosibirsk, USSR
VNG	2.5, 5, 8.634, 12.984, 16	Lyndhurst, Australia
BPM	5, 5.43, 9.351, 10, 15	Xiang, China
BSF	15	Taoyuan, Taiwan
JJY	2.5, 5, 8, 10, 15	Tokyo, Japan
LOL	5, 10, 15	Buenos Aires, Argentina

*The call, taken from an international table, may not be the one used during actual transmission. Locations and frequencies appear to be accurate as provided.

other points on some frequency under the existing conditions.) Conditions when amateur sky-wave communication is impossible between two fixed points occur commonly for long distances where the total path is in darkness, and for very great distances in the daytime during periods of low solar activity.

Fig 26 shows a typical propagation prediction from the *ARRLWeb* members-only site (**www.arrl.org/qst/propcharts/**, previously from the "How's DX" column in *QST*). In this instance, the MUF and the LUF lines are blurred together at about 10 UTC, meaning that the statistical likelihood of any amateur frequency being open for that particular path at that particular time was not very good. Later on, after about 11 UTC, the gap between the MUF and LUF increased, indicating that the higher bands would be open on that path.

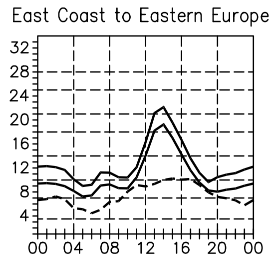

Fig 26—Propagation prediction chart for East Coast of US to Europe. This appeared in December 1994 *QST*, where an average 2800-MHz (10.7-cm) solar flux of 83 was assumed for the mid-December to mid-January period. On 10% of these days, the highest frequency propagated was predicted at least as high as the uppermost curve (the Highest Possible Frequency, or HPF, approximately 21 MHz), and for 50% of the days as high as the middle curve, the MUF. The broken lines show the Lowest Usable Frequency (LUF) for a 1500-W CW transmitter.

DISTURBED IONOSPHERIC CONDITIONS

So far, we have discussed the Earth's ionosphere when conditions at the Sun are undisturbed. There are three general types of major disturbances on the Sun that can affect radio propagation here on the Earth. On the air, you may hear people grousing about *Solar Flares*, *Coronal Holes* or *Sudden Disappearing Filaments*, especially when propagation conditions are not good. Each of these disturbances causes both electromagnetic radiation and ejection of material from the Sun.

Solar Flares

Solar flares are cataclysmic eruptions that suddenly release huge amounts of energy, including sustained, high-energy bursts of radiation from VLF to X-ray frequencies and vast amounts of solar material. Most solar flares occur around the peak of the 11-year solar cycle.

The first Earthly indication of a huge flare is often a visible brightness near a sunspot group, along with increases in UV, X-ray radiation and VHF radio noise. If the geometry between the Sun and Earth is right, intense X-ray radiation takes eight minutes, traveling the 93 million miles to Earth at the speed of light. The sudden increase in X-ray energy can immediately increase RF absorption in the Earth's lowest ionospheric layers, causing a phenomenon known as a *Sudden Ionospheric Disturbance* (SID).

An SID affects all HF communications on the sunlit side of the Earth. Signals in the 2 to 30-MHz range may disappear entirely, and even most background noise may cease in extreme cases. When you experience a big SID, your first inclination may be to look outside to see if your antenna fell down! SIDs may last up to an hour before ionospheric conditions temporarily return to normal.

Between 45 minutes and 2 hours after an SID begins, particles from the mass eruption on the Sun may begin to arrive. These high-energy particles are mainly protons and they can penetrate the ionosphere at the Earth's magnetic poles, where intense ionization can occur, with attendant absorption of HF signals propagating through the polar regions. This is called a *Polar Cap Absorption* (PCA) event and it may last for several days. A PCA results in spectacular auroral displays at high latitudes.

Coronal Holes

As described earlier in the section dealing with auroral propagation at VHF, a second major solar disturbance is a so-called "coronal hole" in the Sun's outer layer (the *corona*). Temperatures in the corona can be more than four million °C over an active sunspot region but more typically are about two million °C. A coronal hole is an area of somewhat lower temperature. Solar-terrestrial scientists have a number of competing theories about how coronal holes are formed.

Matter ejected through this "hole" takes the form of a *plasma*, a highly ionized gas made up of electrons, protons and neutral particles, traveling at speeds up to 1,000 km per second (2 million miles per hour). The plasma becomes part of the solar wind and can affect the Earth's magnetic field, but only if the Sun-Earth geometry is right. A plasma has a very interesting and somewhat bizarre ability. It can lock-in the orientation of the magnetic field where it originates and carry it outwards into space. However, unless the locked-in magnetic field orientation is aligned properly with the Earth's magnetic field, even a large plasma mass may not severely disrupt our magnetosphere, and thence our ionosphere.

Presently, we don't have the ability to predict very long in advance when the Sun might erupt in a disturbance that results in Earthly propagation problems. The SOHO satellite can help determine whether a mass ejection is heading towards Earth, and the ACE satellite about 1 million miles away from Earth can give about an hour's warning whether the imbedded magnetic field in a mass ejection from the Sun might impact the Earth's magnetosphere, causing propagation problems for hams.

Statistically, coronal holes tend to occur most often during the declining phase of the 11-year solar cycle and they can last for a number of solar rotations. This means that a coronal hole can be a "recurring coronal hole," disrupting communications for several days about the same time each month for as long as a year, or even more.

Sudden Disappearing Filaments

A sudden disappearing filament (SDF) is the third major category of solar disturbance that can affect propagation. SDFs take their names from the manner in which they suddenly arch upward from the Sun's surface, spewing huge amounts of matter as plasma out into space in the solar wind. They tend to occur mostly during the rising phase of the 11-year solar cycle.

IONOSPHERIC STORMS

When the conditions are right, a flare, coronal hole or an SDF can launch a plasma cloud into the solar wind, resulting in an *ionospheric storm* here on Earth. Unlike a hurricane or a winter Nor'easter storm in New England, an ionospheric storm is not something we can see with our eyes or feel on our skins. We can't easily measure things occurring in the ionosphere some 200 miles overhead. However, we can see the indirect effects of an ionospheric storm on magnetic instruments located on the Earth's surface, because disturbances in the ionosphere are closely related to the Earth's magnetic field. The term *Geomagnetic Storm* ("Geo" means "Earth" in Greek) is used almost synonymously with ionospheric storm.

During a ionospheric storm, we may experience extraordinary radio noise and interference, especially at HF. You may hear solar radio emissions as increases of noise at VHF. A geomagnetic storm generally adds noise and weakens or disrupts ionospheric propagation for several days. Transpolar signals at 14 MHz or higher may be particularly weak, with a peculiar hollow sound or flutter—even more than normal for transpolar signals.

Depending on the severity of the disturbance to the Earth's geomagnetic field and the consequent disturbance of the ionosphere, propagation may be disrupted completely or it might be at least degraded for a period of time that ranges from a day to three or four days before returning to normal propagation conditions.

What can we do about the solar disturbances and related disturbed ionospheric propagation on Earth? The truth is that we are powerless faced with the truly awesome forces of solar disturbances like flares, coronal holes or sudden disappearing filaments. Perhaps there is some comfort, however, in understanding what has happened to cause our HF bands to be so poor. And as a definite consolation, conditions on the VHF bands are often exceptionally good just when HF propagation is remarkably poor due to solar disturbances. VHF operators enthusiastically look forward to conditions when they can engage in auroral communications—exactly the kind of conditions that have HF operators scratching their heads, wondering where the ionosphere went.

ELEVATION ANGLES FOR HF COMMUNICATION

It was shown in connection with Fig 25 that the distance at which a ray returns to Earth depends on the elevation angle at which it left the Earth (also known by other names: takeoff, launch or wave angle). Chapter 3, The Effects of Ground, in this book deals with the effects of local terrain, describing how the elevation angle of a horizontally polarized antenna is determined mainly by its height above the ground.

Although it is not shown specifically in Fig 25, propagation distance also depends on the layer height at the time, as well as the elevation angle. As you can probably imagine, the layer height is a very complex function of the state of the ionosphere and the Earth's geomagnetic field. There is a large difference in the distance covered in a single hop, depending on the height of the E or the F_2 layer. The maximum single-hop distance by the E layer is about 2000 km (1250 miles) or about half the maximum distance via the F_2 layer. Practical communicating distances for single-hop E or F layer work at various wave angles are shown in graphic form in **Fig 27**.

Actual communication experience usually does not fit the simple patterns shown in Fig 25. Propagation by means of the ionosphere is an enormously complicated business (which makes it all the more intriguing and challenging to radio amateurs, of course), even when the Sun is not in a disturbed state. Until the appearance of sophisticated computer models of the ionosphere, there was little definitive information available to guide the radio amateur in the design of his antenna systems for optimal performance over all portions of the 11-year solar cycle. Elevation angle information that had appeared for many years in *The ARRL Antenna Book* was measured for only one transmitting path, during the lowest portion of Solar Cycle 17 in 1934.

The *IONCAP* Computer Propagation Model

Since the 1960s several agencies of the US government have been working on a detailed computer program that models the complex workings of the ionosphere. The program has been dubbed *IONCAP*, short for "Ionospheric Communications Analysis and Prediction Program." *IONCAP* was originally written for a mainframe computer, but later versions have been rewritten to allow them to be run by high-performance personal computers. *IONCAP* incorporates a detailed database covering almost three complete solar cycles. The program allows the operator to specify a wide range of parameters, including detailed antenna models for multiple frequency ranges, noise models tailored to specific local environments (from low-noise rural to noisy residential QTHs), minimum elevation angles suitable for a

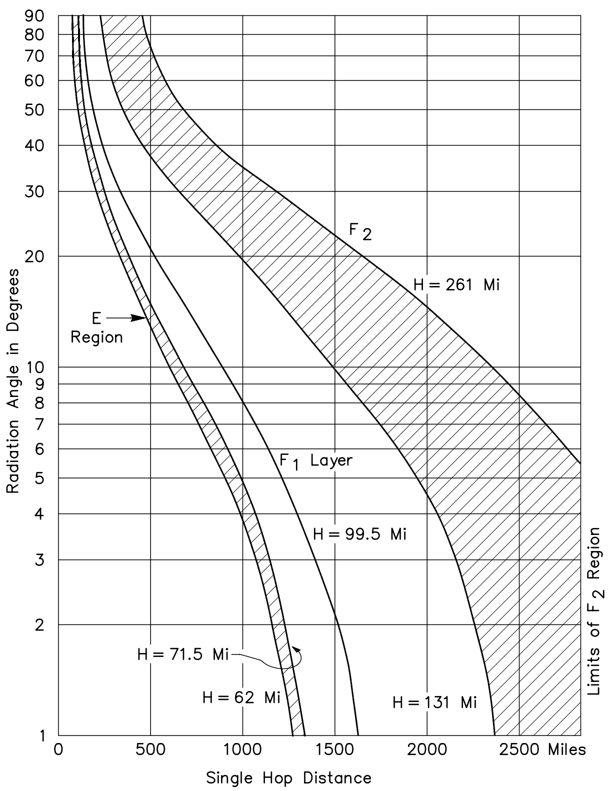

Fig 27—Distance plotted against wave angle (one-hop transmission) for the nominal range of heights for the E and F2 layers, and for the F1 layer.

particular location and antenna system, different months and UTC times, maximum levels of multipath distortion, and finally solar activity levels, to name the most significant of a bewildering array of options.

While *IONCAP* has a well-justified reputation for being very *unfriendly* to use, due to its mainframe, non-interactive background, it is also the one ionospheric model most highly regarded for its accuracy and flexibility, both by amateurs and professionals alike. It is the program used for many years to produce the long-term MUF charts formerly included in the "How's DX" monthly column of *QST* and now available on the Members Only ARRLWeb page.

IONCAP is not well suited for short-term forecasts of propagation conditions based on the latest solar indices received from WWV. It is an excellent tool, however, for long-range, detailed planning of antenna systems and shortwave transmitter installations, such as that for the Voice of America, or for radio amateurs. See the section later in this chapter describing other computer programs that can be used for short-term, interactive propagation predictions.

IONCAP/VOACAP Parameters

The elevation-angle statistical information contained in this section was compiled from thousands of *VOACAP* runs (an improved version of *IONCAP* developed by scientists from VOA, the Voice of America). These runs were done for a number of different transmitting locations throughout the world to important DX locations throughout the world.

Some assumptions were needed for setting *VOACAP* parameters. The transmitting and receiving sites were all assumed to be located on flat ground, with "average" ground conductivity and dielectric constant. Each site was assumed to have a clear shot to the horizon, with a minimum elevation angle less than or equal to 1°. Electrical noise at each receiving location was also assumed to be very low.

Transmitting and receiving antennas for the 3.5 to 30-MHz frequency range were specified to be isotropic-type antennas, but with +6 dBi gain, representing a good amateur antenna on each frequency band. These theoretical antennas radiate uniformly from the horizon, up to 90° directly overhead. With response patterns like this, these are obviously not real-world antennas. They do, however, allow the computer program to explore all possible modes and elevation angles.

Looking at the Elevation-Angle Statistical Data

Table 3 shows detailed statistical elevation information for the path from Boston, Massachusetts, near ARRL HQ in Newington, Connecticut, to all of Europe. The data incorporated into Table 3 shows the percentage of time versus elevation angle for all HF bands from 80 meters to 10 meters, over all portions of the 11-year solar cycle. The CD-ROM accompanying this book contains more tables such as this for more than 150 transmitting sites around the world. These tables are used by the *HFTA* program (and earlier *YT* program) and can also be imported into many programs, such as word processors or spreadsheets. Six important areas throughout the world are covered, one per table: all of Europe (from London, England, to Kiev, Ukraine), the Far East (centered on Japan), South America (Paraguay), Oceania (Melbourne, Australia), Southern Africa (Zambia) and South Asia (New Delhi, India).

You may be surprised to see in Table 3 that angles lower than 10° dominate the possible range of incoming angles for this moderate-distance path from New England to Europe. In fact, 1.7% of all the times when the 20-meter band is open to Europe, the takeoff angle is as low as 1°. You should recognize that very few real-world 20-meter antennas achieve much gain at such an extremely low angle—unless they just happen to be mounted about 400 feet high over flat ground or else are located on the top of a tall, steep mountain.

The situation is even more dramatic on 40 and 80 meters. **Fig 28** shows the "cumulative distribution function" of the total percentage of time (derived from Table 3) when 40 meters is open from Boston to the rest of the world, plotted against the elevation angle. For example, into Europe from Boston, 50% of the time when the band is open, it is at 10° or less. Into Japan from Boston, the statistics are even more revealing: 50% of the time when the band is open, the

Table 3
Boston, Massachusetts, to All of Europe

E*lev*	*80 m*	*40 m*	*30 m*	*20 m*	*17 m*	*15 m*	*12 m*	*10 m*
1	4.1	9.6	4.6	1.7	2.1	4.4	5.5	7.2
2	0.8	2.3	7.2	1.4	2.8	2.8	3.7	5.3
3	0.3	0.7	4.3	3.1	2.4	2.2	4.4	7.9
4	0.5	4.1	8.7	11.6	12.2	9.4	8.1	3.9
5	4.6	4.8	7.5	12.7	14.3	13.1	9.2	11.2
6	7.1	8.9	5.5	9.2	9.6	12.2	9.2	7.2
7	8.5	6.9	7.2	4.6	7.9	7.4	10.0	5.9
8	5.1	7.0	5.4	3.2	5.9	7.4	4.8	6.6
9	3.3	5.6	3.2	3.1	2.1	3.9	8.1	9.2
10	1.0	4.0	7.9	6.3	5.1	3.7	11.1	6.6
11	1.9	3.8	9.7	10.2	7.2	5.4	3.7	7.9
12	5.6	3.4	4.8	8.5	6.9	7.4	4.8	6.6
13	11.0	3.0	2.4	4.1	5.9	4.6	3.3	2.6
14	7.6	4.8	2.0	2.7	3.8	3.9	6.3	5.9
15	5.3	7.9	2.0	1.5	2.4	1.7	1.5	2.0
16	2.8	6.4	3.8	2.9	1.5	1.3	2.6	2.6
17	5.0	3.4	4.5	3.1	1.0	1.5	0.0	0.0
18	4.2	2.0	3.1	3.1	2.0	2.2	1.8	1.3
19	5.7	1.4	1.4	2.3	1.3	0.7	0.0	0.0
20	6.6	1.4	1.2	1.8	1.1	1.3	0.7	0.0
21	4.4	1.4	0.5	0.8	0.7	0.7	0.4	0.0
22	2.3	2.4	1.0	1.1	0.6	1.3	0.7	0.0
23	1.3	1.8	0.1	0.3	0.1	0.0	0.0	0.0
24	0.6	1.0	0.5	0.5	0.4	0.7	0.0	0.0
25	0.3	0.8	0.3	0.1	0.4	0.0	0.0	0.0
26	0.0	0.5	0.7	0.2	0.1	0.4	0.0	0.0
27	0.1	0.1	0.1	0.2	0.1	0.2	0.0	0.0
28	0.0	0.3	0.1	0.2	0.0	0.2	0.0	0.0
29	0.1	0.0	0.2	0.0	0.0	0.0	0.0	0.0
30	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
31	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
32	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
33	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
34	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
35	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Percentage of time a particular frequency band is open on this specific propagation path.

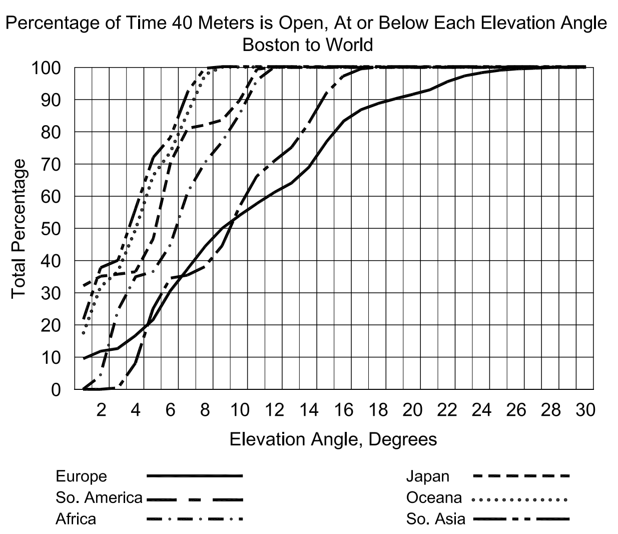

Fig 28—The cumulative distribution function showing the total percentage of time that 40 meters is open, at or below each elevation angle, from Boston to the world. For example, 50% of the time the band is open to Europe from Boston, it is at 10° or less. The angles for DX work are indeed low.

angle is 6° or less, and 90% of the time the angle 13° or less!

Fig 29 shows the same sort of information for 80 meters from Boston to the world. For 50% of the time from Boston to Europe the elevation angle is 13° or less; at the 90% level the angle is 20° or less. For the path to Japan on 80 meters from Boston, 50% of the time the angle is 8° or less; at the 90% level, the angle is 13° or less. Now, to achieve peak gain on 80 meters at an elevation angle of 8° over flat land, a horizontally polarized antenna must be 500 feet high. You can begin to see why verticals can do very well on long-

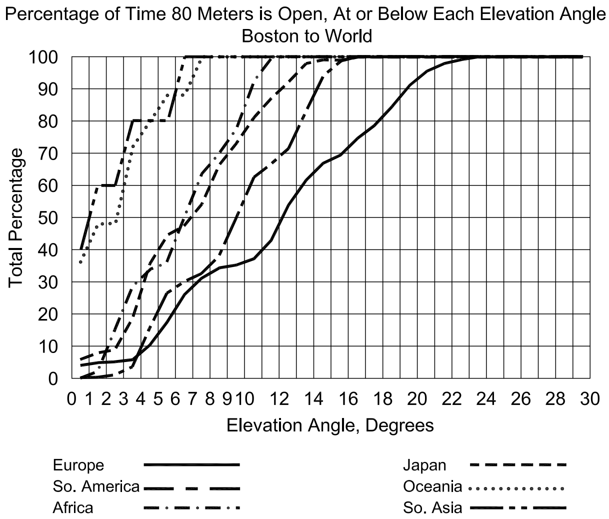

Fig 29—The cumulative distribution function showing the total percentage of time that 80 meters is open, at or below each elevation angle, from Boston to the world. For example, 50% of the time the band is open to Europe from Boston, it is at 13° or less.

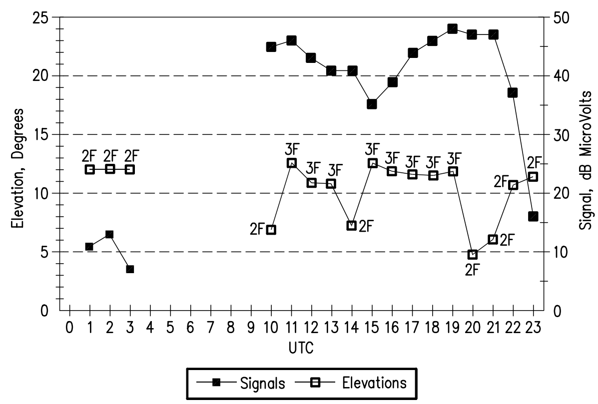

Fig 30—Overlay of signals and elevation angles, together with hop-mode information. This is for one month, October, at one level of solar activity, SSN=70, for the path from Newington, CT, to London, England. The mode of propagation does not closely follow the elevation angle. From 15 to 19 UTC the mode is 3F2 hops, and the elevation angle is approximately 12°. The same elevation angle is required from 23 to 03 UTC, but here the mode is 2F2 hops.

distance contacts on 80 meters, even when they are mounted over poorly conducting, rocky ground. Clearly, low angles are very important for successful DXing.

The Ionosphere Controls Propagation

You should always remember that it is the *ionosphere* that controls the elevation angles, *not* the transmitting antenna. The elevation response of a particular antenna only determines how strong or weak a signal is, at whatever angle (or angles) the ionosphere is supporting at that particular instant, for that propagation path and for that frequency.

If only one propagation mode is possible at a particular time, and if the elevation angle for that one mode happens to be 5°, then your antenna will have to work satisfactorily at that very low angle or else you won't be able to communicate. For example, if your low dipole has a gain of –10 dBi at 5°, compared to your friend's Yagi on a mountain top with +10 dBi gain at 5°, then you will be down 20 dB compared to his signal. It's not that the elevation angle is somehow *too low*—the real problem here is that you don't have *enough gain* at that particular angle where the ionosphere is supporting propagation. Many "flatlanders" can vividly recall the times when their mountain-top friends could easily work DX stations, while they couldn't even hear a whisper.

Looking at the Data—Further Cautions

A single propagation mode is quite common at the opening and the closing of daytime bands like 20, 15 or 10 meters, when the elevation angle is often lower (but not always) than when the band is wide open. The lower-frequency bands tend to support multiple propagation modes simultaneously. For example, **Fig 30** plots the signal strength (in dBμV) and the elevation angle for the dominant mode (with the strongest signal) over a 24-hour period from Newington to London in October, for a medium-level SSN = 70. The morning opening at 10 UTC starts out with a two-hop $2F_2$ mode (labeled 2F) at an elevation angle of 6°. By 11 UTC the mode has changed to a three-hop $3F_2$ (labeled 3F) at a 12° elevation angle. The band starts to close down with weaker signals after about 23 UTC. Note that this path actually supports both $2F_2$ and $3F_2$ modes most of the time. Either mode may be stronger than the other, depending on the particular time of day.

It is tempting to think that two-hop signals always occur at lower elevation launch angles, while three-hop signals require higher elevation angles. In reality, the detailed workings of the ionosphere are enormously complicated. From 22 UTC to 03 UTC, the elevation angles are higher than 11° for $2F_2$ hops. During much of the morning and early afternoon in Newington (from 11 to 13 UTC, and from 15 to 19 UTC), the angles are also higher than 11°. However, $3F_2$ hops are involved during these periods of time. The number of hops is not directly related to the elevation angles needed—changing layer heights account for this.

Note that starting around 15 UTC, the mid-morning 20-meter "slump" (down some 10 dB from peak signal level) is caused by higher levels of mainly E-layer absorption when the Sun is high overhead. This condition favors higher elevation angles, since signals launched at lower angles must travel for a longer time through the lossy lower layer.

How does the situation change with different levels of solar activity? **Fig 31** overlays predicted signals and elevation angles for three levels of solar activity in October, again for the Newington-London path. Fig 31 shows the mid-morning slump dramatically when the solar activity is at a very high level, represented by SSN = 160. At 15 UTC, the signal level drops 35 dB from peak level, and the elevation angle rises all the way to 24°. By the way, as a percentage of all possible openings, the 24° angle occurs only rarely, 0.5% of the time. It barely shows up as a blip in Table 3. Elevation angles are *not* closely related to the level of solar activity.

IONCAP/VOACAP demonstrates that elevation angles do not follow neat, easily identified patterns, even over a 24-hour period—much less over all portions of the solar cycle. Merely looking at the percentage of all openings versus elevation angle, as shown in Table 3, does not tell the whole story, although it is probably the most statistically valid approach to station design, and possibly the most emotionally satisfying approach too. Neither is the whole story revealed by looking only at a snapshot of elevation angles versus time for one particular month, or for one solar activity level.

What is important to recognize is that the most effective antenna system will be one that can cover the *full range* of elevation angles, over the whole spectrum of solar activity, even if the actual angle in use at any one moment in time may not be easy to determine. For this particular path, from New England to all of Europe, an ideal antenna would have equal response over the full range of angles from 1° to 28°. Unfortunately, real-world antennas have a tough time covering such a wide range of elevation angles equally well.

Antenna Elevation Patterns

Figs 32 through **36** show overlays of the same sort of elevation angle information listed in Table 3, together with the elevation response patterns for typical antennas for the HF amateur bands 80, 40, 20, 15 and 10 meters. For example, Fig 34 shows an overlay for 20 meters, with three different types of 20-meter antennas. These are a 4-element Yagi at 90 feet, a 4-element Yagi at 120 feet and a large stack of four 4-element Yagis located at 120, 90, 60 and 30 feet. Each antenna is assumed to be mounted over flat ground. Placement on a hill with a long slope in the direction of interest would lower the required elevation angle by the amount of the hill's slope. For example, if a 10° launch angle is desired, and the antenna is placed on a hill with a slope of –5°, the antenna itself should be designed for a

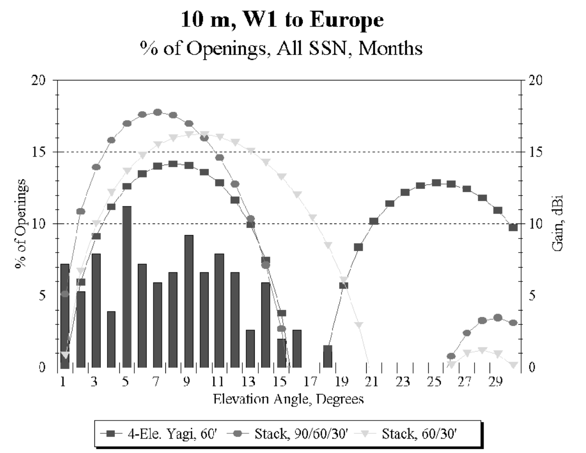

Fig 32—10-meter graph of the percentage of all openings versus elevation angles, together with overlay of elevation patterns over flat ground for three 10-meter antenna systems. Stacked antennas have wider "footprints" in elevation angle coverage for this example from New England to Europe.

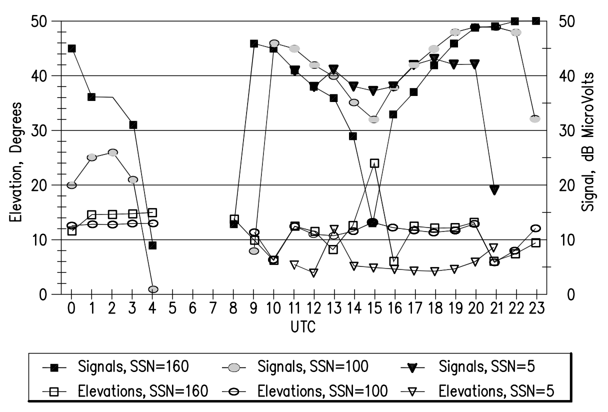

Fig 31—October 20-meter signals and elevation angles for the full range of solar activity, from W1 to England. The elevation angle does not closely follow the level of solar activity. What is important in designing a station capable of covering all levels of solar activity is to have flexibility in antenna elevation pattern response — to cover a wide range of possible angles.

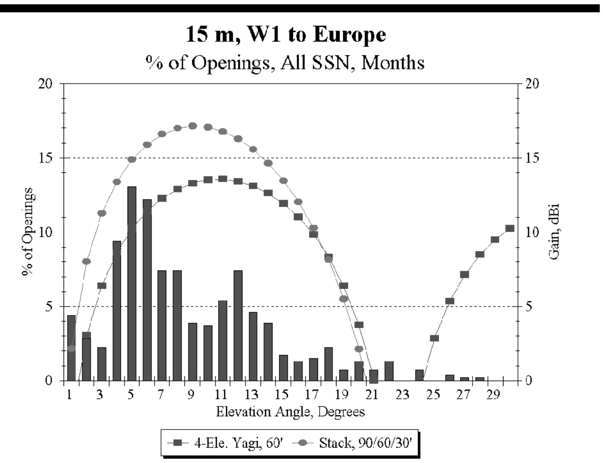

Fig 33—15-meter graph of the percentage of all openings versus elevation angles, together with overlay of elevation patterns over flat ground for two 15-meter antenna systems. Like 10 meters, 15-meter stacked antennas have wider footprints in elevation angle coverage for this example from New England to Europe.

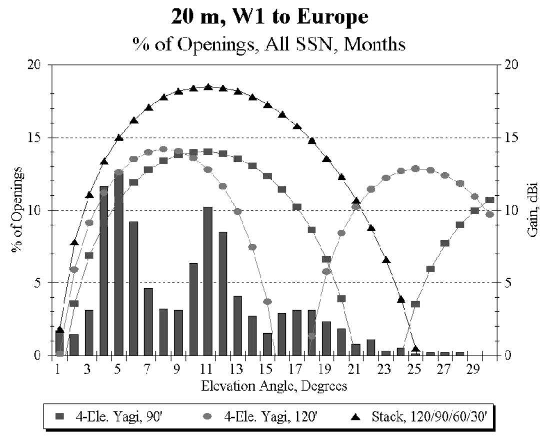

Fig 34—20-meter graph of the percentage of all openings from New England to Europe versus elevation angles, together with overlay of elevation patterns over flat ground for three 20-meter antenna systems.

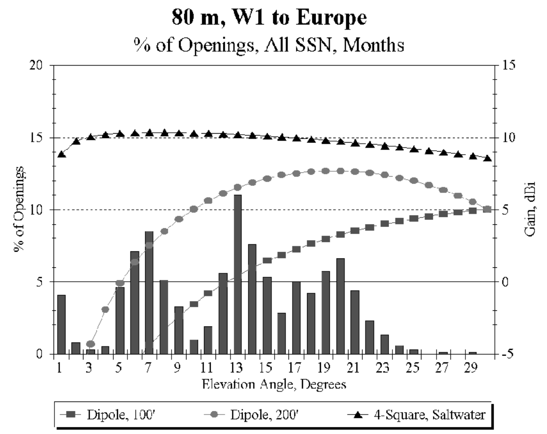

Fig 36—80-meter graph of the percentage of all openings from New England to Europe versus elevation angles, together with overlay of elevation patterns over flat ground for dipoles at two different heights. The 200-foot-high dipole clearly covers the necessary elevation angles better than does the 100-foot-high dipole, although a Four Square vertical array located over saltwater is even better for all angles needed.

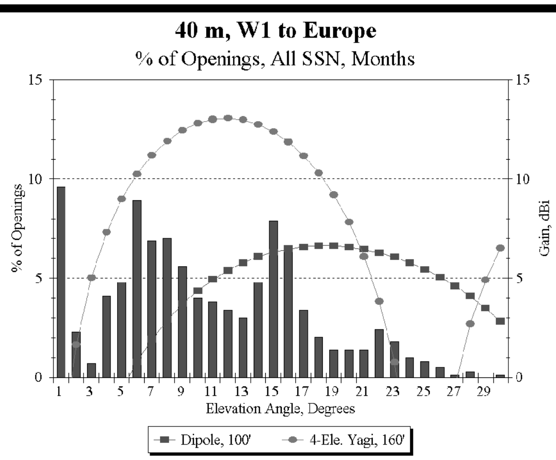

Fig 35—40-meter graph of the percentage of all openings from New England to Europe versus elevation angles, together with overlays of elevation patterns over flat ground for a 100-foot high dipole and a large 4-element Yagi at 160 feet. Achieving gain at very low elevation angles requires very high heights above ground.

height that would optimize the response at 15° over flat ground—one wavelength high.

In Fig 34, the large stack of four 20-meter Yagis over flat ground comes closest to being ideal, but even this large array will not work well for that very small percentage of time when the angle needed is higher than about 20°. Some hams might conclude that the tiny percentage of time when the angles are very high doesn't justify an antenna tailored for that response. However, when that new DX country pops up on a band, or when a rare multiplier shows up in a contest, doesn't it always seem that the desired signal only comes in at some angle your antenna doesn't cover well? What do you do then, if your only antenna happens to be a large stack?

The answer to this, perhaps unique, high-angle problem lies in switching to using only the top antenna in the stack. In this example, the second elevation lobe of the 120-foot high antenna would cover the angles from 20° to 30° well, much better than the stack does. Note that the top antenna by itself would not be ideal for all conditions. It is simply too high much of the time when the elevation angles are higher than about 12°. The experience of many amateurs on the US East Coast with high 20-meter antennas bears this out—they find that 60 to 90-foot high antennas are far more consistent performers into Europe.

ONE-WAY PROPAGATION

On occasion a signal may be started on the way back toward the Earth by reflection from the F region, only to come down onto the top of the E region and be reflected back up again. This set of conditions is one possible explanation for the often-reported phenomenon called *one-way skip*. The reverse path may not necessarily have the same multilayer characteristic. The effect is more often a difference in the signal strengths, rather than a complete lack of signal in one direction, and many times there may be local noises that mask signals at one end of the path. It is important to remember these sorts of possibilities when a long-distance test with a new antenna system yields apparently conflicting results. Even many tests, on paths of different lengths and headings, may provide data that are difficult to understand. Communication by way of the ionosphere is not always a source of consistent answers to antenna questions.

Fig 36 shows the 80-meter path from New England to Europe with three different antennas. A really high dipole at a height of 200 feet above flat ground would certainly be an impressive antenna. But it would still be overshadowed dramatically by a Four-Square vertical array, at least at the low elevation angles needed often on this path. This is predicated on the Four Square being located over salt water, which provides a virtually perfect RF ground. At an elevation angle of 7°, the Four Square has 7 dB more gain than the 200-foot high dipole.

SHORT OR LONG PATH?

Propagation between any two points on the Earth's surface is usually by the shortest direct route—the *great-circle path* found by stretching a string tightly between the two points on a globe. If an elastic band going completely around the globe in a straight line is substituted for the string, it will show another great-circle path, going "the long way around." The long path may serve for communication over the desired circuit when conditions are favorable along the longer route. There may be times when communication is possible over the long path but not possible at all over the short path. Especially if there is knowledge of this potential at both ends of the circuit, long-path communication may work very well. Cooperation is almost essential, because both the aiming of directional antennas and the timing of the attempts must be right for any worthwhile result. The *IONCAP/VOACAP* computations in the preceding tables were made for short-path azimuths only.

Sunlight is a required element in long-haul communication via the F layer above about 10 MHz. This fact tends to define long-path timing and antenna aiming. Both are essentially the reverse of the "normal" for a given circuit. We know also that salt-water paths work better than overland ones. This can be significant in long-path work.

We can better understand several aspects of long-path propagation if you become accustomed to thinking of the Earth as a ball. This is easy if you use a globe frequently. A flat map of the world, of the azimuthal-equidistant projection type, is a useful substitute. The ARRL World Map is one, centered on Wichita, Kansas. A similar world map prepared by K5ZI and centered on Newington, Connecticut, is shown in **Fig 37**. These help to clarify paths involving those areas of the world.

Long-Path Examples

There are numerous long-path routes well known to DX-minded amateurs. Two long paths that work frequently and well when 28 MHz is open from the northeastern US are New England to Perth, Western Australia, and New England to Tokyo. Although they represent different beam headings and distances, they share some favorable conditions. By the long path, Perth is close to halfway around the world; Tokyo is about three-quarters of the way. On 28 MHz, both areas come through in the early daylight hours, Eastern Time, but not necessarily on the same days. Both paths are at their best around the equinoxes. (The sunlight is more uniformly distributed over transequatorial paths at these times.) Probably the factor that most favors both is the nature of the first part of the trip at the US end. To work Perth by way of long path, northeastern US antennas are aimed southeast, out over salt water for thousands of miles—the best low-loss start a signal could have. It is salt water essentially all the way, and the distance, about 13,000 miles, is not too much greater than the "short" path.

The long path to Japan is more toward the south, but still with no major land mass at the early reflection points. It is much longer, however, than that to Western Australia. Japanese signals are more limited in number on the long path than on the short, and signals on the average somewhat weaker, probably because of the greater distance.

On the short path, an amateur in the Perth area is looking at the worst conditions—away from the ocean, and out across the huge land mass of North America, unlikely to provide strong ground reflections. The short paths to both Japan and Western Australia, from most of the eastern half of North America, are hardly favorable. The first hop comes

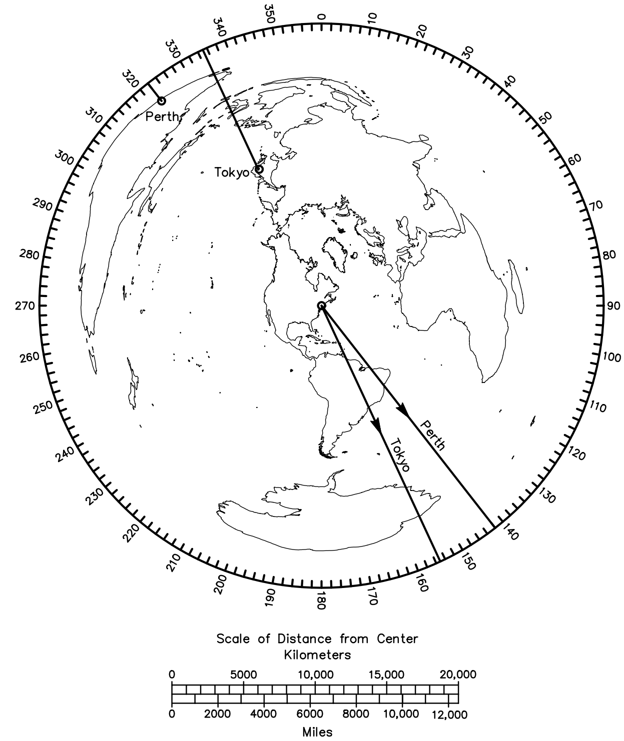

Fig 37—K5ZI's computer-generated azimuthal-equidistant projection centered on Newington, Connecticut. (See Bibliography for ordering information.) Land masses and information showing long paths to Perth and Tokyo have been added. Notice that the paths in both cases lie almost entirely over water, rather than over land masses.

down in various western areas likely to be desert or mountains, or both, and not favored as reflection points.

A word of caution: Don't count on the long-path signals always coming in on the same beam heading. There can be notable differences in the line of propagation via the ionosphere on even relatively short distances. There can be more variations on long path, especially on circuits close to halfway around the world. Remember, for a point exactly halfway around, all directions of the compass represent great-circle paths.

FADING

When all the variable factors in long-distance HF communication are taken in account, it is not surprising that signals vary in strength during almost every contact beyond the local range. In VHF communication we can also encounter some fading at distances greater than just to the visible horizon. These are mainly the result of changes in the temperature and moisture content of the air in the first few thousand feet above the ground.

On paths covered by HF ionospheric modes, the causes of fading are very complex—constantly changing layer height and density, random polarization shift, portions of the signal arriving out of phase, and so on. The energy arriving at the receiving antenna has components that have been acted upon differently by the ionosphere. Often the fading is very different for small changes in frequency. With a signal of a wideband nature, such as high-quality FM, or even double-sideband AM, the sidebands may have different fading rates from each other, or from the carrier. This causes severe distortion, resulting in what is termed *selective fading*. The effects are greatly reduced (but still present to some extent) when single-sideband (SSB) is used. Some immunity from fading during reception (but not to the distortion induced by selective fading) can be had by using two or more receivers on separate antennas, preferably with different polarizations, and combining the receiver outputs in what is known as a *diversity* receiving system.

OTHER PROPAGATION MODES

In propagation literature there is a tendency to treat the various propagation modes as if they were separate and distinct phenomena. This they may be at times, but often there is a shifting from one to another, or a mixture of two or more kinds of propagation affecting communication at one time. In the upper part of the usual frequency range for F-region work, for example, there may be enough tropospheric bending at one end (or both ends) to have an appreciable effect on the usable path length. There is the frequent combination of E and F-region propagation in long-distance work. And in the case of the E region, there are various causes of ionization that have very different effects on communication. Finally, there are weak-signal variations of both tropospheric and ionospheric modes, lumped under the term "scatter." We look at these phenomena separately here, but in practice we have to deal with them in combination, more often than not.

Sporadic E (E_s)

First, note that this is *E-subscript-s*, a usefully descriptive term, wrongly written "Es" so often that it is sometimes called "ease," which is certainly not descriptive. *Sporadic E* is ionization at E-layer height, but of different origin and communication potential from the E layer that affects mainly our lower amateur frequencies.

The formative mechanism for sporadic E is believed to be wind shear. This explains ambient ionization being distributed and compressed into a ledge of high density, without the need for production of extra ionization. Neutral winds of high velocity, flowing in opposite directions at slightly different altitudes, produce shears. In the presence of the Earth's magnetic field, the ions are collected at a particular altitude, forming a thin, overdense layer. Data from rockets entering E_s regions confirm the electron density, wind velocities and height parameters.

The ionization is formed in clouds of high density, lasting only a few hours at a time and distributed randomly. They vary in density and, in the middle latitudes in the Northern Hemisphere, move rapidly from southeast to northwest. Although E_s can develop at any time, it is most prevalent in the Northern Hemisphere between May and August, with a minor season about half as long beginning in December (the summer and winter solstices). The seasons and distribution in the Southern Hemisphere are not so well known. Australia and New Zealand seem to have conditions much like those in the US, but with the length of the seasons reversed, of course. Much of what is known about E_s came as the result of amateur pioneering in the VHF range.

Correlation of E_s openings with observed natural phenomena, including sunspot activity, is not readily apparent, although there is a meteorological tie-in with high-altitude winds. There is also a form of E_s, mainly in the northern part of the north temperate zone, that is associated with auroral phenomena.

At the peak of the long E_s season, most commonly in late June and early July, ionization becomes extremely dense and widespread. This extends the usable range from the more common "single-hop" maximum of about 1400 miles to "double-hop" distances, mostly 1400 to 2500 miles. With 50-MHz techniques and interest improving in recent years, it has been shown that distances considerably beyond 2500 miles can be covered. There is also an E_s "link-up" possibility with other modes, believed to be involved in some 50-MHz work between antipodal points, or even long-path communication beyond 12,500 miles.

When E_s is particularly strong and widespread, even the HF bands can suddenly go *short skip* producing exceptionally strong signals from distances that would normally be in the no-signal "skip zone." Editor N6BV distinctly remembers a spectacular 20-meter E_s opening in September 1994, during the "Hiram Percy Maxim/125" anniversary celebration, when he was living in New Hampshire. Signals on 20 meters were 30 to 40 dB over S9 from all along the Eastern Seaboard, from W2 to W4. One exasperated W3 complained that he had been calling in the huge pileup for 20 minutes. N6BV glanced at the S meter and saw that the W3 was 20 dB over S9, normally a very strong 20-meter SSB signal, but not when almost everybody else was 40 dB over S9!

Such short-skip conditions caused by Sporadic E are more common on 10 meters than they are on 15 or 20 meters. They can result in excellent transAtlantic 10-meter openings during the summer months—when 10 meters is not normally open for F_2 ionospheric propagation.

The MUF for E_s is not known precisely. It was long thought to be around 100 MHz, but in the last 25 years or so there have been thousands of 144-MHz contacts during the summer E_s season. Presumably, the possibility also exists at 222 MHz. The skip distance at 144 MHz does average much longer than at 50 MHz, and the openings are usually brief and extremely variable.

The terms "single" and "double" hop may not be accurate technically, since it is likely that cloud-to-cloud paths are involved. There may also be "no-hop" E_s. At times the very high ionization density produces critical frequencies up to the 50-MHz region, with no skip distance at all. It is often said that the E_s mode is a great equalizer. With the reflecting region practically overhead, even a simple dipole close to the ground may do as well over a few hundred miles as a large stacked antenna array designed for low-angle radiation. It's a great mode for low power and simple antennas on 28 and 50 MHz.

HF Scatter Modes

The term "skip zone" (where no signals are heard) should not be taken too literally. Two stations communicating over a single ionospheric hop can be heard to some degree by other stations at almost any point along the way, unless the two are running low power and using simple antennas. Some of the wave energy is *scattered* in all directions, including back to the starting point and farther.

Backscatter functions like a sort of HF ionospheric radar. **Fig 38** shows a schematic for a simple backscatter path. The signal launched from point A travels through the ionosphere back to earth at Point S, the scattering point. Here, the rough terrain of the land scatters signals in many directions, one of which propagates a weak signal back through the ionosphere to land at point B. Point B would normally be in the no-signal skip zone between A and S. Because backscatter signals arrive from multiple directions, through various paths through the ionosphere, they have a characteristic "hollow" sound, much like you get when you talk into a paper tube with its many internal reflections.

Because backscatter involves mainly scattering from the Earth at the point where the strong ionospherically propagated signal comes down, it is a part of HF over-the-horizon radar techniques. (The infamous 1970s-era "woodpecker" was an over-the-horizon HF radar.) Amateurs using sounding techniques have shown that you can tell to what part of the world a band is usable (single-hop F) by probing

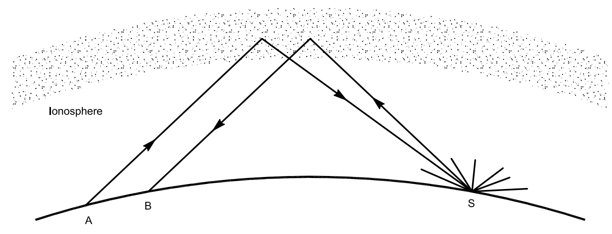

Fig 38—Schematic of a simple backscatter path. Stations A and B are too close to make contact via normal F-layer ionospheric refraction. Signals scattered back from a distant point on the Earth's surface (S), often the ocean, may be accessible to both A and B to create a backscatter circuit. (*Courtesy of The ARRL Handbook.*)

the backscatter with a directive antenna and high transmitter power, even when the Earth contact point is open ocean. In fact, that's where the mode is at its best, because ocean waves can be efficient backscatter reflectors.

Backscatter is very useful on 28 MHz, particularly when that band seems dead simply because nobody is active in the right places. The mode keeps the 10-meter band lively in the low years of the solar cycle, thanks to the never-say-die attitude of some users. The mode is also an invaluable tool of 50-MHz DX aspirants, in the high years of the sunspot cycle, for the same reasons. On a high-MUF morning, hundreds of 6-meter beams may zero in on a hot spot somewhere in the Caribbean or South Atlantic, where there is no land, let alone other 6-meter stations—keeping in contact while they wait for the band to open to a place where there is somebody.

Sidescatter is similar to backscatter, except the ground scatter zone is off the direct line between participants. A typical example, often observed during the lowest years of the solar cycle, is communication on 28 MHz between the eastern US (and adjacent areas of Canada) and much of the European continent. Often, this may start as "backscatter chatter" between Europeans whose antennas are turned toward the Azores. Then suddenly the North Americans join the fun, perhaps for only a few minutes, but sometimes much longer, with beams also pointed toward the Azores. Duration of the game can be extended, at times, by careful reorientation of antennas at both ends, as with backscatter. The secret, of course, is to keep hitting the highest-MUF area of the ionosphere and the most favorable ground-reflection points.

The favorable route is usually, but not always, south of the great-circle heading (for stations in the Northern Hemisphere). There can also be sidescatter from the auroral regions. Sidescatter signals are stronger than backscatter signals using the same general area of ground scattering.

Sidescatter signals have been observed frequently on the l4-MHz band, and can take place on any band where there is a large window between the MUF and the LUF. For sidescatter communications to occur, the thing to look for is a common area to which the band is open from both ends of the path (the Azores, in the above example), when there is no direct-path opening. It helps if the common area is in the open ocean, where there is less scattering loss than over land.

GRAY-LINE PROPAGATION

The *gray line*, sometimes called the *twilight zone*, is a band around the Earth between the Sunlit portion and darkness. Astronomers call this the *terminator*. The terminator is a somewhat diffused region because the Earth's atmosphere tends to scatter the light into the darkness. **Fig 39** illustrates the gray line. Notice that on one side of the Earth, the gray line is coming into daylight (sunrise), and on the other side it is coming into darkness (sunset).

Propagation along the gray line is very efficient, particularly on the lower bands, especially on 80 or 160 meters, so greater distances can be covered than might be expected for the frequency in use. One major reason for this is that the D layer, which absorbs HF signals, disappears rapidly on the sunset side of the gray line, and has not yet built up on the sunrise side.

The gray line runs generally north and south, but varies as much as 23° either side of the north-south line. This variation is caused by the tilt of the Earth's axis relative to its orbital plane around the Sun. The gray line will be exactly north and south at the equinoxes (March 21 and September 21). On the first day of Northern Hemisphere summer, June 21, it is tilted to the maximum of 23° one way, and on December 21, the first day of winter, it is tilted 23° the other way.

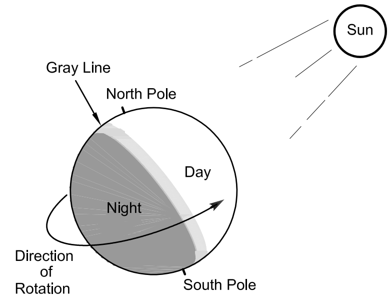

Fig 39—The gray line or terminator is a transition region between daylight and darkness. One side of the Earth is coming into sunrise, and the other is just past sunset.

To an observer on the Earth, the direction of the terminator is always at right angles to the direction of the Sun at sunrise or sunset. It is important to note that, except at the equinoxes, the gray-line direction will be different at sunrise from that at sunset. This means you can work different areas of the world in the evening than you worked in the morning.

It isn't necessary to be located inside the twilight zone in order to take advantage of gray-line propagation. The effects can be used to advantage before sunrise and after sunset. This is because the Sun "rises" earlier and "sets" later on the ionospheric layers than it does on the Earth below.

What HF Bands Are Open—Where and When?

The CD-ROM included at the back of this book includes summary and detailed propagation predictions for more than 150 transmitting locations around the world. This propagation data was calculated using *CapMAN*, an upgraded variety of the mainframe propagation program *IONCAP*. The predictions were done for default antennas and powers that are representative of a "big-gun" station. Of course, not everyone has a big-gun station in his/her backyard, but this represents what the ultimate possibilities are, statistically speaking. After all, if the bands aren't open for the big guns, they are unlikely to be open for the "little pistols" too.

Let's see how propagation is affected if the smoothed sunspot number is 0 (corresponding to a smoothed solar flux of about 65), which is classified as a "Very Low" level of solar activity. And we'll examine the situation for a sunspot number of 100 (a smoothed solar flux of 150), which is typical of a "Very High" portion of the solar cycle.

Five-Band Summary Predictions

Tables 4 and **5** are Summary tables showing the predicted signal levels (in S units) from Boston, Massachusetts, to the rest of the world for the month of January. The Boston transmitting site is representative of the entire New England area of the USA. The target geographic receiving regions for the major HF bands from 80 through 10 meters are tabulated versus UTC (Universal Coordinated Time) in hours. Table 4 represents a Very Low level of solar activity, while Table 5 is for a Very High level of solar activity.

Each transmitting location is organized by six levels of solar activity over the whole 11-year solar cycle:

- VL (Very Low: SSN between 0 to 20)
- LO (Low: SSN between 20 to 40)
- ME (Medium: SSN between 40 to 60)
- HI (High: SSN between 60 to 100)
- VH (Very High: SSN between 100 to 150)

Table 4

Printout of summary propagation table for Boston to the rest of the world, for a Very Low level of solar activity in the month of January. The abbreviations for the target geographic areas are: EU = Europe, FE = Far East, SA = South America, AF = Africa, AS = south Asia, OC = Oceania, and NA = North America.

Jan., MA (Boston), for SSN = Very Low, Sigs in S-Units. By N6BV, ARRL.

	80 Meters							40 Meters							20 Meters							15 Meters							10 Meters							
UTC	EU	FE	SA	AF	AS	OC	NA	EU	FE	SA	AF	AS	OC	NA	EU	FE	SA	AF	AS	OC	NA	EU	FE	SA	AF	AS	OC	NA	EU	FE	SA	AF	AS	OC	NA	UTC
0	9	-	9+	9	9	-	9+	9	8	9+	9+	9	2	9+	-	8	9+	7	4	8	9+	-	-	-	-	-	-	1	-	-	-	-	-	-	2	0
1	9	-	9+	9	9	-	9+	9	6	9+	9+	9+	6	9+	-	4	9	4	2	6	9+	-	-	-	-	-	-	1	-	-	-	-	-	-	2	1
2	9	-	9+	9+	8	1	9+	9	6	9+	9+	9	8	9+	-	1	8	1	2	3	9+	-	-	-	-	-	-	1	-	-	-	-	-	-	2	2
3	9	-	9+	9+	8	6	9+	9	6	9+	9+	9	8	9+	-	-	8	2	2	-	9+	-	-	-	-	-	-	1	-	-	-	-	-	-	2	3
4	9	-	9+	9+	1	8	9+	9	8	9+	9+	9	9	9+	-	1	8	7	2	-	9+	-	-	-	-	-	-	1	-	-	-	-	-	-	2	4
5	9	-	9+	9+	-	9	9+	9	8	9+	9+	8	9	9+	-	1	9	8	2	-	9	-	-	-	-	-	-	1	-	-	-	-	-	-	2	5
6	9+	-	9+	9+	-	9	9+	7	8	9+	9+	8	9	9+	-	1	9+	8	-	-	9	-	-	-	-	-	-	1	-	-	-	-	-	-	2	6
7	9	7	9+	9	-	9	9+	7	8	9+	9	8	9	9+	-	1	9+	1	-	1	8	-	-	-	-	-	-	1	-	-	-	-	-	-	2	7
8	9	8	9+	9	-	9	9+	8	9	9+	9	8	9+	9+	-	1	9+	-	-	5	9	-	-	-	-	-	-	1	-	-	-	-	-	-	2	8
9	8	8	9+	7	6	9	9+	8	9	9+	9	9	9+	9+	-	-	9	1	-	7	9	-	-	-	-	-	-	1	-	-	-	-	-	-	2	9
10	5	8	9+	4	6	9	9+	9	9	9+	9	9	9+	9+	-	3	9	5	-	6	9	-	-	-	-	-	-	1	-	-	-	-	-	-	2	10
11	3	8	9+	-	5	9	9+	8	9	9+	7	9	9+	9+	5	-	9+	9	5	1*	8	-	-	-	-	-	-	1	-	-	-	-	-	-	2	11
12	1	8	9	-	4	9	9+	7	9	9+	4	8	9	9+	9	5	9+	9+	9	2*	8	-	-	5	6	-	-	1	-	-	-	-	-	-	2	12
13	-	6	1	-	-	7	9+	6	8	9+	1	8	9	9+	9+	9	9+	9	9	7	8	4	-	9+	9	7	-	1	-	-	-	-	-	-	1	13
14	-	-	-	-	-	1	9+	5	7	8	-	8	8	9+	9+	9	9+	9	9	9	9+	7	2*	9+	9	9	-	8	-	-	5	-	-	-	1	14
15	-	-	-	-	-	-	9+	4	6	5	-	6	7	9+	9+	9	9+	9	9	9	9+	7	5	9+	9	2	2	5	-	-	5	-	-	-	-	15
16	-	-	-	-	-	-	9+	5	6	4	2	5	4	9+	9+	8	9+	9+	9	9	9+	5	1	9+	8	2*	2	9	-	-	5	-	-	-	1	16
17	-	-	-	-	-	-	9+	6	5	5	5	6	1	9+	9+	5	9+	9+	3	9	9+	-	-	9+	9	-	3	9+	-	-	5	-	-	-	1	17
18	1	-	-	-	-	-	9+	8	6	6	7	6	-	9+	9+	6	9+	9+	4	9	9+	-	-	9+	9	-	7	9+	-	-	5	-	-	-	1	18
19	3	-	-	2	-	-	9+	9	7	8	8	8	-	9+	6	6	9+	9+	6	9	9+	-	-	9+	9	-	9	9+	-	-	2	-	-	-	1	19
20	5	-	7	5	-	-	9+	9	8	9+	9	8	4	9+	1	7	9+	9+	8	9	9+	-	-	9+	4	-	9	9	-	-	-	-	-	-	1	20
21	8	3	9	8	6	-	9+	9	8	9+	9+	9	7	9+	-	8	9+	9	8	9	9+	-	-	9+	-	-	9	6	-	-	-	-	-	-	1	21
22	9	3	9+	9	8	-	9+	9	8	9+	9+	9	5	9+	-	9+	9+	9	8	9	9+	-	-	9	-	-	7	1	-	-	-	-	-	-	1	22
23	9	2	9+	9	9	-	9+	9	8	9+	9+	9	4	9+	-	9+	9+	9	5	9	9+	-	1	6	-	-	2	3	-	-	-	-	-	-	2	23
	EU	FE	SA	AF	AS	OC	NA	EU	FE	SA	AF	AS	OC	NA	EU	FE	SA	AF	AS	OC	NA	EU	FE	SA	AF	AS	OC	NA	EU	FE	SA	AF	AS	OC	NA	

- UH (Ultra High: SSN greater than 150)

The receiving geographic regions for each frequency band are abbreviated:

- EU All of Europe
- FE The Far East, centered on Japan
- SA South America, centered on Paraguay
- AF All of Africa, centered on Zambia
- AS South Asia, centered on India
- OC Oceania, centered on Sydney, Australia
- NA North America, all across the USA

These propagation files show the highest predicted signal strength (in S-units) throughout the generalized receiving area, for a 1500-W transmitter and rather good antennas on both sides of the circuit. The standard antennas are:

- 100-foot high inverted-V dipoles for 80 and 40 meters
- 3-element Yagi at 100 feet for 20 meters
- 4-element Yagi at 60 feet for 15 and 10 meters.

For example, Summary Table 4 shows that in January during a period of Very Low solar activity, 15 meters is open to somewhere in Europe from Boston for only 4 hours, from 13 to 16 UTC, with a peak signal level between S4 and S7. Now look at Table 5, where 15 meters is predicted to be open to Europe during a period of Very High solar activity for 7 hours, from 12 to 18 UTC, with peak signals ranging from S9 to S9+.

Both Tables 4 and 5 represent *snapshots* of predicted signal levels to generalized receiving locations—that is, they are computed for a particular month, from a particular transmitting location, and for a particular level of solar activity. These tables provide summary information that is particularly valuable for someone planning for an operating event such as a DXpedition or a contest.

What happens if you don't have a big-gun station with high antennas or the 1500-W power assumed in the analyzes above? You can discount the S-Meter readings to reflect a smaller station:

- Subtract 2 S units for a dipole instead of a Yagi at same height on 20/15/10 meters.
- Subtract 3 S units for a dipole at 50 feet instead of a Yagi at 100 feet on 20 meters.

Table 5

Printout of summary propagation table for Boston to the rest of the world, for a Very High level of solar activity in the month of January.

Jan., MA (Boston), for SSN = Very High, Sigs in S-Units. By N6BV, ARRL.

	80 Meters							40 Meters							20 Meters							15 Meters							10 Meters							
UTC	EU	FE	SA	AF	AS	OC	NA	EU	FE	SA	AF	AS	OC	NA	EU	FE	SA	AF	AS	OC	NA	EU	FE	SA	AF	AS	OC	NA	EU	FE	SA	AF	AS	OC	NA	UTC
0	9+	-	9+	9+	8	-	9+	9+	5	9+	9+	9	-	9+	1	9+	9+	9+	9+	9	9+	-	9	9+	2	2	9+	9+	-	1	8	-	-	8	9+	0
1	9+	-	9+	9+	8	-	9+	9+	4	9+	9+	9	2	9+	1	9	9+	8	9+	9+	9+	-	3	9	-	7	9+	9	-	-	-	-	-	4	2	1
2	9+	-	9+	9+	7	-	9+	9+	4	9+	9+	9	7	9+	1	9	9+	8	9	9+	9+	-	-	3	-	-	7	9	-	-	-	-	-	-	2	2
3	9+	-	9+	9+	1	2	9+	9+	4	9+	9+	9	9	9+	-	7	9+	7	8	9+	9	-	-	-	-	-	-	-	-	-	-	-	-	-	2	3
4	9+	-	9+	9+	-	7	9+	9+	5	9+	9+	8	9	9+	-	5	9+	9	9	9	9+	-	-	1	-	-	-	-	-	-	-	-	-	-	2	4
5	9+	-	9+	9+	-	8	9+	9+	6	9+	9+	7	9	9+	-	5	9+	9	9	5	9+	-	-	-	-	-	-	-	-	-	-	-	-	-	2	5
6	9+	-	9+	9+	-	8	9+	9+	7	9+	9+	7	9	9+	-	8	9+	8	9	5	9+	-	-	-	-	-	-	-	-	-	-	-	-	-	2	6
7	9+	-	9+	9+	-	8	9+	9	8	9+	9+	7	9+	9+	-	9	9+	-	7	9	9+	-	-	1	-	-	-	-	-	-	-	-	-	-	2	7
8	9	7	9+	9	-	8	9+	9	8	9+	9+	8	9+	9+	-	9	9+	-	4	9+	9+	-	-	1	-	-	-	2	-	-	-	-	-	-	2	8
9	8	7	9+	7	-	8	9+	9	9	9+	9	8	9+	9+	-	6	9+	-	1	9+	9+	-	-	-	-	-	-	1	-	-	-	-	-	-	2	9
10	5	8	9+	2	3	8	9+	9	9	9+	8	8	9	9+	4	-	9+	9+	1	5	9	-	-	-	-	-	-	-	-	-	-	-	-	-	2	10
11	1	8	9+	-	4	9	9+	8	9	9+	5	8	9	9+	9+	4*	9+	9+	7	-	8	-	-	9	9	-	-	-	-	-	-	-	-	-	2	11
12	-	7	8	-	1	9	9+	6	9	9+	1	8	9	9+	9+	9	9+	9	9	1*	9+	9	8*	9+	9+	9	5*	-	-	2*	9	9	1	1*	2	12
13	-	-	-	-	-	2	9+	4	8	8	-	7	9	9+	9+	9	9+	9	9	9+	9+	9+	7	9+	9+	9+	3*	9	9	5*	9+	9+	9	6*	2	13
14	-	-	-	-	-	-	9+	2	7	4	-	5	8	9+	9+	9	9+	8	9	9	9+	9+	9	9+	9+	9+	9	9+	9	6*	9+	9+	9	1*	1	14
15	-	-	-	-	-	-	9	1	5	-	-	4	5	9+	9+	9	9+	9	9	9	9+	9+	9+	9+	9+	9+	9	9+	9	5	9+	9+	6	6	8	15
16	-	-	-	-	-	-	8	3	4	-	-	3	1	9+	9+	8	9	9	9	9	9+	9+	9+	9+	9+	9	9+	9+	9	8	9+	9+	-	8	9	16
17	-	-	-	-	-	-	8	5	3	-	2	4	-	9+	9+	8	9+	9+	9	9	9+	9+	9	9+	9+	1*	9+	9+	-	8	9+	9+	-	8	9+	17
18	-	-	-	-	-	-	9	7	4	2	5	5	-	9+	9+	9	9+	9+	9	9	9+	9+	9	9+	9+	1	9+	9+	-	7	9+	9+	-	9+	9+	18
19	1	-	-	1	-	-	9+	8	5	6	8	7	-	9+	9+	9	9+	9+	9	9	9+	-	9+	9+	9+	2	9	9+	-	6	9+	9+	-	9+	9+	19
20	4	-	2	5	-	-	9+	9	6	9	9	8	-	9+	9+	9	9+	9+	9	9	9+	-	8	9+	9+	3	9	9+	-	1	9+	9	-	9	9+	20
21	7	-	8	7	1	-	9+	9+	7	9+	9+	8	1	9+	8	9	9+	9+	9	9	9+	-	6	9+	9+	3	9	9+	-	-	9+	5*	-	9+	9+	21
22	9	2	9+	9	8	-	9+	9+	7	9+	9+	9	4	9+	2	9+	9+	9+	9	9	9+	-	9+	9+	9	1	9+	9+	-	5	9+	4*	-	9	6	22
23	9	-	9+	9	8	-	9+	9+	7	9+	9+	9	-	9+	1	9+	9+	9+	9	9	9+	-	9+	9+	6	-	9	9+	-	7	9+	2*	-	9	2	23
	EU	FE	SA	AF	AS	OC	NA	EU	FE	SA	AF	AS	OC	NA	EU	FE	SA	AF	AS	OC	NA	EU	FE	SA	AF	AS	OC	NA	EU	FE	SA	AF	AS	OC	NA	

- Subtract 1 S unit for a dipole at 50 feet rather than a dipole at 100 feet on 40/80 meters.
- Subtract 3 S units for 100 W rather than 1500 W.
- Subtract 6 S units for 5 W (QRP) rather than 1500 W.

For example, Table 4 predicts an S7 signal into Boston from Europe on 15 meters at 14 UTC. If a European station is using a dipole at 50 feet, with 100 W of power, what would this do to the predicted signal level in Boston? You would compute: S7 – 2 S units (for a dipole instead of Yagi) – 3 S units (100 W rather than 1500 W) = an S2 signal in Boston. A QRP station with a 4-element 15-meter Yagi at 60 feet would yield: S7 – 6 S units = an S1 signal in Boston.

More Detailed Predictions

Let's now look at table in **Fig 40**, which is the Detailed 20-meter page for the same conditions in Table 5: January at a Very High level of solar activity from Boston to the world. There are six such pages per month/SSN level, covering 160, 80, 40, 20, 15 and 10 meters.

In a Detailed prediction table, the world is divided into the 40 CQ Zones, with a particular sample location in each zone. For example, Zone 14 in Western Europe is represented by a location in London, England (call sign G), while Zone 25 is represented by a location in Tokyo, Japan (call sign JA1). Note that Zones with large ham populations are highlighted with dark shadowing for easy identification. For example, Zones 3, 4 and 5 cover the USA, while Zones 14, 15 and 16 cover the majority of Europe. Zone 25 covers the big ham population in Japan.

Let's revisit the example above for computing the signal strength for a station in London, but this time on 20 meters. Again, we'll assume that the G station has a dipole at 50 feet and 100 W of transmitter power. At 14 UTC in Zone 14, the table in Fig 40 predicts a very healthy signal for the reference big-gun station, at S9+. This is a signal at least S9 + 10 dB. Here, we're going to round off the plus 10 dB to 2 S units, giving a fictional 11 S units to start. We discount this for the smaller station: S11 – 3 S units (for a dipole at 50 feet instead of a 3-element Yagi at 100 feet) – 3 S units (100 W rather than 1500 W) = S5 signal in Boston. This is a respectable signal and will probably get through, in the absence of stronger signals calling the Boston station at the same time, of course.

20 Meters: Jan., MA (Boston), for SSN = Very High, Sigs in S-Units. By N6BV, ARRL.

UTC -->

Zone	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
KL7 = 01	9+	9+	9+	7	-	-	-	-	-	-	-	-	-	-	-	3	9+	9+	9+	9+	9+	9+	9+	9+
VO2 = 02	9+	9	9	9	9	9	8	7	5	3	2	1	5	9+	9+	9+	9+	9+	9+	9+	9+	9+	8	9+
W6 = 03	9+	9+	9+	7	7	1	1	5	8	8	3	-	-	1	9	9+	9+	9+	9+	9	9	9+	9+	9+
W0 = 04	9+	9+	9+	8	5	5	5	5	3	2	1	-	-	9+	9+	9+	9+	9+	9+	9+	9+	9+	9+	9+
W3 = 05	4	2	2	2	2	2	2	3	3	3	3	2	1	1	8	9+	9+	9+	9+	9+	9+	9+	9+	9
XE1 = 06	9+	9+	7	9	9+	9+	9+	9+	9+	9+	9	8	9+	9+	9+	9+	9	9	9	9	9+	9+	9+	9+
TI = 07	9+	9+	8	9	9	9	9	9	9	9+	9	9+	9+	9+	9+	9+	9	8	9	9	9+	9+	9+	9+
VP2 = 08	9+	9+	9+	9+	9+	9+	9+	9+	9+	8	9	9+	9+	9+	9+	9+	9	9+	9+	9+	9+	9+	9+	9+
P4 = 09	9+	9+	9+	9+	9+	9+	9+	9+	9+	9+	9+	9+	9+	9+	9+	9	9	9	9	9+	9+	9+	9+	9+
HC = 10	9+	8	9+	9	9	9	9	9	7	3	1	7	9+	9+	9	5	5	5	7	8	9+	9+	9+	9+
PY1 = 11	9+	9+	9+	9	9	9+	9+	9	8	6	9	9+	8	2	1	-	-	1	4	8	9	9+	9+	9+
CE = 12	9+	9+	9+	9+	9+	9+	9+	9+	9	8	8	9+	9	8	2	1	1	-	1	3	7	9	9+	9+
LU = 13	9+	9+	9+	9+	9+	9+	9+	9+	8	8	8	9+	8	4	2	1	-	-	1	4	8	9	9+	9+
G = 14	-	-	-	-	-	-	-	-	-	-	-	9+	9+	9+	9+	9+	9+	9+	9+	9+	9+	8	2	-
I = 15	-	-	-	-	-	-	-	-	-	-	4	9	9	9	9	9	9	9+	9+	9	8	2	-	-
UA3 = 16	1	1	1	-	-	-	-	-	-	-	-	8	9	9+	9+	9+	9	8	5	-	-	-	-	1
UN = 17	1	-	-	8	7	7	7	1	-	-	-	2	9	9	9	6	-	-	2	4	8	9	5	4
UA9 = 18	6	7	6	6	9	9	9	7	4	1	-	-	8	8	6	6	5	6	7	8	9	9	8	7
UA0 = 19	9+	9	9	6	5	5	8	8	8	4	-	-	2	6	8	8	8	7	4	4	7	9	9+	9+
4X = 20	8	6	3	1	-	3	4	-	-	-	1	8	8	8	8	8	9	9	9+	9	9	8	7	7
HZ = 21	9+	9	4	3	8	8	2	-	-	-	1	7	8	9	8	8	9	9	9	9	9	9	9	9
VU = 22	7	5	8	7	6	7	5	-	-	-	-	6	9	9	9	9	3	2	2	2	8	8	9	8
JT = 23	9	9+	9	5	7	8	8	6	3	-	-	2*	8	8	5	6	8	8	8	8	9	7	5	6
VS6 = 24	9	9	9	5	4	5	7	8	6	1	-	1*	5	7	1	1	1	1	4	2	-	-	-	9
JA1 = 25	9	9	8	7	5	5	8	9	9	6	-	1	1	2	7	7	6	2	-	-	7	9	9+	9
HS = 26	9	9	6	4	2	-	-	2	1	-	-	2*	9	9	9	9	8	7	5	4	5	-	1*	1
DU = 27	9	8	7	-	-	-	5	7	7	1	-	-	1*	9	9	7	6	4	5	3	1*	1*	8	9
YB = 28	9	8	1	-	-	-	-	-	-	-	-	4*	8	9	9	9	8	8	9	9	9	9	9+	9+
VK6 = 29	3*	4*	-	-	-	-	-	-	5	3	-	-	-	5	9	9	9	8	9	9	9	9	9	8
VK3 = 30	1*	-	-	-	-	-	1	3	9	9	4	-	-	9+	9	8	2	1	-	-	1	2*	5*	4*
KH6 = 31	9	9+	9+	9+	8	2	2	6	4	-	-	-	-	-	-	-	9	9	8	7	6	4	6	7
KH8 = 32	-	2	9	9	9	5	5	9	9+	9+	5	-	-	9+	9	9	8	5	3	1	-	-	-	-
CN = 33	-	-	-	-	-	-	-	-	-	-	9	9+	9	9	8	9	9	9+	9+	9+	9+	9+	9+	7
SU = 34	9	8	3	3	-	1	4	-	-	-	2	7	8	8	8	8	9	9	9+	9+	9+	9+	8	8
6W = 35	9+	8	-	-	2	7	5	-	-	-	9+	9+	8	5	4	3	7	9	9+	9+	9+	9+	9+	9+
D2 = 36	9+	9+	5	3	9	9	8	-	-	-	3	-	-	-	-	4	4	7	8	9	9+	9+	9+	9+
5Z = 37	9+	9	2	4	8	8	1	-	-	-	2	-	-	3	5	5	7	8	9	9	9+	9+	9+	9+
ZS6 = 38	9+	9+	8	7	8	9	6	-	-	-	-	-	-	-	1*	1	2	6	8	9	9+	9+	9+	9+
FR = 39	9+	8	2	1	4	1	-	-	-	-	-	-	-	2*	3*	1*	1	3	8	9	9+	9+	9+	9+
FJL = 40	9+	9+	7	4	7	8	7	1	-	-	-	1*	8	9	9	9	9	9	9	9	9+	9+	9+	9+
Zone	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23

UTC -->

Expected signal levels using 1500 W and 3-element Yagis at 100 feet at each station.

Fig 40—The 20-meter page from Detailed propagation-prediction for the month of January, during Very High solar conditions, from Boston to 40 CQ Zones throughout the world. There are similar pages for each month/SSN level for 160, 80, 40, 20, 15 and 10 meters. These Detailed tables are very useful for planning DX work.

Here's another example of how to use the Detailed propagation-prediction tables. Let's say that at 1230 UTC in January you work a VU2 station in New Delhi on 15 meters from Boston, where the local time is 7:30 AM. You need a 20-meter contact also for the 5-Band DXCC award, so you quickly check the table in Fig 40 for Zone 22 (VU) and find that the predicted signal strength is S9. Your new VU2 friend is willing to jump to 20 meters and so you QSY to make the contact.

But perhaps you are late leaving for work and so you ask your new VU2 friend to make a schedule with you later that evening. Again, you consult the Detailed prediction table for 20 meters and find that signals are predicted to be S8 or stronger from 20 to 23 UTC, dropping to S7 at 00 UTC. You quickly ask your new friend whether he minds waking up at 4:30 AM his time to make a schedule with you at 2300 UTC, because New Delhi is 5½ hours ahead of UTC. You determined this using the program *GeoClock*, which is included with the software on the CD-ROM in the back of this book and which you run in the background on Windows. Luckily, he's a very gracious fellow and agrees to meet you on a specific frequency at that time.

The Detailed propagation-prediction tables give you all the information needed to plan your operations to maximize your enjoyment chasing DX. You can use these tables to plan a 48-hour contest next month, or next year—or you can use them to plan a schedule with your ham cousin on the West Coast on Saturday afternoon.

THE PROPAGATION BIG PICTURE

A newcomer to the HF bands could easily be overwhelmed with the sheer amount of data available in the Summary (and particularly the Detailed) prediction tables on the CD-ROM included with this book. So here's a long-term, "big-picture" view of HF propagation that might help answer some common questions. For example, what month really is the best for working DX around the clock? Or what level of solar activity is necessary to provide an opening between your QTH and somewhere in the South Pacific?

Table 6 is a table showing the number of hours in a day during each month when each major HF band is open to the same receiving areas shown in Tables 4 and 5. The listing is for New England, for three levels of solar activity: Very Low, Medium and Very High. The number of hours are separated in Table 6 by slashes. (Versions of Table 6 for other areas around the US are on the CD-ROM that accompanies this book in **Fig6Tab.PDF**.)

Let's examine the conditions for New England to Europe on 15 meters for October. The entry shows "7/11/17," meaning that for a Very Low level of solar activity, 15 meters is open for 7 hours; for a Medium level, it is open for 11 hours and for a Very High level of solar activity it is open for 17 hours a day.

Even for a Very Low level of solar activity, the month with the most hours available per day from Boston to somewhere in Europe is October, with 7 hours, followed by the next largest month of March, with 6 hours. For a Very High level of solar activity, however, the 15-meter band is open to Europe for 18 hours in April, followed by 17 hours availability in September and October. Arguably, the CQ World Wide Contest Committee picked the very best month for higher-frequency propagation when they chose October for the Phone portion of that contest.

You can easily see that even at a Very High level of solar activity, the summer months are not very good to work DX, particularly on east-west paths. For example, the 10-meter band is very rarely open from New England to Europe after the month of April, even when solar activity is at the highest levels possible. Things pick up after September, even for a Medium level of solar activity. Again, October looks like the most fruitful month in terms of the number of hours 10 meters is open to Europe under all levels of solar conditions.

Ten meters is open more regularly on north-south paths, such as from New England to South America or to southern Africa. It is open as much as 10 hours a day during March and October to deep South America, and 7 hours a day in October to Africa—even during the lowest parts of the solar cycle. (Together with the sporadic-E propagation that 10 meters enjoys during the summer, this band can often be a lot of fun even during the sunspot doldrums. You just have to *be operating* on the band, rather than avoiding it because you know the sunspots are "spotty!")

Now, look at the 20-meter band in Table 6. From New England, twenty is open to somewhere in South America for 24 hours a day, no matter the level of solar activity. Note that Table 6 doesn't predict the level of signals available; it just shows that the band is open with a signal strength greater than 0 on the S meter. Look back at Summary Table 4 for the predicted signal strengths in January at a Very Low level of solar activity. There, you can see that the signal strength from New England into deep South America is always S8 or greater for a big gun station. A lot of the time during the night the band sounds dead, simply because everyone is either asleep or operating on a lower frequency.

For the 40-meter band in Table 6, during the month of January the band is open to Europe for 24 hours a day, whatever the level of solar activity is. Look now at Table 4, and you'll see that the predicted level for Very Low solar activity varies from S4 to S9. Local QRM or QRN would probably disrupt communications on 40 meters in Europe for stateside signals weaker than perhaps S3 or S4. Even though you might well be able to hear Europeans from New England during the day, they probably won't hear you because of local conditions, including local S9+ European stations and atmospheric noise from nearby thunderstorms. New England stations with big antennas can often hear Europeans on 40 meters as early as noontime, but must wait until the late afternoon before the Europeans can hear them above their local noise and QRM.

Let's say that you want to boost your country total on 80 meters by concentrating on stations in the South Pacific. The best months would be from November to February in terms of the number of hours per day when the 80-meter band is open to Oceania. You can see by reading across the line for each month that the level of solar activity is not hugely important on 80 meters to any location. Common experience (backed by the statistical information in Table 6) is that the 80-meter band is open only marginally longer when sunspots are low.

This is true to a greater extent on 40 meters. Thus you may hear the generalization that the low bands tend to be better during periods of low solar activity, while the upper HF bands (above 10 MHz) tend to be better when the sun is more active.

Table 6 can give you a good handle on what months are the most productive for DXing and contesting. It should be no surprise to most veteran operators that the fall and winter months are the best times to work DX.

Table 6

The number of hours per day when a particular band is open to the target geographic areas in Table 4, as related to the level of solar activity (Very Low, Medium and Very High). This table is customized for Boston to the rest of the world. Some paths are open 24 hours a day, plus or minus QRM and local QRN, no matter what the level of solar activity is. See CD-ROM for other transmitting locations.

MA (Boston)
Hours Open to Each Region for Very-Low/Medium/Very-High SSNs

80 Meters:

Month	Europe	Far East	So. Amer.	Africa	So. Asia	Oceania	No. Amer.
Jan	17/17/16	5/ 4/ 3	17/17/16	16/16/15	8/ 7/ 5	11/10/ 9	24/24/24
Feb	17/16/15	3/ 3/ 2	17/16/16	15/15/14	6/ 4/ 4	10/ 9/ 9	24/24/24
Mar	15/15/14	3/ 2/ 1	16/16/15	15/13/13	4/ 4/ 3	9/ 8/ 7	24/24/24
Apr	13/13/12	1/ 0/ 0	16/16/14	13/13/13	3/ 3/ 1	9/ 8/ 7	24/24/24
May	12/11/10	0/ 0/ 0	16/15/14	12/11/10	2/ 1/ 1	7/ 6/ 6	24/24/24
Jun	10/ 9/ 8	0/ 0/ 0	14/14/14	11/10/10	1/ 1/ 0	6/ 5/ 5	24/24/24
Jul	11/11/ 9	0/ 0/ 0	15/14/14	11/11/11	2/ 1/ 1	7/ 6/ 5	24/24/24
Aug	13/11/11	0/ 0/ 0	16/16/14	13/12/11	3/ 2/ 1	7/ 7/ 6	24/24/24
Sep	14/13/11	2/ 1/ 0	17/16/14	13/13/12	4/ 4/ 2	9/ 8/ 8	24/24/24
Oct	15/15/13	3/ 2/ 1	17/17/16	14/14/13	5/ 4/ 4	9/ 9/ 7	24/24/24
Nov	17/17/15	4/ 4/ 2	17/17/16	16/15/14	8/ 7/ 4	11/10/ 9	24/24/24
Dec	19/18/17	7/ 6/ 4	18/18/17	16/16/16	11/ 9/ 7	12/11/11	24/24/24

40 Meters:

Month	Europe	Far East	So. Amer.	Africa	So. Asia	Oceania	No. Amer.
Jan	24/24/24	15/16/15	24/24/21	21/20/19	21/21/19	19/18/15	24/24/24
Feb	24/24/21	13/11/11	24/23/20	20/19/18	19/19/17	16/15/14	24/24/24
Mar	23/22/19	10/ 9/ 7	24/21/18	19/17/17	17/17/13	13/13/13	24/24/24
Apr	21/19/18	8/ 6/ 4	22/20/18	17/16/15	16/11/ 8	13/13/11	24/24/24
May	19/17/17	5/ 4/ 3	22/18/17	17/16/14	9/ 8/ 5	12/11/10	24/24/24
Jun	17/15/13	4/ 2/ 2	22/18/16	16/15/14	7/ 5/ 5	11/10/ 9	24/24/24
Jul	18/16/15	5/ 4/ 2	24/18/17	17/15/14	8/ 7/ 5	12/11/10	24/24/24
Aug	19/17/16	7/ 5/ 4	24/19/18	18/16/15	11/10/ 6	13/12/11	24/24/24
Sep	22/21/17	9/ 8/ 5	23/20/18	18/17/16	14/11/ 7	13/13/12	24/24/24
Oct	24/23/20	12/11/ 8	24/23/19	20/18/17	17/16/14	16/13/13	24/24/24
Nov	24/24/22	14/13/12	24/24/20	21/19/18	21/20/17	17/17/13	24/24/24
Dec	24/24/24	18/19/22	24/24/21	23/21/19	24/23/22	21/19/18	24/24/24

Do-It-Yourself Propagation Prediction

Very reliable methods of determining the MUF for any given radio path have been developed over the last 50 years. As discussed previously, these methods are all based on the smoothed sunspot number (SSN) as the measure of solar activity. It is for this reason that smoothed sunspot numbers hold so much meaning for radio amateurs and others concerned with radio-wave propagation—they are the link to past (and future) propagation conditions.

Early on, the prediction of propagation conditions required tedious work with numerous graphs, along with charts of frequency contours overlaid, or overprinted, on world maps. The basic materials were available from an agency of the US government. Monthly publications provided the frequency-contour data a few months in advance. Only rarely did amateurs try their hand at predicting propagation conditions using these hard-to-use methods.

Today's powerful PCs have given the amateur wonderful tools to make quick-and-easy HF propagation predictions, whether for a contest or a DXpedition. The summary and detailed prediction tables described earlier in this chapter were generated using *CAPMan*, a modernized version of the mainframe *IONCAP* program, on a PC.

While tremendously useful to setting up schedules and for planning strategy for contests, both the Summary and Detailed prediction tables located on the CD-ROM accompanying this book show signal strength. They do not show

20 Meters:

Month	Europe	Far East	So. Amer.	Africa	So. Asia	Oceania	No. Amer.
Jan	13/16/22	15/22/22	24/24/24	20/21/21	18/20/22	18/23/22	24/24/24
Feb	12/18/23	13/21/24	24/24/24	22/22/24	15/21/24	18/23/24	24/24/24
Mar	15/18/24	17/20/24	24/24/24	22/24/24	18/21/24	16/24/24	24/24/24
Apr	15/20/24	19/22/24	24/24/24	21/24/24	19/22/24	18/24/24	24/24/24
May	19/23/24	22/24/24	24/24/24	23/24/24	23/24/24	21/24/24	24/24/24
Jun	22/24/24	24/24/24	24/24/24	24/24/24	24/24/24	24/24/24	24/24/24
Jul	19/24/24	24/24/24	24/24/24	21/24/24	24/24/24	23/24/24	24/24/24
Aug	15/20/24	20/24/24	24/24/24	20/24/24	20/24/24	19/24/24	24/24/24
Sep	16/19/24	17/21/24	24/24/24	21/24/24	18/21/24	17/24/24	24/24/24
Oct	15/21/24	16/20/24	24/24/24	22/24/24	19/22/24	17/24/24	24/24/24
Nov	14/20/23	14/22/24	24/24/24	20/24/24	17/21/24	19/23/24	24/24/24
Dec	11/17/24	13/22/24	24/24/24	17/23/24	12/22/24	16/24/24	24/24/24

15 Meters:

Month	Europe	Far East	So. Amer.	Africa	So. Asia	Oceania	No. Amer.
Jan	4/ 6/ 7	2/ 9/13	12/15/16	9/13/13	3/ 4/ 7	9/12/13	24/15/16
Feb	4/ 7/12	4/10/14	13/18/23	11/13/16	3/ 7/13	8/13/15	22/16/19
Mar	6/ 9/14	2/13/15	14/21/24	13/17/22	5/11/17	10/14/17	15/16/23
Apr	0/10/18	3/13/18	15/23/24	15/18/24	9/15/19	11/15/21	16/16/24
May	1/13/16	6/10/19	17/20/24	14/18/24	13/17/18	10/16/19	20/19/24
Jun	0/ 2/16	0/ 9/15	16/21/24	14/18/24	5/15/18	10/12/20	24/22/22
Jul	0/ 2/16	0/ 5/18	15/19/24	12/18/24	0/12/18	4/12/20	24/22/21
Aug	0/ 2/14	0/ 8/17	14/18/22	13/16/22	0/12/17	6/10/19	22/19/21
Sep	1/10/17	6/13/17	14/16/24	13/17/22	9/14/17	9/14/17	16/16/22
Oct	7/11/17	10/13/17	12/16/22	12/15/22	7/12/17	12/13/15	18/15/22
Nov	5/ 8/14	8/11/14	12/16/22	11/14/17	3/ 7/16	10/13/15	20/16/21
Dec	3/ 6/ 9	2/10/13	12/15/23	8/13/15	2/ 4/12	9/12/14	24/15/18

10 Meters:

Month	Europe	Far East	So. Amer.	Africa	So. Asia	Oceania	No. Amer.
Jan	0/ 1/ 4	0/ 1/ 8	6/11/13	0/ 7/10	0/ 1/ 3	0/ 3/11	23/24/24
Feb	0/ 2/ 7	0/ 2/10	8/12/14	0/ 9/13	0/ 3/ 5	0/ 7/13	24/24/24
Mar	0/ 0/ 8	0/ 1/10	10/14/20	1/11/14	0/ 0/ 8	0/ 7/13	23/24/24
Apr	0/ 0/ 8	0/ 0/ 8	7/14/21	0/12/17	0/ 0/13	0/ 5/11	18/24/24
May	0/ 0/ 0	0/ 0/ 1	7/12/20	1/10/17	0/ 1/12	0/ 2/11	17/20/22
Jun	0/ 0/ 0	0/ 0/ 0	7/11/18	0/ 3/17	0/ 0/ 0	0/ 0/ 2	21/19/23
Jul	0/ 0/ 0	0/ 0/ 0	2/ 9/19	0/ 2/18	0/ 0/ 7	0/ 0/ 6	16/16/24
Aug	0/ 0/ 0	0/ 0/ 0	2/10/17	0/ 1/16	0/ 0/10	0/ 0/ 8	17/17/24
Sep	0/ 0/ 8	0/ 1/10	7/13/18	0/11/16	0/ 0/10	0/ 2/ 9	19/24/24
Oct	0/ 5/ 9	0/ 2/11	10/12/16	7/12/14	0/ 5/ 9	0/ 8/12	24/24/24
Nov	0/ 4/ 8	0/ 3/11	9/12/15	5/10/13	0/ 3/ 6	4/10/12	24/24/24
Dec	0/ 3/ 6	0/ 1/ 8	8/11/13	1/ 8/12	0/ 1/ 4	2/ 7/12	23/23/24

other information that is also in the underlying databases used to generate them. They don't, for example, show the dominant elevation angles and neither do they show reliability statistics. You may want to run propagation-prediction software yourself to get into the really "nitty-gritty" details.

Modern programs are designed for quick-and-easy predictions of propagation parameters. See **Table 7** for a listing of a number of popular programs. The basic input information required is the smoothed sunspot number (SSN) or smoothed solar flux, the date (month and day), and the latitudes and longitudes at the two ends of the radio path. The latitude and longitude, of course, are used to determine the great-circle radio path. Most commercial programs tailored for ham use allow you to specify locations by the call sign. The date is used to determine the latitude of the Sun, and this, with the sunspot number, is used to determine the properties of the ionosphere at critical points on the path.

Of course, just because a computer program predicts that a band will be open on a particular path, it doesn't follow that the Sun and the ionosphere will always cooperate! A sudden solar flare can result in a major geomagnetic storm, taking out HF communication anywhere from hours to days. There is still art, as well as a lot of science, in predicting propagation. In times of quiet geomagnetic activity, however, the prediction programs are good at forecasting band openings and closings.

Obtaining Sunspot Number/Solar Flux Data

After you have chosen and then set up a computer program for evaluation of a particular path, you will still need the sunspot number or solar flux level for the period in ques-

Table 7
Features and Attributes of Propagation Prediction Programs

	ASAPS V. 4	*CAPMan*	*VOACAP Windows*	*ACE-HF*	*W6ELProp V. 2.70*	*WinCAP Wizard 2*	*PropLab Pro*
User Friendliness	Good	Good	Good	Excellent	Good	Good	Poor
Operating System	Windows	DOS	Windows	Windows	Windows	Windows	DOS
Uses k or A index	No	Yes	No	No	Yes	Yes	Yes
User library of QTHs	Yes	Yes	Yes	Yes-RX	Yes	Yes	No
Bearings, distances	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MUF calculation	Yes	Yes	Yes	Yes	Yes	Yes	Yes
LUF calculation	Yes	Yes	Yes	Yes	No	Yes	Yes
Wave angle calculation	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Vary minimum wave angle	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Path regions and hops	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Multipath effects	Yes	Yes	Yes	Yes	No	Yes	Yes
Path probability	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Signal strengths	Yes	Yes	Yes	Yes	Yes	Yes	Yes
S/N ratios	Yes	Yes	Yes	Yes	No	Yes	Yes
Long-path calculation	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Antenna selection	Yes	Yes	Yes	Yes	Indirectly	Isotropic	Yes
Vary antenna height	Yes	Yes	Yes	Yes	Indirectly	No	Yes
Vary ground characteristics	Yes	Yes	Yes	Yes	No	No	No
Vary transmit power	Yes	Yes	Yes	Yes	Indirectly	Yes	Yes
Graphic displays	Yes	Yes	Yes	Yes	Yes	Yes	2D/3D
UT-day graphs	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Area Mapping	No	Yes	Yes	Yes	Yes	No	Yes
Documentation	Yes	Yes	On-line	Yes	Yes	Yes	Yes
Price class	$275+	$89	free†	$99	free§	$29.95+	$150††

Price classes are for late 2003 and subject to change.
†Available on the World Wide Web: **elbert.its.bldrdoc.gov/hf.html**
§Available on the World Wide Web at: **www.qsl.net/w6elprop/**
+ Shipping and handling extra.
††Available on the World Wide Web: **www.spacew.com/www/proplab.html**

tion. A caution must be stated here—for best accuracy and consistency, use the average of solar flux values taken from actual observations, perhaps from WWV/WWVH, over the previous three or four days. Many amateur packet systems archive WWV flux numbers (plus planetary k_p and A_p indices). Solar flux numbers can vary dramatically from day to day, but the Earth's ionosphere is relatively slow to respond to instantaneous changes in solar radiation. This caveat also holds for sunspot numbers derived, using Fig 18, from WWV/WWVH solar flux numbers.

Fig 41 shows a graph produced in the early 1980s of smoothed sunspot numbers for Solar Cycles 17 through 21, with predictions for Cycles 22 through 26. The graph covers a period of 100 years, from 1940 to 2040, and may be used for making long-term or historical calculations. Just remember that the graph shows smoothed numbers. The solar activity at any given time can be significantly lower or significantly higher than the graph indicates. In fact, Cycle 22 peaked at the end of 1989, as predicted, but with a monthly smoothed sunspot level of 158, quite a bit higher than pre-

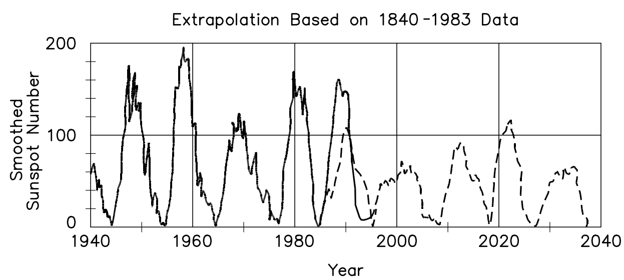

Fig 41—Smoothed sunspot number, with predictions, from 1940 to 2040. This was extrapolated based on data from 1840 to 1983. Cycle 22 actually peaked in Nov 1989, at a monthly smoothed sunspot number of 158. Propagation on the higher frequencies throughout the peak of Cycle 22 was good to excellent, since the monthly smoothed sunspot number stayed at 100 or above from July 1988 through May 1992. (*Courtesy of Naval Ocean Systems Center,* San Diego.*)*

dicted. Cycle 23 peaked in early 2002 at a level of about 115, a considerably higher level than the predicted value.

WWV PROPAGATION DATA

For the most current data on what the Sun is doing, National Institute of Standards and Technology stations WWV and WWVH broadcast information on solar activity at 18 and 45 minutes past each hour, respectively. These propagation bulletins give the solar flux, geomagnetic A-Index, Boulder K-Index, and a brief statement of solar and geomagnetic activity in the past and coming 24-hour periods, in that order. The solar flux and A-Index are changed daily with the 2118 UT bulletin, the rest every three hours—0018, 0318, 0618 UT and so on. On the Web, up-to-date WWV information can be found at: **ftp://ftp.sel.noaa.gov/pub/latest/wwv.txt** or on the NOAA Web page **www.sec.noaa.gov/**.

Some other useful Web sites are: **dx.qsl.net/propagation/**, **www.dxlc.com/solar**, **hfradio.org/propagation.html**. The Solar Terrestrial Dispatch page contains a wealth of propagation-related information: **www.spacew.com/**. You may also access propagation information on your local PacketCluster. Use the command SH/WWV/*n*, where *n* is the number of spots you wish to see (five is the default).

Another excellent method for obtaining an "equivalent sunspot number" (SSN_e) is to go to the Space Weather site of Northwest Research Services: **www.nwra-az.com/spawx/ssne24.html**. NWRA compares real-time ionospheric sounder data around the world with predictions using various levels of SSN looking for the best match. They thus "back into" the actual effective sunspot number. **Fig 42** is a typical NWRA graph, which covers the week ending 6 October 2002. Note the sudden decrease in SSN_e after a geomagnetic storm depressed SSN_e by more than 50%.

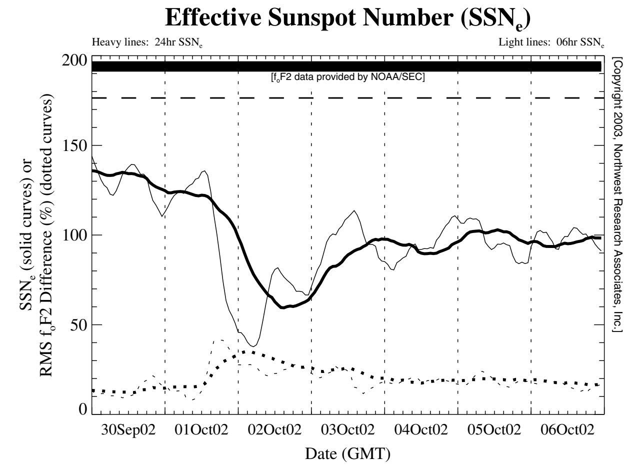

Fig 42—Effective Sunspot Number (SSN_e) produced by NWRA. Note large drop in effective SSN due to a geomagnetic storm commencing Oct 1, 2002. (*Courtesy of Northwest Research Associates.*)

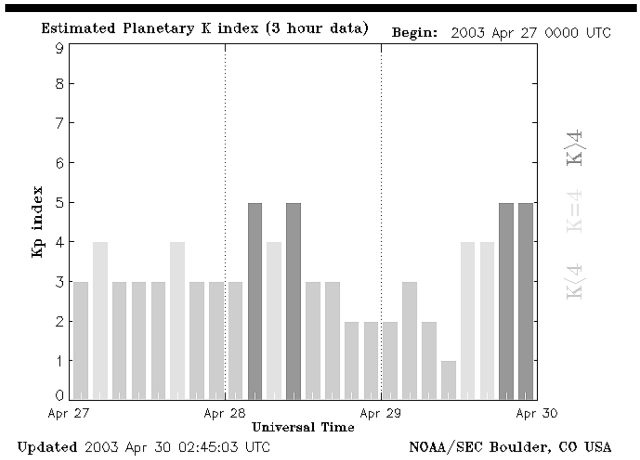

Fig 43—Plot of the estimated planetary k index, K_p, for the last four days. (*Courtesy NOAA/SEC.*)

The A-Index

The WWV/WWVH A-Index is a daily figure for the state of activity of the Earth's magnetic field. It is updated with the 2118/2145 UT bulletin. The A-Index tells you mainly how yesterday was, but it is very revealing when charted regularly, because geomagnetic disturbances nearly always recur at four-week intervals.

The K-Index

The K-Index (new every three hours) reflects Boulder readings of the Earth's geomagnetic field in the hours just preceding the bulletin data changes. It is the nearest thing to current data on radio propagation available. With new data every three hours, K-Index trend is important. Rising is bad news; falling is good, especially related to propagation on paths involving latitudes above 30° north. Because this is a Boulder, Colorado, reading of geomagnetic activity, it may not correlate closely with conditions in other areas.

The K-Index is also a timely clue to aurora possibilities. Values of 4, and rising, warn that conditions associated with auroras and degraded HF propagation are present in the Boulder area at the time of the bulletin's preparation. A NOAA Web site that carries up-to-date planetary K_p data is: **www.sel.noaa.gov/ftpmenu/plots/2003_plots/kp.html**. **Fig 43** is a graph from this Web site for four days starting 27 April 2003 to 30 April 2003. This was a period of significant geomagnetic activity, indicated by K_p indices of 5 and 4.

BIBLIOGRAPHY

Source material and more extended discussion of topics covered in this chapter can be found in the references given below.

E. V. Appleton and W.R. Piggott, "Ionospheric Absorption Measurements during a Sunspot Cycle," *J. Atmos. Terr. Phys.*, Vol 3, p 141, 1954.

D. Bilitiza, *International Reference Ionosphere (IRI 90)*, National Space Science Data Center, Greenbelt, MD, 1990.

D. Bray, "Method of Determining VHF/HF Station Capabilities," *QST*, Nov 1961.

A. Brekke, "Physics of the Upper Polar Atmosphere," (John Wiley and Sons: New York, 1997).

R. R. Brown, "Demography, DXpeditions and Magneto-Ionic Theory," *The DX Magazine*, Vol. X, No. 2, p 44, Mar/Apr 1998.

R. R. Brown, *The Little Pistol's Guide to HF Communication* (Sacramento: WorldRadio Books, 1996).

R. R. Brown, "Signal Ducting on the 160 Meter Band," *Communications Quarterly*, p 65, Spring 1998.

R. R. Brown, "Unusual Low-Frequency Signal Propagation at Sunrise," *Communications Quarterly*, p 67, Fall 1998.

R. R. Brown,, "Atmospheric Ozone, a Meteorological Factor in Low-Frequency and 160 Meter Propagation," *Communications Quarterly*, Spring 1999.

K. Davies, *Ionospheric Radio* (London: Peter Peregrinus Ltd, 1990). Excellent technical reference.

R. Garcia, S. Solomon, S. Avery, G. C. Reid, "Transport of Nitric Oxide and the D-Region Winter Anomaly," *J. Geophys. Res.*, Vol 92, p 977, 1987.

J. Hall, "Propagation Predictions and Personal Computers," Technical Correspondence, *QST*, Dec 1990, pp 58-59 (description of *IONCAP* as used for ARRL. publications).

E . Harper, *Rhombic Antenna Design* (New York: D. Van Nostrand Co, Inc, 1941).

H. Hertz, *Electric Waves*, translated by D. E. Jones (London: MacMillan, 1893).

R. D. Hunsucker, *Radio Techniques for Probing the Terrestrial Ionosphere* (New York: Springer-Verlag).

R. D. Hunsucker, J. K. Hargreaves, *The High Latitude Ionosphere and Its Effects on Radio Propagation* (Cambridge: Cambridge University Press, 2003).

W. D. Johnston, Computer-calculated and computer-drawn great-circle maps are offered. An 11 × 14-inch map is custom made for your location. Write to K5ZI, PO Box 640, Organ, NM 88052, tele 505-382-7804.

T.L. Killeen, R.M. Johnsson, "Upper Atmospheric Waves, Turbulence, and Winds: Importance for Mesospheric and Thermospheric Studies," **http://earth.agu.org/revgeophys/killee00/killee00.html**.

J. L. Lynch, "The Maunder Minimum," *QST*, Jul 1976, pp 24-26.

J. C. Maxwell, *A Treatise on Electricity and Magnetism*, Vols I and II (Oxford: Oxford University Press, 1873).

M. W. Maxwell, *Reflections—Transmission Lines and Antennas* (Newington, CT: ARRL, 1990) [out of print].

M. W. Maxwell, *Reflections II—Transmission Lines and Antennas* (Sacramento, CA: 2001).

L. F. McNamara, *The Ionosphere: Communications, Surveillance, and Direction Finding* (Malabar, FL: Krieger Publishing Company, 1991). Another excellent technical reference on propagation.

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

A. K. Paul, "Medium Scale Structure of the F Region," *Radio Science*, Volume 24, No. 3, p. 301, 1989.

W. R. Piggott, K. Rawer, "URSI Handbook of Ionogram Interpretation and Reduction," Report UAG-50. World Data Center A for Solar-Terrestrial Physics, Boulder, CO, 1975.

E. Pocock, "Sporadic-E Propagation at VHF: A Review of Progress and Prospects," *QST*, Apr 1988, pp 33-39.

E. Pocock, "Auroral-E Propagation at 144 MHz," *QST*, Dec 1989, pp 28-32.

E. Pocock, "Propagation Forecasting During Solar Cycle 22," *QST*, Jun 1989, pp 18-20.

G. C. Reid, "Ion Chemistry of the D-region," *Advances in Atomic and Molecular Physics*, Vol 12, Academic Press, 1976.

R. B. Rose, "MINIMUF: A Simplified MUF-Prediction Program for Microcomputers," *QST*, Dec 1982, pp 36-38

M. L. Salby, "Fundamentals of Atmospheric Physics," (Academic Press: Boulder, CO, 1996).

S. C. Shallon, W6EL: *MINIPROP PLUS*, a commercially prepared program written for Amateur Radio users; 11058 Queensland St, Los Angeles, CA 90034-3029.

R. D. Straw, *All the Right Angles* (New Bedford, PA: LTA, 1993). Out of print.

R. D. Straw, "*ASAPS* and *CAPMAN*: HF Propagation-Prediction Software for the IBM PC," *QST*, Dec 1994, pp 79-81.

R. D. Straw, "Heavy-Duty HF Propagation-Prediction/Analysis Software," Part 1: *QST*, Sep 1996, pp 28-32; Part 2: *QST*, Oct 1996, pp 28-30.