Kristin Alexander

From: John McGovern [John.McGovern@Sun.COM]
Sent: Friday, February 11, 2005 4:11 PM
To: Planning Department
Cc: Board of Selectmen
Subject: Copy of proposed By Law changes related to amateur radio

antplnr.pdf (366 KB)

I understand there may be discussion of changes to the town by-laws under consideration that may affect amateur radio facilities in Acton.

I'd like a copy of the latest proposals sent to me by return email, or US postal mail :

John McGovern, (FCC Callsign W1JMC)
6 Winter Street,
Acton, MA 01720

In advance of your next meeting and response, I offer this attachment for Community Officials on antenna heights and radio communications effectiveness.

As you are aware from the FCC Memorandum and Order PRB-1 (9/16/85) "there is also a strong federal interest in promoting amateur communications." This attached document will help the planning board better understand the engineering basis for amateur radio antenna heights in Acton so that if any bylaw changes are proposed they are not ignorant, (nor arbitrary) of the radio communications effectiveness involved with antenna selection.

In this technical area of considerable federal interest the board is obligated to undertake such understanding and analysis, before substantive by-law changes can be proposed to Meeting authoritatively.

Regards

--

John McGovern, Corp. Customs Compliance Manager
Sun Microsystems, Inc., 3 Network Drive,
Burlington, MA 01804
ph. (978) 429-4035; fx. (978) 429-4035

~~~~~~
NOTICE: This email message is for the sole use of the intended recipient(s) and may contain confidential and privileged information. Any unauthorized review, use, disclosure or distribution is prohibited. If you are not the intended recipient, please contact the sender by reply email and destroy all copies of the original message.
~~~~~~

Antenna Height and Communications Effectiveness

Second Edition

A Guide for City Planners and Amateur Radio Operators

By R. Dean Straw, N6BV, and Gerald L. Hall, K1TD
Senior Assistant Technical Editor and Retired Associate Technical Editor

Copyright ©1999
The American Radio Relay League, Inc.
225 Main Street
Newington, CT 06111

Executive Summary

Amateur radio operators, or "hams" as they are called, communicate with stations located all over the world. Some contacts may be local in nature, while others may be literally halfway around the world. Hams use a variety of internationally allocated frequencies to accomplish their communications.

Except for local contacts, which are primarily made on Very High and Ultra High Frequencies (VHF and UHF), communicating between any two points on the earth rely primarily on high-frequency (HF) signals propagating through the ionosphere. The earth's ionosphere acts much like a mirror at heights of about 150 miles. The vertical angle of radiation of a signal launched from an antenna is one of the key factors determining effective communication distances. The ability to communicate over long distances generally requires a low radiation angle, meaning that an antenna must be placed high above the ground in terms of the wavelength of the radio wave being transmitted.

A beam type of antenna at a height of 70 feet or more will provide greatly superior performance over the same antenna at 35 feet, all other factors being equal. A height of 120 feet or even higher will provide even more advantages for long-distance communications. To a distant receiving station, a transmitting antenna at 120 feet will provide the effect of approximately 8 to 10 times more transmitting power than the same antenna at 35 feet. Depending on the level of noise and interference, this performance disparity is often enough to mean the difference between making distant radio contact with fairly reliable signals, and being unable to make distant contact at all.

Radio Amateurs have a well-deserved reputation for providing vital communications in emergency situations, such as in the aftermath of a severe icestorm, a hurricane or an earthquake. Short-range communications at VHF or UHF frequencies also require sufficient antenna heights above the local terrain to ensure that the antenna has a clear horizon.

In terms of safety and aesthetic considerations, it might seem intuitively reasonable for a planning board to want to restrict antenna installations to low heights. However, such height restrictions often prove very counterproductive and frustrating to all parties involved. If an amateur is restricted to low antenna heights, say 35 feet, he will suffer from poor transmission of his own signals as well as poor reception of distant signals. In an attempt to compensate on the transmitting side (he can't do anything about the poor reception problem), he might boost his transmitted power, say from 150 watts to 1,500 watts, the maximum legal limit. This ten-fold increase in power will very significantly increase the *potential* for interference to telephones, televisions, VCRs and audio equipment in his neighborhood.

Instead, if the antenna can be moved farther away from neighboring electronic devices—putting it higher, in other words—this will greatly reduce the likelihood of interference, which decreases at the inverse square of the distance. For example, doubling the distance reduces the potential for interference by 75%. As a further benefit, a large antenna doesn't look anywhere near as large at 120 feet as it does close-up at 35 feet.

As a not-so-inconsequential side benefit, moving an antenna higher will also greatly reduce the potential of exposure to electromagnetic fields for neighboring human and animals. Interference and RF exposure standards have been thoroughly covered in recently enacted Federal Regulations.

Antenna Height and Communications Effectiveness

By R. Dean Straw, N6BV, and Gerald L. Hall, K1TD
Senior Assistant Technical Editor and Retired Associate Technical Editor

The purpose of this paper is to provide general information about communications effectiveness as related to the physical height of antennas. The intended audience is amateur radio operators and the city and town Planning Boards before which a radio amateur must sometimes appear to obtain building permits for radio towers and antennas.

The performance of horizontally polarized antennas at heights of 35, 70 and 120 feet is examined in detail. Vertically polarized arrays are not considered here because at short-wave frequencies, over average terrain and at low radiation angles, they are usually less effective than horizontal antennas.

Ionospheric Propagation

Frequencies between 3 and 30 megahertz (abbreviated MHz) are often called the "short-wave" bands. In engineering terms this range of frequencies is defined as the *high-frequency* or *HF* portion of the radio spectrum. HF radio communications between two points that are separated by more than about 15 to 25 miles depend almost solely on propagation of radio signals through the *ionosphere*. The ionosphere is a region of the Earth's upper atmosphere that is ionized primarily by ultraviolet rays from the Sun.

The Earth's ionosphere has the property that it will refract or bend radio waves passing through it. The ionosphere is not a single "blanket" of ionization. Instead, for a number of complex reasons, a few discrete layers are formed at different heights above the earth. From the standpoint of radio propagation, each ionized layer has distinctive characteristics, related primarily to different amounts of ionization in the various layers. The ionized layer that is most useful for HF radio communication is called the *F layer*.

The F layer exists at heights varying from approximately 130 to 260 miles above the earth's surface. Both the layer height and the amount of ionization depend on the latitude from the equator, the time of day, the season of the year, and on the level of sunspot activity. Sunspot activity varies generally in cycles that are approximately 11 years in duration, although short-term bursts of activity may create changes in propagation conditions that last anywhere from a few minutes to several days. The ionosphere is not homogeneous, and is undergoing continual change. In fact, the exact state of the ionosphere at any one time is so variable that is best described in statistical terms.

The F layer disappears at night in periods of low and medium solar activity, as the ultraviolet energy required to sustain ionization is no longer received from the Sun. The amount that a passing radio wave will bend in an ionospheric layer is directly related to the intensity of ionization in that layer, and to the frequency of the radio wave.

A triangle may be used to portray the cross-sectional path of ionospheric radio-wave travel, as shown in **Fig 1**, a highly simplified picture of what happens in propagation of radio waves. The base of the triangle is the surface of the Earth between two distant points, and the apex of the triangle is the point representing refraction in the ionosphere. If all the necessary conditions are

met, the radio wave will travel from the first point on the Earth's surface to the ionosphere, where it will be bent (*refracted*) sufficiently to travel to the second point on the earth, many hundreds of miles away.

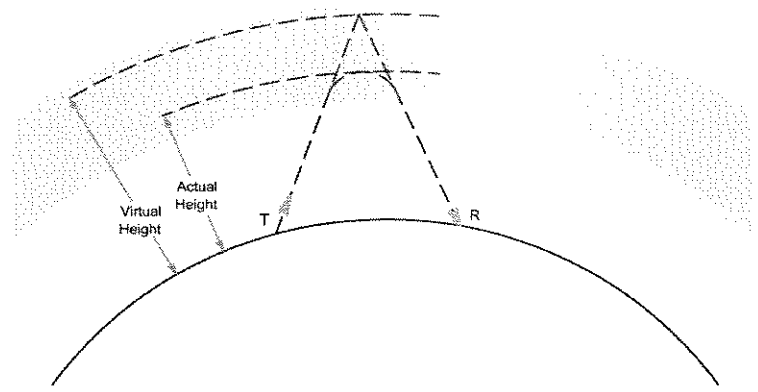

Fig 1—A simplified cross-sectional representation of ionospheric propagation. The simple triangle goes from the Transmitter T up to the virtual height and then back down to the Receiver R. Typically the F layer exists at a height of 150 miles above the Earth at mid-latitudes. The distance between T and R may range from a few miles to 2500 miles under normal propagation conditions.

Of course the Earth's surface is not a flat plane, but instead is curved. High-frequency radio waves behave in essentially the same manner as light waves—they tend to travel in straight lines, but with a slight amount of downward bending caused by refraction in the air. For this reason it is not possible to communicate by a direct path over distances greater than about 15 to 25 miles in this frequency range, slightly farther than the optical horizon. The curvature of the earth causes the surface to "fall away" from the path of the radio wave with greater distances. Therefore, it is the ionosphere that permits HF radio communications to be made between points separated by hundreds or even thousands of miles. The range of frequencies from 3 to 30 MHz is unique in this respect, as ionospheric propagation is not consistently supported for any frequencies outside this range.

One of the necessary conditions for ionospheric communications is that the radio wave must encounter the ionosphere at the correct angle. This is illustrated in **Fig 2**, another very simplified drawing of the geometry involved. Radio waves leaving the earth at high elevation angles above the horizon may receive only very slight bending due to refraction, and are then lost to outer space. For the same fixed frequency of operation, as the elevation angle is lowered toward the horizon, a point is reached where the bending of the wave is sufficient to return the wave to the Earth. At successively lower angles, the wave returns to the Earth at increasing distances.

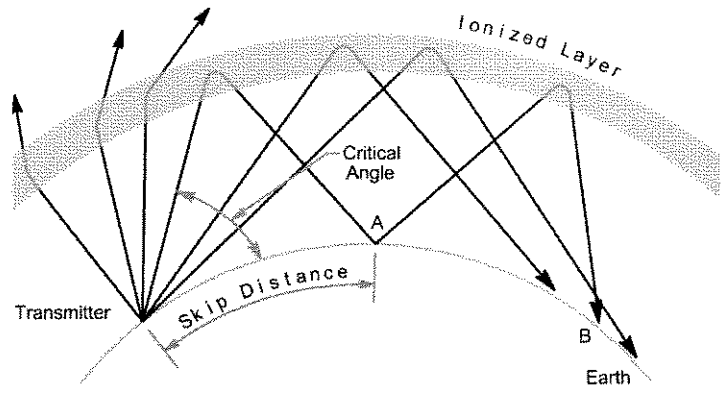

Fig 2—Behavior of radio waves encountering the ionosphere. Rays entering the ionized region at angles above the critical angle are not bent enough to return to Earth and are lost to space. Waves entering at angles below the critical angle reach the Earth at increasingly greater distances as the angle approaches the horizontal. The maximum distance that may normally be covered in a single hop is 2500 miles. Greater distances may be covered with multiple hops.

If the radio wave leaves the earth at an *elevation angle* of zero degrees, just toward the horizon (or just tangent to the earth's surface), the maximum distance that may be reached under usual ionospheric conditions is approximately 2,500 miles (4,000 kilometers). However, the Earth itself also acts as a reflector of radio waves coming down from the ionosphere. Quite often a radio signal will be reflected from the reception point on the Earth back into the ionosphere again, reaching the Earth a second time at a still more distant point.

As in the case of light waves, the angle of reflection is the same as the angle of incidence, so a wave striking the surface of the Earth at an angle of, say, 15° is reflected upward from the surface at the same angle. Thus, the distance to the second point of reception will be approximately twice the distance of the first. This effect is also illustrated in Fig 2, where the signal travels from the transmitter at the left of the drawing via the ionosphere to Point A, in the center of the drawing. From Point A the signal travels via the ionosphere again to Point B, at the right. A signal traveling from the Earth through the ionosphere and back to the Earth is called a *hop*. Under some conditions it is possible for as many as four or five signal hops to occur over a radio path, but no more than two or three hops is the norm. In this way, HF communications can be conducted over thousands of miles.

With regard to signal hopping, two important points should be recognized. First, a significant loss of signal occurs with each hop. Lower layers of the ionosphere absorb energy from the signals as they pass through, and the ionosphere tends to scatter the radio energy in various directions, rather than confining it to a tight bundle. The earth also scatters the energy at a reflection point. Thus, only a small fraction of the transmitted energy actually reaches a distant receiving point.

Again refer to Fig 2. Two radio paths are shown from the transmitter to Point B, a one-hop path and a two-hop path. Measurements indicate that although there can be great variation in the ratio of the two signal strengths in a situation such as this, the signal power received at Point B will generally be from five to ten times greater for the one-hop wave than for the two-hop wave. (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.) Signal levels are generally compared in decibels, abbreviated dB. The decibel is a logarithmic unit. Three decibels difference in signal strengths is equivalent to a power ratio of 2:1; a difference of 10 dB equates to a power ratio of 10:1. Thus the signal loss for an additional hop is about 7 to 10 dB.

The additional loss per hop becomes significant at greater distances. For a simplified example, a distance of 4,000 miles can be covered in two hops of 2,000 miles each or in four hops of 1,000 miles each. For illustration, assume the loss for additional hops is 10 dB, or a 1/10 power ratio. Under such conditions, the four-hop signal will be received with only 1/100 the power or 20 dB below that received in two hops. The reason for this is that only 1/10 of the two-hop signal is received for the first additional (3rd) hop, and only 1/10 of that 1/10 for the second additional (4th) hop. It is for this reason that no more than four or five propagation hops are useful; the received signal eventually becomes too weak to be heard.

The second important point to be recognized in multihop propagation is that the geometry of the first hop establishes the geometry for all succeeding hops. And it is the elevation angle at the transmitter that sets up the geometry for the first hop.

It should be obvious from the preceding discussion that one needs a detailed knowledge of the range of elevation angles for effective communication in order to do a scientific evaluation of a possible communications circuit. The range of angles should be statistically valid over the full 11-year solar sunspot cycle, since the behavior of the Sun determines the changes in the nature of the Earth's ionosphere. ARRL did a very detailed computer study in the early 1990s to determine the angles needed for propagation throughout the world. The results of this study will be examined later, after we introduce the relationship between antenna height and the elevation pattern for an antenna.

Horizontal Antennas Over Flat Ground

A simple antenna that is commonly used for HF communications is the horizontal half-wave *dipole*. The dipole is a straight length of wire (or tubing) into which radio-frequency energy is fed at the center. Because of its simplicity, the dipole may be easily subjected to theoretical performance analyses. Further, the results of proper analyses are well borne out in practice. For these reasons, the half-wave dipole is a convenient performance standard against which other antenna systems can be compared.

Because the earth acts as a reflector for HF radio waves, the directive properties of any antenna are modified considerably by the ground underneath it. If a dipole antenna is placed horizontally above the ground, most of the energy radiated downward from the dipole is

reflected upward. The reflected waves combine with the direct waves (those radiated at angles above the horizontal) in various ways, depending on the height of the antenna, the frequency, and the electrical characteristics of the ground under and around the antenna.

At some vertical angles above the horizon, the direct and reflected waves may be exactly in phase—that is, the maximum signal or field strengths of both waves are reached at the same instant at some distant point. In this case the resultant field strength is equal to the sum of the two components. At other vertical angles the two waves may be completely out of phase at some distant point—that is, the fields are maximum at the same instant but the phase directions are opposite. The resultant field strength in this case is the difference between the two. At still other angles the resultant field will have intermediate values. Thus, the effect of the ground is to increase the intensity of radiation at some vertical angles and to decrease it at others. The elevation angles at which the maxima and minima occur depend primarily on the antenna height above ground. (The electrical characteristics of the ground have some slight effect too.)

For simplicity here, we consider the ground to be a perfectly conducting, perfectly flat reflector, so that straightforward trigonometric calculations can be made to determine the relative amount of radiation intensity at any vertical angle for any dipole height. Graphs from such calculations are often plotted on rectangular axes to show best resolution over particularly useful ranges of elevation angles, although they are also shown on polar plots so that both the front and back of the response can be examined easily. **Fig 3** shows an overlay of the polar elevation-pattern responses of two dipoles at different heights over perfectly conducting flat ground. The lower dipole is located a half wavelength above ground, while the higher dipole is located one wavelength above ground. The pattern of the lower antenna peaks at an elevation angle of about 30°, while the higher antenna has two main lobes, one peaking at 15° and the other at about 50° elevation angle.

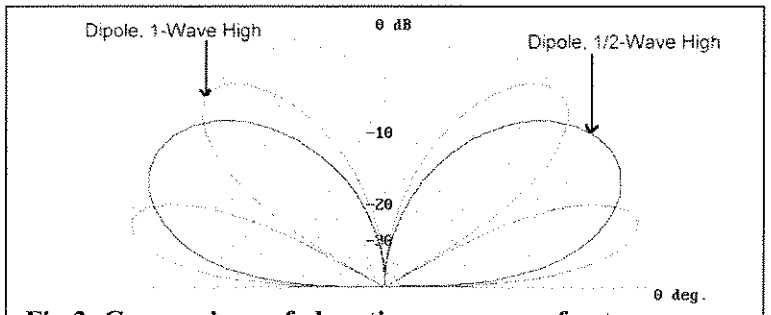

Fig 3–Comparison of elevation responses for two dipoles: one ½-wavelength high, and the other 1-wavelength high.

In the plots shown in Fig 3, the elevation angle above the horizon is represented in the same fashion that angles are measured on a protractor. The concentric circles are calibrated to represent ratios of field strengths, referenced to the strength represented by the outer circle. The circles are calibrated in decibels. Diminishing strengths are plotted toward the center.

You may have noted that antenna heights are often discussed in terms of *wavelengths*. The reason for this is that the length of a radio wave is inversely proportional to its frequency. Therefore a fixed physical height will represent different electrical heights at different radio frequencies. For example, a height of 70 feet represents one wavelength at a frequency of 14 MHz. But the same 70-foot height represents a half wavelength for a frequency of 7 MHz and only a quarter wavelength at 3.5 MHz. On the other hand, 70 feet is 2 wavelengths high at 28 MHz.

The lobes and nulls of the patterns shown in Fig 3 illustrate what was described earlier, that the effect of the ground beneath an antenna is to increase the intensity of radiation at some vertical elevation angles and to decrease it at others. At a height of a half wavelength, the radiated energy is strongest at a rather high elevation angle of 30°. This would represent the situation for a 14-MHz dipole 35 feet off the ground.

As the horizontal antenna is raised to greater heights, additional lobes are formed, and the lower ones move closer to the horizon. The maximum amplitude of each of the lobes is roughly equal. As may be seen in Fig 3, for an antenna height of one wavelength, the energy in the lowest lobe is strongest at 15°. This would represent the situation for a 14-MHz dipole 70 feet high.

The elevation angle of the lowest lobe for a horizontal antenna above perfectly conducting ground may be determined mathematically:

$$\theta = \sin^{-1}\left(\frac{0.25}{h}\right)$$

Where

θ = the wave or elevation angle
h = the antenna height above ground in wavelengths

In short, the higher the horizontal antenna, the lower is the lowest lobe of the pattern. As a very general rule of thumb, the higher an HF antenna can be placed above ground, the farther it will provide effective communications because of the resulting lower radiation angle. This is true for any horizontal antenna over real as well as theoretically perfect ground.

You should note that the *nulls* in the elevation pattern can play an important role in communications—or lack of communication. If a signal arrives at an angle where the antenna system exhibits a deep null, communication effectiveness will be greatly reduced. It is thus quite possible that an antenna can be *too high* for good communications efficiency on a particular frequency. Although this rarely arises as a significant problem on the amateur bands below 14 MHz, we'll discuss the subject of optimal height in more detail later.

Actual earth does not reflect all the radio-frequency energy striking it; some absorption takes place. Over real earth, therefore, the patterns will be slightly different than those shown in Fig 3, however the differences between theoretical and perfect earth ground are not significant for the range of elevation angles necessary for good HF communication. Modern computer programs can do accurate evaluations, taking all the significant ground-related factors into account.

Beam Antennas

For point-to-point communications, it is beneficial to concentrate the radiated energy into a beam that can be aimed toward a distant point. An analogy can be made by comparing the light

from a bare electric bulb to that from an automobile headlight, which incorporates a built-in focusing lens. For illuminating a distant point, the headlight is far more effective.

Antennas designed to concentrate the radiated energy into a beam are called, naturally enough, *beam antennas*. For a fixed amount of transmitter power fed to the transmitting antenna, beam antennas provide increased signal strength at a distant receiver. In radio communications, the use of a beam antenna is also beneficial during reception, because the antenna pattern for transmission is the same for reception. A beam antenna helps to reject signals from unwanted directions, and in effect boosts the strength of signals received from the desired direction.

The increase in signal or field strength a beam antenna offers is frequently referenced to a dipole antenna in free space (or to another theoretical antenna in free space called an *isotropic antenna*) by a term called *gain*. Gain is commonly expressed in decibels. The isotropic antenna is defined as being one that radiates equally well in all directions, much like the way a bare lightbulb radiates essentially equally in all directions.

One particularly well known type of beam antenna is called a *Yagi*, named after one of its Japanese inventors. Different varieties of Yagi antennas exist, each having somewhat different characteristics. Many television antennas are forms of multi-element Yagi beam antennas. In the next section of this paper, we will refer to a four-element Yagi, with a gain of 8.5 dBi in free space, exclusive of any influence due to ground.

This antenna has 8.5 dB more gain than an isotropic antenna in free space and it achieves that gain by squeezing the pattern in certain desired directions. Think of a normally round balloon and imagine squeezing that balloon to elongate it in one direction. The increased length in one direction comes at the expense of length in other directions. This is analogous to how an antenna achieves more signal strength in one direction, at the expense of signal strength in other directions.

The elevation pattern for a Yagi over flat ground will vary with the electrical height over ground in exactly the same manner as for a simpler dipole antenna. The Yagi is one of the most common antennas employed by radio amateurs, second in popularity only to the dipole.

Putting the Pieces Together

In **Fig 4**, the elevation angles necessary for communication from a particular transmitting site, in Boston, Massachusetts, to the continent of Europe using the 14-MHz amateur band are shown in the form of a bargraph. For each elevation angle from 1° to 30°, Fig 4 shows the percentage of time when the 14-MHz band is open at each elevation angle. For example, 5° is the elevation angle that occurs just over 12% of the time when the band is available for communication, while 11° occurs about 10% of the time when the band is open. The useful range of elevation angles that must accommodated by an amateur station wishing to talk to Europe from Boston is from 1° to 28°.

In addition to the bar-graph elevation-angle statistics shown in Fig 4, the elevation pattern responses for three Yagi antennas, located at three different heights above flat ground, are overlaid on the same graph. You can easily see that the 120-foot antenna is the best antenna to cover the most likely angles for this particular frequency, although it suffers at the higher elevation angles on this particular propagation path, beyond about 12°. If, however, you can accept somewhat lower gain at the lowest angles, the 70-foot antenna would arguably be the best overall choice to cover all the elevation angles.

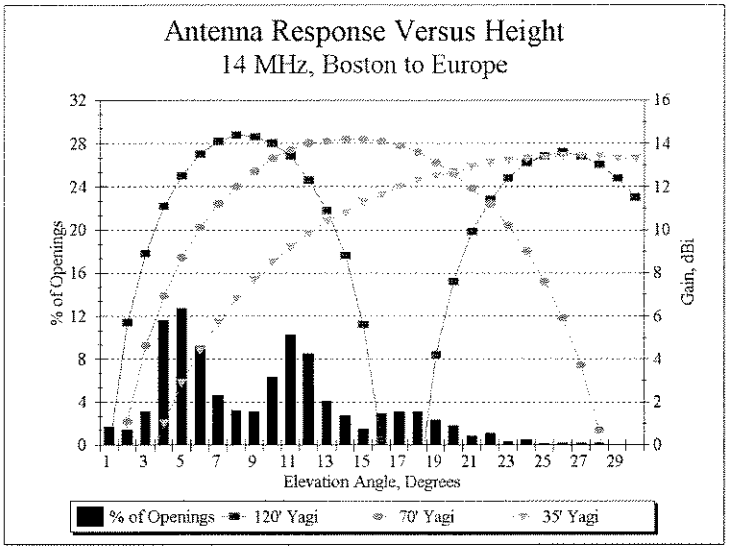

Fig 4—Elevation response patterns of three Yagis at 120, 70 and 35 feet, at 14 MHz over flat ground. The patterns are overlaid with the statistical elevation-angles for the path from Boston to continental Europe over the entire 11-year solar sunspot cycle. Clearly, the 120-foot antenna is the best choice to cover the low angles needed, but it suffers some at higher angles.

Other graphs are needed to show other target receiving areas around the world. For comparison, **Fig 5** is also for the 14-MHz band, but this time from Boston to Sydney, Australia. The peak angle for this very long path is about 2°, occurring 19% of the time when the band is actually open for communication. Here, even the 120-foot high antenna is not ideal. Nonetheless, at a moderate 5° elevation angle, the 120-foot antenna is still 10 dB better than the one at 35 feet.

Fig 4 and Fig 5 have portrayed the situation for the 14-MHz amateur band, the most popular and heavily utilized HF band used by radio amateurs. During medium to high levels of solar sunspot activity, the 21 and 28-MHz amateur bands are open during the daytime for long-distance communication. **Fig 6** illustrates the 28-MHz elevation-angle statistics, compared to the elevation patterns for the same three antenna heights shown in Fig 5. Clearly, the elevation response for the 120-foot antenna has a severe (and undesirable) null at 8°. The 120-foot antenna is almost 3.4 wavelengths high on 28 MHz (whereas it is 1.7 wavelengths high on 14 MHz.) For many launch angles, the 120-foot high Yagi on 28 MHz would simply be too high.

The radio amateur who must operate on a variety of frequencies might require two or more towers at different heights to maintain essential elevation coverage on all the authorized bands. Antennas can sometimes be mounted at different heights on a single supporting tower, although it is more difficult to rotate antennas that are "vertically stacked" around the tower to point in all the needed directions. Further, closely spaced antennas tuned to different frequencies usually interact electrically with each other, often causing severe performance degradation.

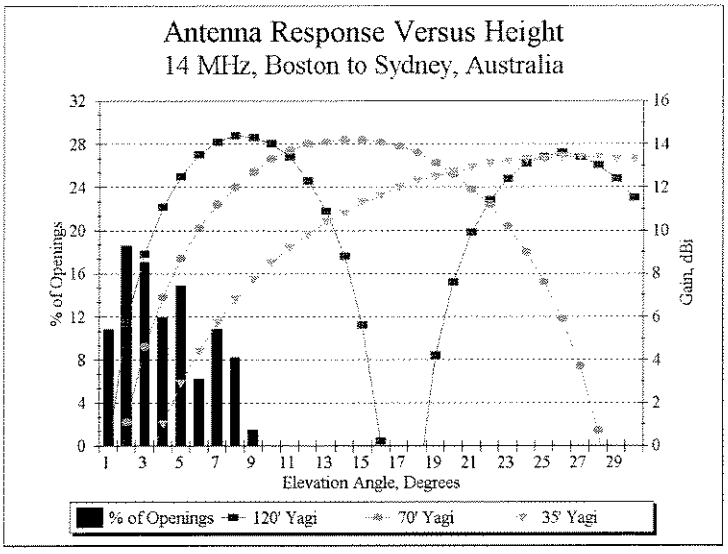

Fig 5—Elevation responses for same antennas as Fig 4, but for a longer-range path from Boston to Sydney, Australia. Note that the prevailing elevation angles are very low.

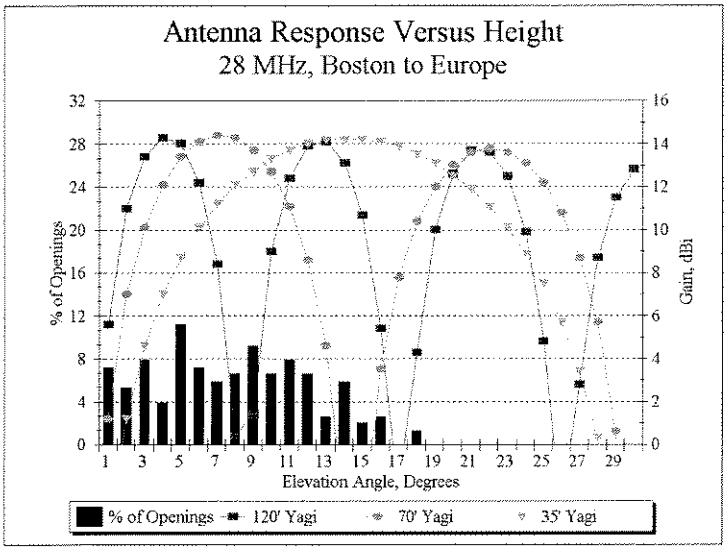

Fig 6—Elevation angles compared to antenna responses for 28-MHz path from Boston to Europe. The 70-foot antenna is probably the best overall choice on this path.

During periods of low to moderate sunspot activity (about 50% of the 11-year solar cycle), the 14-MHz band closes down for propagation in the early evening. A radio amateur wishing to continue communication must shift to a lower frequency band. The next most highly used band below the 14-MHz band is the 7-MHz amateur band. **Fig 7** portrays a 7-MHz case for another transmitting site, this time from San Francisco, California, to the European continent. Now, the range of necessary elevation angles is from about 1° to 16°, with a peak statistical likelihood of about 16% occurring at an elevation of 3°. At this low elevation angle, a 7-MHz antenna must be *very* high in the air to be effective. Even the 120-foot antenna is hardly optimal for the peak angle of 3°. The 200-foot antenna shown would be far better than a 120-foot antenna. Further, the 35-foot high antenna is *greatly* inferior to the other antennas on this path and would provide far less capabilities, on both receiving and transmitting.

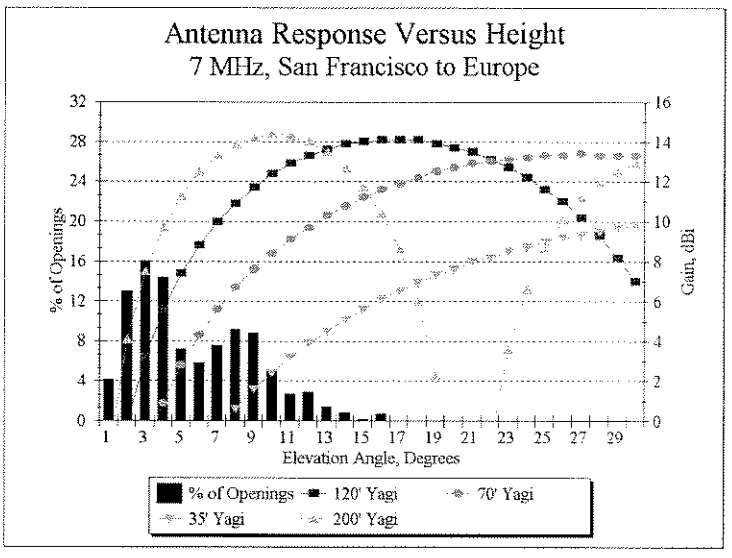

Fig 7—Comparison of antenna responses for another propagation path: from San Francisco to Europe on 7 MHz. Here, even a 120-foot high antenna is hardly optimal for the very low elevation angles required on this very long path. In fact, the 200-foot high antenna is far better suited for this path.

What If the Ground Isn't Flat?

In the preceding discussion, antenna radiation patterns were computed for antennas located over *flat ground.* Things get much more complicated when the exact local terrain surrounding a tower and antenna are taken into account. In the last few years, sophisticated ray-tracing computer models have become available that can calculate the effect that local terrain has on the elevation patterns for real-world HF installations—and *each* real-world situation is indeed different.

For simplicity, first consider an antenna on the top of a hill with a constant slope downward. The general effect is to lower the effective elevation angle by an amount equal to the downslope of the hill. For example, if the downslope is –3° for a long distance away from the tower and the flat-ground peak elevation angle is 10° (due to the height of the antenna), then the net result will be 10° – 3° = 7° peak angle. However, if the local terrain is rough, with many bumps and valleys in the desired direction, the response can be modified considerably. **Fig 8** shows the fairly complicated terrain profile for Jan Carman, K5MA, in the direction of Japan. Jan is located on one of the tallest hills in West Falmouth, Massachusetts. Within 500 feet of his tower is a small hill with a water tower on the top, and then the ground quickly falls away, so that at a distance of about 3000 feet from the tower base, the elevation has fallen to sea level, at 0 feet.

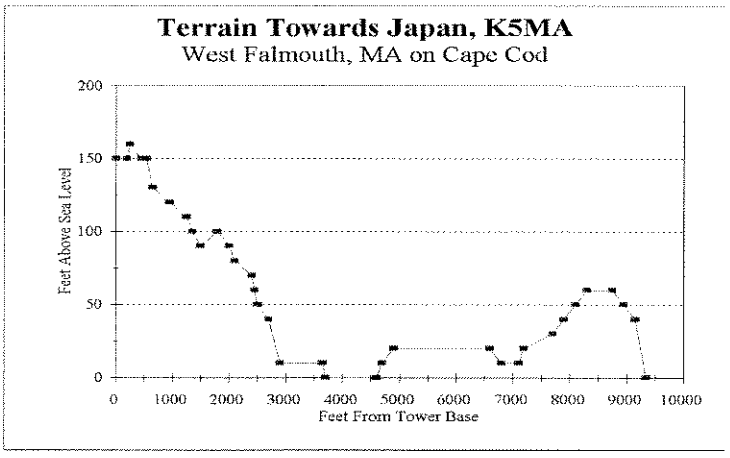

Fig 8—Terrain profile from location of K5MA, Jan Carman, in West Falmouth, MA, towards Japan. This is a moderately complicated real-world terrain on one of the highest hills on Cape Cod.

The computed responses toward Japan from this location, using a 120- and a 70-foot high Yagi, are shown in **Fig 9**, overlaid for comparison with the response for a 120-foot Yagi over flat ground. Over this particular terrain, the elevation pattern for the 70-foot antenna is actually better than that of the 120-foot antenna for angles below about 3°, but not for medium angles! The responses for each height oscillate around the pattern for flat ground — all due to the complex reflections and diffractions occurring off the terrain.

At an elevation angle of 5°, the situation reverses itself and the gain is now higher for the 120-foot-high antenna than for the 70-foot antenna. A pair of antennas on one tower would be required to cover all the angles properly. To avoid any electrical interactions between similar antennas on one tower, two towers would be much better. Compared to the flat-ground situation, the responses of real-world antenna can be very complicated due to the interactions with the local terrain.

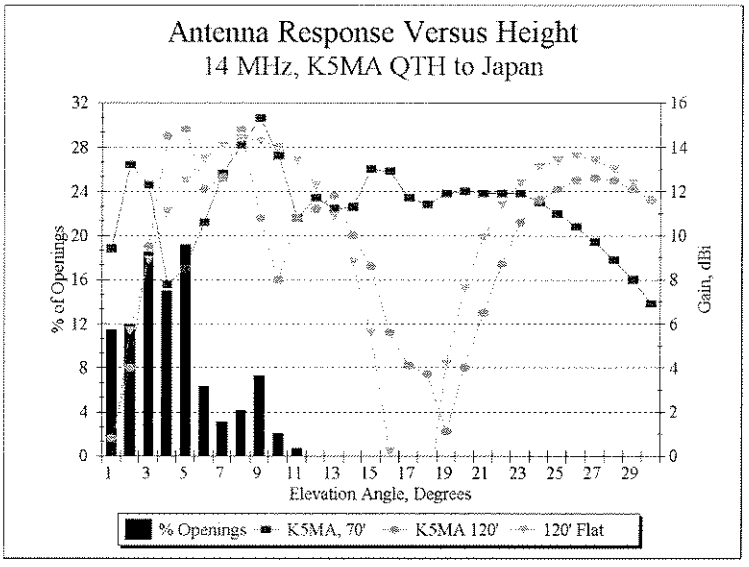

Fig 9—Computed elevation responses of 120- and 70-foot high Yagis, at the K5MA location on Cape Cod, in the direction of Japan and over flat ground, for comparison. The elevation response of the real-world antenna has been significantly modified by the local terrain.

Fig 10 shows the situation for the same Cape Cod location, but now for 7 MHz. Again, it is clear that the 120-foot high Yagi is superior by at least 3 dB (equivalent to twice the power) to the 70-foot high antenna at the statistical elevation angle of 6°. However, the response of the real-world 120-foot high antenna is still up some 2 dB from the response for an identical antenna over flat ground at this angle. On this frequency, the local terrain has helped boost the gain at the medium angles more than a similar antenna 120 feet over flat ground. The gain is even greater at lower angles, say at 1° elevation, where most signals take off, statistically speaking. Putting the antenna up higher, say 150 feet, will help the situation at this location, as would adding an additional Yagi at the 70-foot level and feeding both antennas in phase as a vertical stack.

Although the preceding discussion has been in terms of the transmitting antenna, the same principles apply when the antenna is used for reception. A high antenna will receive low-angle signals more effectively than will a low antenna. Indeed, amateur operators know very well that "If you can't hear them, you can't talk to them." Stations with tall towers can usually hear far better than their counterparts with low installations.

The situation becomes even more difficult for the next lowest amateur band at 3.5 MHz, where optimal antenna heights for effective long-range communication become truly heroic! Towers that exceed 120 feet are commonplace among amateurs wishing to do serious 3.5-MHz long-distance work.

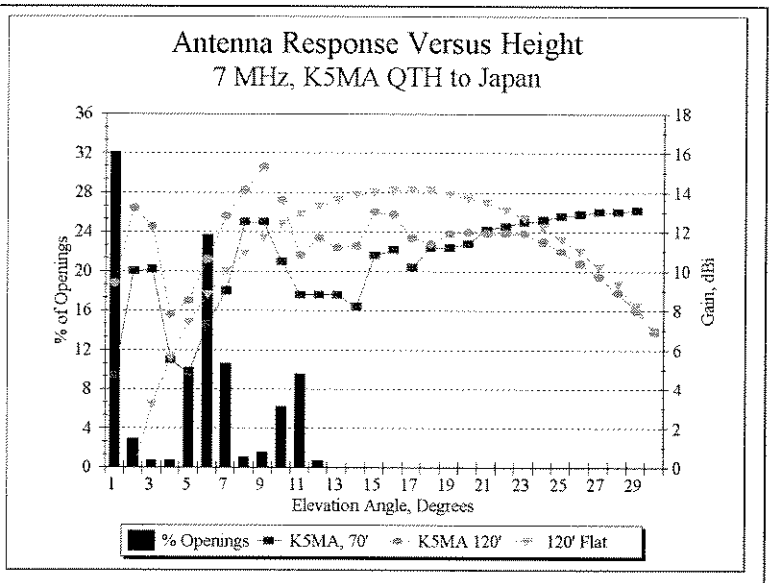

Fig 10—Elevation response on 7 MHz from K5MA location towards Japan on 7 MHz. The 120-foot high Yagi is definitely superior to the one only 70-feet high.

The 3.5 and 7-MHz amateur bands are, however, not always used strictly for long-range work. Both bands are crucial for providing communications throughout a local area, such as might be necessary in times of a local emergency. For example, earthquakes, tornadoes and hurricanes have often disrupted local communications—because telephone and power lines are down and because local police and fire-department VHF/UHF repeaters are thus knocked out of action. Radio amateurs often will use the 3.5 and 7-MHz bands to provide communications out beyond the local area affected by the disaster, perhaps into the next county or the next metropolitan area. For example, an earthquake in San Francisco might see amateurs using emergency power providing communications through amateurs in Oakland across the San Francisco Bay, or even as far away as Los Angeles or Sacramento. These places are where commercial power and telephone lines are still intact, while most power and telephones might be down in San Francisco itself. Similarly, a hurricane that selectively destroys certain towns on Cape Cod might find amateurs in these towns using 3.5 or 7.0 MHz to contact their counterparts in Boston or New York.

However, in order to get the emergency messages through, amateurs must have effective antennas. Most such relatively local emergency situations require towers of moderate height, less than about 100 feet tall typically.

Antenna Height and Interference

Extensive Federal Regulations cover the subject of interference to home electronic devices. It is an unfortunate fact of life, however, that many home electronic devices (such as stereos, TVs, telephones and VCRs) do not meet the Federal standards. They are simply inadequately designed to be resistant to RF energy in their vicinity. Thus, a perfectly legal amateur-radio transmitter may cause interference to a neighbor's VCR or TV because cost-saving shortcuts were taken in

the design and manufacture of these home entertainment devices. Unfortunately, it is difficult to explain to an irate neighbor why his brand-new $1000 stereo is receiving the perfectly legitimate transmissions by a nearby radio operator.

The potential for interference to any receiving device is a function of the transmitter power, transmitter frequency, receiver frequency, and most important of all, the proximity of the transmitter to the potential receiver. The transmitted field intensity decreases as the inverse square of the distance. This means that doubling the height of an antenna from 35 to 70 feet will reduce the potential for interference by 75%. Doubling the height again to 140 feet high would reduce the potential another 75%. Higher is better to prevent interference in the first place!

Recently enacted Federal Regulations address the potential for harm to humans because of exposure to electromagnetic fields. Amateur-radio stations rarely have problems in this area, because they use relatively low transmitting power levels and intermittent duty cycles compared to commercial operations, such as TV or FM broadcast stations. Nevertheless, the potential for RF exposure is again directly related to the distance separating the transmitting antenna and the human beings around it. Again, doubling the height will reduce potential exposure by 75%. The higher the antenna, the less there will any potential for significant RF exposure.

THE WORLD IS A VERY COMPLICATED PLACE

It should be pretty clear by now that designing scientifically valid communication systems is an enormously complex subject. The main complications come from the vagaries of the medium itself, the Earth's ionosphere. However, local terrain can considerably complicate the analysis also.

The main points of this paper may be summarized briefly:

> **The radiation elevation angle is the key factor determining effective communication distances beyond line-of-sight. Antenna height is the primary variable under control of the station builder, since antenna height affects the angle of radiation.**
>
> **In general, placing an amateur antenna system higher in the air enhances communication capabilities and also reduces chances for electromagnetic interference with neighbors.**