Needs Analysis
for Height of
Amateur Radio Antenna Support Structures

Submitted on Behalf of
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Executive Summary

The purpose of this report is to show the need for an antenna system of sufficient height and dimensions to provide reliable High Frequency (HF), or "shortwave," communications, under the changing variables that impact amateur radio communications. It was prepared for Thomas S. and Midge A. Taormina, Amateur Radio Operators K5RC and K7AFO, located at their home in VC Highlands, Nevada.

This report considers amateur radio antenna systems on proposed supporting structures that have already received permits but which are presently under a stop-work order. The studies presented consider antenna heights to compute standard reliability criteria for communications on the 80 and 40-meter Amateur Radio bands for:

1. A height of 195 feet for the 80-meter band (3.5 to 4.0 MHz) to Asia and Europe
2. A height of 45 feet, for the 80-meter band (3.5 to 4.0 MHz) to Asia and Europe
3. A height of 140 feet for the 40-meter band (7.0 to 7.3 MHz) to Asia and Europe
4. A height of 45 feet for the 40-meter band (7.0 to 7.3 MHz) to Asia and Europe

Mr. Taormina has specified that the purpose the High Frequency (1.8 to 30 MHz) antenna systems is intended to serve to provide effective communications with Europe, Asia and North America. These three geographic areas are the most highly populated areas for Amateur Radio operators. North America, basically Canada, the USA and Mexico, is located relatively close to Nevada, while Asia and Europe are far more distant, requiring higher antennas for reliable communications.

It is the conclusion of this report that the proposed antenna systems at the proposed heights for the antennas are barely adequate for the modest needs of these Amateur Radio operators, when measured against commonly used engineering metrics. Mr. and Mrs. Taormina have indicated that the new structures are acceptable compromises, however, as they wish to avoid litigation and don't wish to install flashing red lights under FAA rules for towers higher than 200 feet.

A height of 45 feet for these HF antenna systems results in clearly unacceptable performance, which cannot meet the needs of the two Amateur Radio operators when measured against commonly used engineering metrics.

In addition, this report studies the effect of raising the UHF repeater antenna, which is designed to support county-wide emergency communications, from its present height to 195 feet. The conclusion reached is that there is a dramatic increase in coverage. Furthermore, reducing the height to 45 feet would substantially hinder emergency communications, in view of surrounding terrain.

Outline

This report is organized as follows:

1. Resume of the author.
2. A brief discussion of communications reliability as pertaining to amateur radio.
3. An HF communications reliability study of the installation, using industry standard tools.
4. A VHF/UHF communications reliability study of the installation, using industry standard tools.
5. A reprint of a publication from the American Radio Relay League, "Antenna Height and Communications Effectiveness," that provides the basic technical background as to why higher antennas perform more reliably.

Resume of the Author

R. Dean Straw received the degree of Bachelor of Engineering and Applied Science from Yale University in New Haven, CT, in 1967.

After a 25-year career in the Marine Electronics field, doing engineering and technical marketing for major manufacturers (ITT/Mackay, Furuno, Datamarine, and Raytheon Marine), in 1993 Mr. Straw started work at the ARRL (American Radio Relay League) as a Senior Assistant Technical Editor. ARRL is the National Organization for Amateur Radio.

Straw's primary function was to be the Editor for five different editions (17th through the 21st Editions) of *The ARRL Antenna Book*, the premier publication dealing with antennas, transmission lines and propagation in the Amateur Radio field. Straw wrote not only text for this book, but also created innovative software programs for analysis of propagation, antennas and transmission-lines. This includes the industry-standard *HFTA* (High Frequency Terrain Assessment) program. He has lectured on these subjects at dozens of national and regional conventions, and more than 50 seminars.

Straw also edited a number of books in his 15-year tenure at ARRL, including:

1. Three editions of *The ARRL Handbook*
2. Four volumes of *The ARRL Antenna Compendium* series
3. *ON4UN's Low-Band DXing* (two editions)
4. *Low-Profile Amateur Radio*
5. *The ARRL DXCC Handbook*
6. *Antenna Zoning*
7. *DXing on the Edge—the Thrill of 160 Meters*
8. *Basic Radio*
9. *Basic Antennas*
10. He was co-author of *Simple and Fun Antennas for Hams*.
11. He has authored dozens of technical articles for the ARRL monthly magazine, *QST*.

Straw retired in March 2008, and has been devoting his time primarily to the technical analysis of propagation and antenna phenomena, while indulging also in his passion for traveling and operating ham-radio contests around the world. He has been licensed as a Radio Amateur for 49 years, holding an Amateur Extra, the highest class, license since 1969.

HF Communications Reliability

For the reader to meaningfully interpret the reliability and signal-strength study presented herein, a brief discussion of the major concepts and terms involved is relevant. The reader is also urged to review the document prepared by technical staff at the American Radio Relay League, "Antenna Height and Communications Effectiveness," which provides the physical explanation as to why radio communications reliability and effectiveness is strongly affected by antenna height.

Reliability (REL) in a radio communications context, answers the question "How often, on average, can this communication take place at a specified 'minimum acceptable level'?" Reliability is normally expressed as a percentage, and arriving at a specific value depends on the definition of "Minimum Acceptable Level" (or MAL) in use. Several different MALs are commonly accepted in the engineering community.

Measures of Reliability

Imagine watching a distant VHF or UHF analog TV station (not cable), which occasionally fades in and out. If we define the MAL as "a completely clear picture without snow or fuzziness," then the measured Reliability might be as low as 20 to 30%. On the other hand, if we are willing to accept an MAL of "we can just make out the picture," then the measured Reliability might jump to 80 to 90%… for the same picture.

Or consider this real-world example. Many areas of the communications industry (broadcasting and networking, to pick two) routinely use a Reliability figure of 99.99% (commonly referred to as the 'four nines'). In this case, the MAL is usually "the transmission (or network) is functioning, and of first quality" — nothing less. Being "up" 99.99% of the time, conversely, means you are "down" no more than 0.01% or, equivalently, no more than 52 minutes per year. Radio amateurs do not, generally speaking, require such a high level of Reliability.

Application to HF analysis

If we turn closer to our radio domain, High Frequency (HF) shortwave broadcasters, like the Voice of America or the BBC World Service, look for Reliability numbers in the 80 to 90% range when planning their time and frequency schedules, to achieve an area-coverage goal. In their cases, the MAL parameter (yardstick) is the Signal-to-Noise ratio, or SNR. This is basically the ratio of how loud the broadcast is in relation to background radio "hiss" and static levels (such as noise caused by nearby thunderstorms). Commonly required SNR numbers range anywhere from 40-70 dB (a higher number means better quality reception).

In the analysis presented below, the Reliability (REL) threshold is set at 57%, using an SNR of 40 dB for Single Sideband (SSB) voice communications. This is a *very* conservative (low) value for measuring acceptable communications quality.

HF radio communication is made possible by reflecting signals off an ionized portion of the Earth's atmosphere known as the *ionosphere*. The very nature of this communication is variable (ie, not constant) and depends on many factors, including the time of year, time of day, solar (sunspot) activity, local noise sources and other geomagnetic and atmospheric conditions. In our test cases we have consistently used very conservative models and accepted a low Reliability (REL) factor (57%).

1. A Reliability threshold of 57% is equivalent to four days a week. Imagine if your cell phone or cable TV service worked only four days out of seven during the week — that would be a Reliability of 57%. If your cell phone or cable TV service worked only five days out of seven, that would be a Reliability of 71%. In the area-coverage maps that follow, the Reliability contours are 14, 29, 43, 57, 71 and 86%, to correspond to easily understood levels of one to six days per week.
2. The MAL (Minimum Acceptable Level) is expressed as a percentage of time that communications are available at a specified Signal-to-Noise Ratio (SNR). The SNR value of 40 dB is commonly used in Amateur Radio. It is the *minimum required SNR* for a Single Sideband (voice) transmission. Single sideband transmissions sometimes require an SNR of up to 50 dB or more, which would further lower the results presented here (ie, this would require a larger/taller antenna system). In other words, in presenting the results here, the assumptions about required Reliability are very modest indeed.

High Frequency (HF) Analysis

PROCEDURE

For the High Frequency (HF or shortwave) radio spectrum, the reliability (REL) of a given path (say, Reno to Europe or to Asia) is commonly defined as the percentage of days that the signal at the receiver's end meets or exceeds a defined Signal-to-Noise ratio (SNR). The REL value depends on many parameters. Several directly or indirectly affect the "take-off" angle as described in the well-documented American Radio Relay League (ARRL) publication that accompanies this report. Other parameters include transmitter power, local terrain, and the hourly and daily absorptive and reflective properties of the ionosphere.

In this section, we use two industry standard software tools: the High Frequency Terrain Analysis (*HFTA*) program, which computes the effect of local terrain on the launch of HF signals into the ionosphere, and the Voice of America Coverage Analysis Program (*VOACAP*), which predicts the reliability (REL) and signal strength (SDBW) values to Asia and to Europe, using two different antenna heights for 3.7 and 7.1 MHz (80 and 40 meters).

The process starts by using the USGS National Elevation Dataset terrain data for the exact latitude and longitude of each of the antenna-support locations in VC Highlands, Nevada. This USGS terrain data is used as input for the *HFTA* (High Frequency Terrain Assessment) program. *HFTA* uses the Taorminas' actual (not theoretical) terrain profiles from each proposed support structure location and the actual antenna parameters (free-space antenna gain and height) as inputs. It thus provides the actual antenna gain and take-off (elevation) angle data as output.

The output from *HFTA* is then used as the antenna input to the *VOAAREA* program (a subset of *VOACAP*) to produce Area Coverage maps. *VOACAP* is an HF Propagation Analysis software tool developed by the US Department of Commerce / Institute for Telecommunication Sciences over the last four decades. This software suite is in the public domain, and was made possible by funding from the Voice of America (VOA), the US Army and the US Air Force. Area Coverage is one of many calculations that *VOACAP* can perform. It displays a number of calculated quantities (including REL and signal strength SDBW) for a specified transmitter to a desired reception area, for a specified date, time of day, frequency and sunspot level. The results appear as contours plotted on a world-map background.

On the resulting map, reliability contours that meet our criteria are shown dark green (86%, occurring 6 out of 7 days per week), light green (71%, occurring 5 out of 7 days a week) and then yellow (57%, occurring 4 out of 7 days a week). Those areas that fail to meet the standard 57% reliability criteria are shown in blue, dark gray, light gray or white. **Table 1** shows the relationships.

Table 1, VOAAREA REL Color Coding

Color	% Availability	Days per Week
Dark Green	86%	>6 out of 7
Light Green	71%	5 out of 7
Yellow	57%	4 out of 7
Light Blue	43%	3 out of 7
Dark Gray	29%	2 out of 7
Light Gray	14%	1 out of 7
White	<14%	< 1 out of 7

DETAILED DESCRIPTION OF *VOAAREA* INPUT PARAMETERS

Some parameters are held constant for all the cases analyzed in *VOAAREA*. They are:

1. Transmitter location: the Taormina antenna-support location in VC Highlands, Nevada.
2. Transmitter power: 1.5 kW (kilowatts). This is the maximum legal power limit for Amateur-Radio stations.
3. Transmitter frequency: 3.7 and 7.1 MHz (80 and 40 meters).
4. Receiving antenna type: a 75-foot high dipole over flat ground.
5. The Smoothed Sunspot Number (SSN): 100. This is an acceptable average value over the entire 11-year solar sunspot cycle.
6. Month: November.
7. SNR required: 40 dB for SSB (voice) communications. This is the minimum acceptable signal-to-noise value needed for voice transmissions. A minimum SNR of 24 dB could be used for narrow-band CW (Morse code) transmissions if satisfactory voice communication isn't possible.
8. Level of local noise: Quiet rural man-made noise.
9. Absorption model: IONCAP.

The transmitting antennas created in *HFTA* and used in *VOAAREA* were:

1. 3-element Yagis at 195 and 70 feet to Europe for 3.7 MHz (RC80HIEU.ELE)
2. 3-element Yagi at 45 feet to Europe for 3.7 MHz (RC80LOEU.ELE)
3. 3-element Yagis at 195 and 70 feet to Japan for 3.7 MHz (RC80HIJA.ELE)
4. 3-element Yagi at 45 feet to Japan for 3.7 MHz (RC80LOJA.ELE)
5. 3-element Yagis at 140 and 70 feet to Europe for 7.1 MHz (RC40HIEU.ELE)
6. 3-element Yagi at 45 feet to Europe for 7.1 MHz (RC40LOEU.ELE).
7. 3-element Yagis at 140 and 70 feet to Japan for 7.1 MHz (RC40HIJA.ELE)
8. 3-element Yagi at 45 feet to Europe for 7.1 MHz (RC40LOJA.ELE).

The geographic targets of Europe and Japan (Asia) were specified for both 80 and 40 meters, since these represent the largest concentrations of ham-radio operators outside of the USA. Europe is a challenging target area from Nevada, mainly because of the long distances involved, which results in weak signals. But there is another problem over this path. The signal to Europe from Nevada must transit the northern *auroral zone* HF signals and it can be severely absorbed during periods of high auroral activity.

In the detailed discussion that follows, 57% is used as the minimum acceptable reliability (REL) value. That is, successful communications is defined as a path reliability of 57% or greater — four or more days a week out of seven — of available time when signals achieve the desired 40 dB SNR level.

Note that blackout periods due to solar flares and other solar disturbances, when communications are not realistically possible, are not included. If blackout times were included, the reliability would be even lower, dramatically lower, in fact. The 57% REL requirement is a very conservative service goal, as *Snook v. Missouri City* (Texas)[1], an Amateur-Radio case tried in the U.S. District Court, Southern District of Texas (2003), accepted a service reliability standard of 75 to 90%. This higher level of service reliability would require even larger and higher antennas at the Taormina location.

Fig 1 shows the Terrain Profile from the base of the proposed 80-meter antenna support for two azimuths of special interest: 30° to Europe and 305° to Japan. You can see that the terrain drops off in both directions about 100 feet in the first 1000 feet from the support base. The terrain towards Japan, however, then rises back up to the height of the antenna support base about 1300 feet from the base and rises up to almost 300 feet higher than the base about a mile away. The terrain towards Europe, on the other hand, is more beneficial in that the average height drops gently down until about 2 miles away. The two red diamonds represent the heights of the two Yagis on the 80-meter antenna support structure, at 195 and 70 feet.

[1] *Snook v. City of Missouri City*, No. 03-cv-243, 2003 U.S. Dist. LEXIS 27256, 2003 WL 25258302 (S.D. Tex. Aug. 26, 2003, Hittner, J.) (the Order, Slip Opinion, 63 pp.), see also the Final Judgment, Slip Opinion, 2 pp. PACER citation: https://ecf.txsd.uscourts.gov/cgi-bin/login.pl?387442335892775-L_238_0-14:03-cv-00243_Snook v._City_of_Missouri, (S.D. Tex. 2003). http://www.arrl.org/FandES/field/regulations/PRB-1_Pkg/Snook%20KB5F%20Decision%20&%20Order%2034.pdf

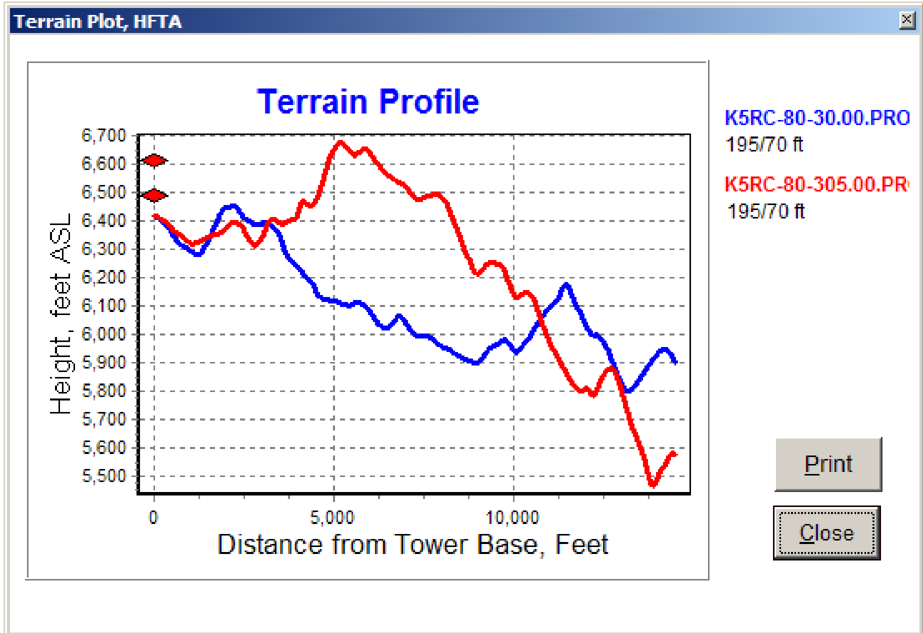


Fig 1 — Terrain profile from the base of the 80-meter antenna towards Europe (blue, at azimuth of 30°) and towards Asia (red, at 305°). The average slope is downwards to Europe, aiding the takeoff of signals along this terrain, but the terrain towards Asia is somewhat more challenging.

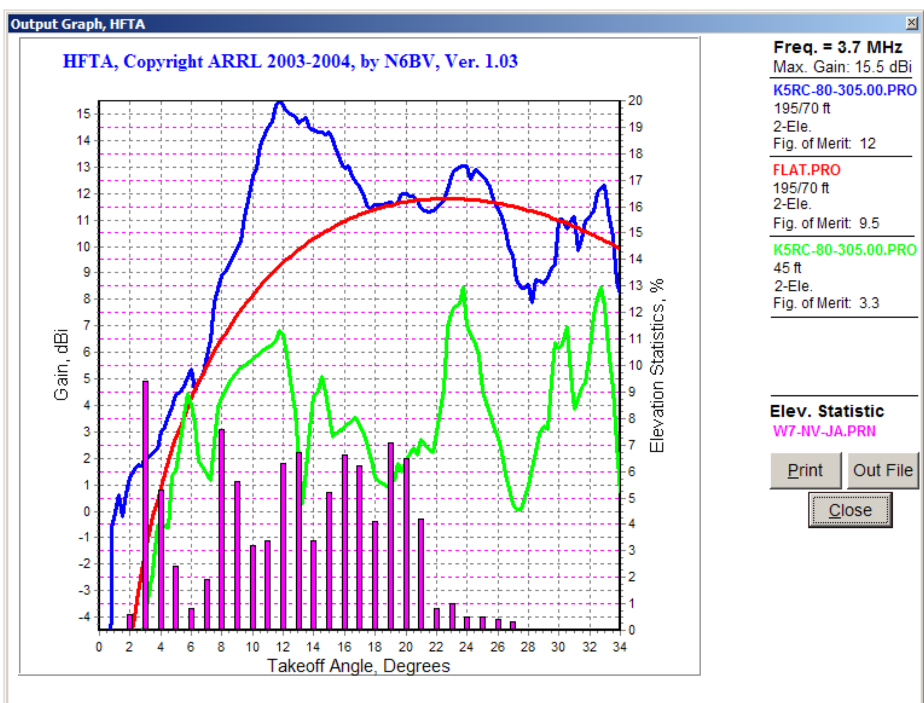


Fig 2 — *HFTA* analysis of the terrain for the 80-meter High antenna towards Asia. The blue line is for the High antenna array, while the green line is for a single Low (45') antenna. The red line is the High array over flat ground, shown for reference. The High antenna is greatly superior.

Fig 2 shows the *HFTA* response pattern created in the direction to Japan for three 80-meter (3.7 MHz) antenna systems:

1. Two 3-element Yagi beam antennas mounted at 195 and 70 feet (blue line).
2. The same antennas mounted 195 and 70 feet over flat ground (red line).
3. One 3-element Yagi mounted at 45 feet (green line)

The single 45-foot high antenna is dramatically less effective than the higher two antennas. You can see that the difference between the blue and red lines is a measure of the effect of the local terrain on the launch of 80-meter signals into the ionosphere.

80 METERS (3.7 MHZ) TO ASIA

What then are the actual effects of using these antennas, in terms of the reliability of signal coverage into Asia?

Fig 3 shows the REL (reliability) contours generated by *VOAAREA* using the high 195 and 70-foot pair of 3-element Yagis pointed towards Asia at 1000 UTC in November. The 57% reliability contour just manages to cover all of Japan plus Korea. Again, this means that on four days out of seven communications are possible with the eastern part of Asia from Reno, NV, using a large antenna array. Coverage further west into mainland China with Beijing or Hong Kong is just out of range.

When a single lower 45-foot high antenna is substituted for the 195 and 70-foot pair, the result is shown in **Fig 4**. Now, only the upper portion of Japan is covered by the 57% reliability contour, and Korea is not covered.

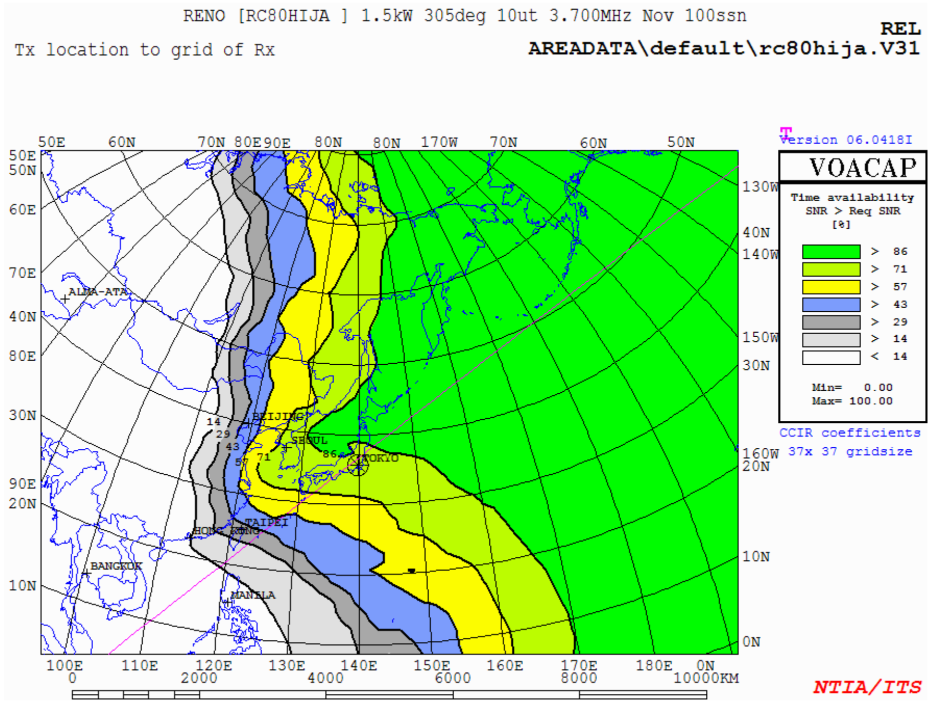


Fig 3 — Reliability of 80-meter coverage in Asia, using High antenna array, generated by *VOAAREA* program. The 57% reliability contour (yellow = 4 days out of 7) just barely covers Japan and Korea, but not Beijing, Taipei or Hong Kong.

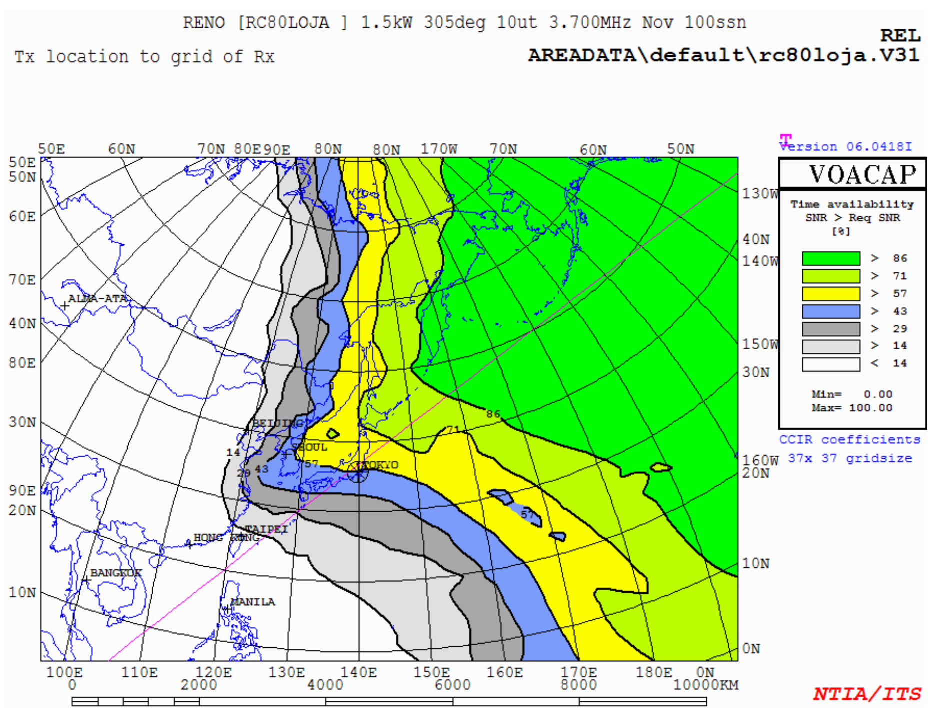


Fig 4 — Reliability of 80-meter coverage in Asia, using single Low (45') antenna. Only the upper part of Japan is adequately covered by 57% (yellow) contour; Korea is not covered nor is Beijing, Taipei or Hong Kong.

Noise

The term "Signal-to-Noise Ratio" suggests that there are two quantities compared to each other — a (desired) voice signal and some sort of (undesired) noise. *VOAAREA* calculates the average noise mainly due to seasonal thunderstorms (whether the lightning crashes are coming from nearby or distant storms, propagating through the ionosphere). *VOAAREA* adds to that the average level of noise coming from the local environment — perhaps noise pulses coming from arcing high-voltage insulators, electric fences or an electric trolley running in the street near your receiving antenna.

What *VOAAREA* doesn't compute explicitly is the "noise" from legitimate transmissions from other stations — most hams would call this "interference," but it too is a form of undesired noise. **Fig 5** shows the 80-meter signal-strength contours that *VOAAREA* computes across the receiving area for the high 195 and 70-foot Yagis. The calibration of the contours is in dB below one watt of power.

The orange contour represents a "strong" signal. A yellow contour represents a "moderate" signal, while a green or blue contour indicates a "weak" signal. The dark brown contour is "very strong" and the deep red color is "extremely strong." If a local transmitter in the target receive area is very strong (dark brown) and the desired signal from Nevada is only a "moderate" yellow then communication will be impossible while the local is transmitting. This means that the actual reliability figure will be worse than Fig 3 would normally indicate. **Fig 6** shows the computed signal strength for the single low 45-foot high antenna.

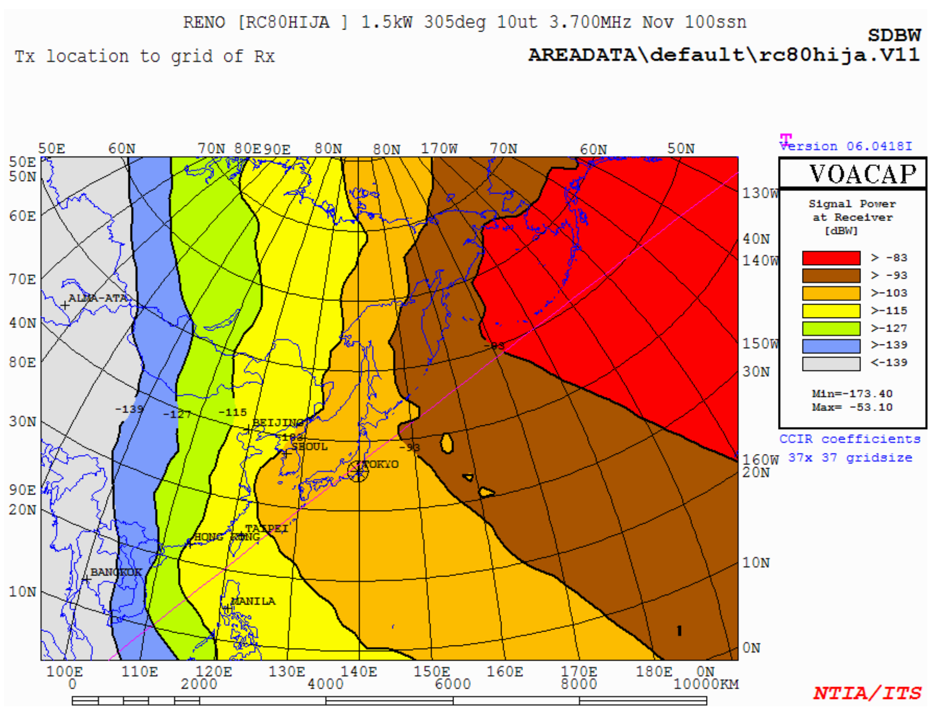


Fig 5 — Signal strength (SDBW) in decibels below 1 W into Asia using High antenna array. The orange contour is a "Strong" level of signal and yellow is "Moderate." The green and blue contours show "Weak" signals. Signal strength is useful when there is competition from other stations.

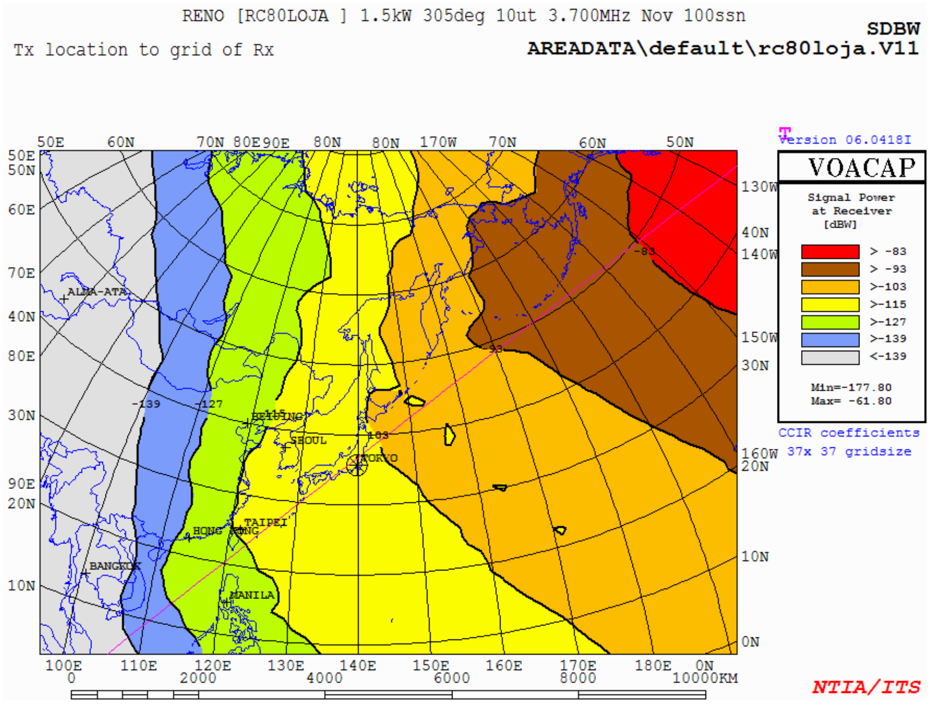


Fig 6 — Signal strength (SDBW) into Asia using a single Low (45') antenna. The weaker signals launched by the Low antenna often have difficulty overcoming lightning static or manmade noise in Asia, or if there is competition or interference from other signals.

80 METERS (3.7 MHZ) TO EUROPE

Fig 7 shows the HFTA analysis of the terrain for the 80-meter high antenna array towards Europe (an azimuth of 30°). The blue line is for the High antenna array, while the green line is for a single Low (45') antenna. The red line is the High array over flat ground, again shown for reference. The High antenna is again greatly superior.

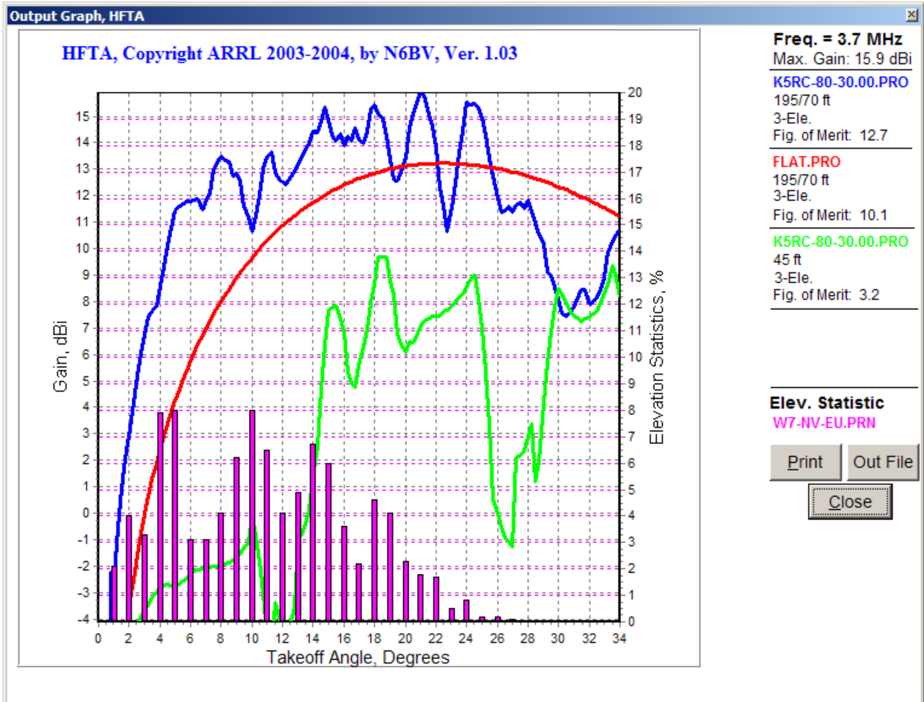


Fig 7 — *HFTA* analysis of the terrain for the 80-meter High antenna towards Europe. The blue line is for the High antenna array, while the green line is for a single Low (45') antenna. The red line is the High array over flat ground, shown for reference. The sloping terrain towards Europe accounts for the improved performance of the antennas, compared to flat ground.

Fig 8 shows the REL (reliability) contours generated by *VOAAREA* using the high 195 and 70-foot pair of 3-element Yagis pointed towards Europe, at 0500 UTC in November. The 57% reliability contour just manages to reach Iceland, while missing the continent of Europe. The light-blue contour (43%) covers England and France. On three days out of seven communications are thus possible with parts of Western Europe from Reno, NV, again when using a large antenna array. It's possible to contact Rome and Berlin only 14% of the time, or in other words one day a week. As I stated earlier: the path from Reno to Europe on 80 meters is a challenging one, requiring the best of equipment.

Fig 9 shows the reliability contours for Reno to Europe using a low 45-foot high 3-element Yagi. In short, the situation is very simple — it's not possible, statistically speaking, to contact Europe with this low antenna.

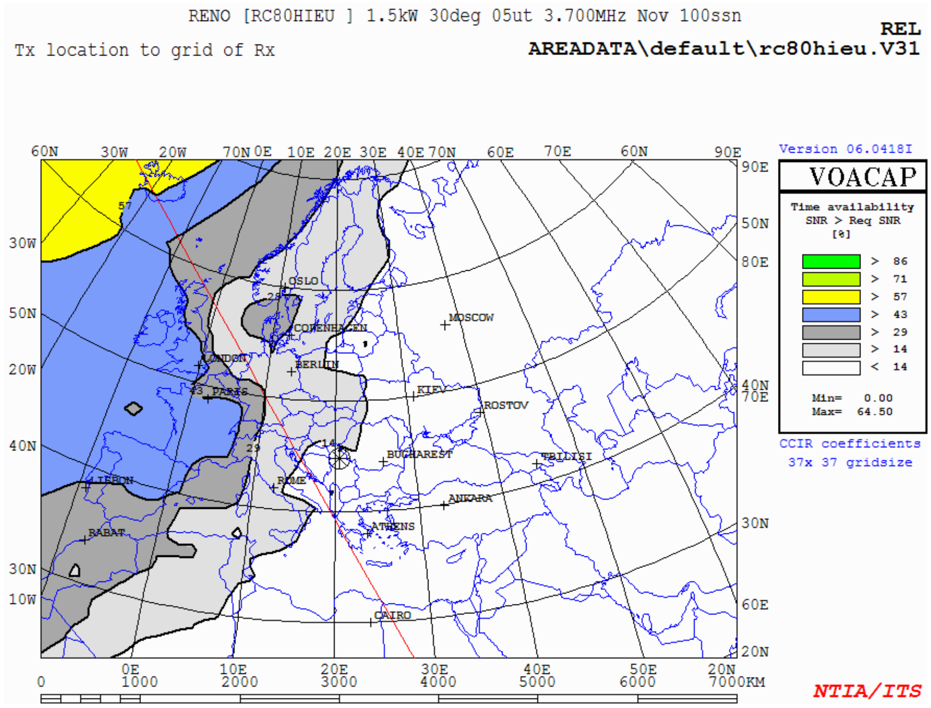


Fig 8 — 80-meter coverage of Europe for High antenna array. Only Iceland can achieve the required 57% time availability criterion. England, France and northern Spain can be covered 3 days out of 7, or 43% of the time. Eastern Europe has no coverage, even with the High array.

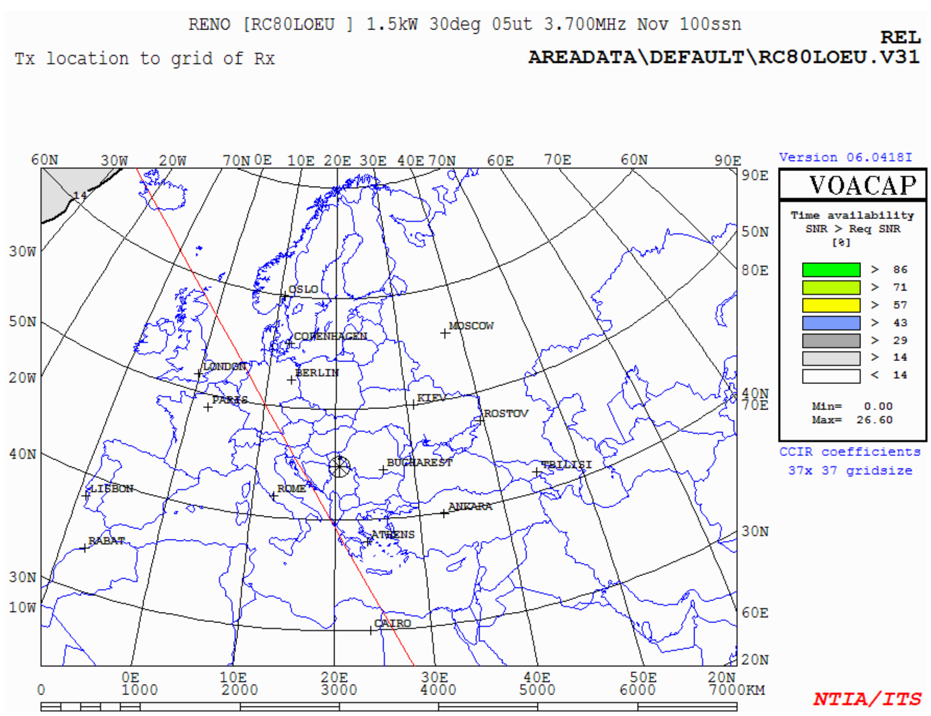


Fig 9 — 80-meter coverage of Europe with a single Low (45') antenna. There is, in short, no coverage of Europe with this low antenna.

40 METER (7.1 MHZ) COVERAGE TO EUROPE

Fig 10 shows the reliability contours for40-meter coverage from Reno to Europe, using a high array of two 3-element Yagis at 140 and 70 feet. Almost all of Europe is covered adequately at the 57% reliability standard level using this antenna system.

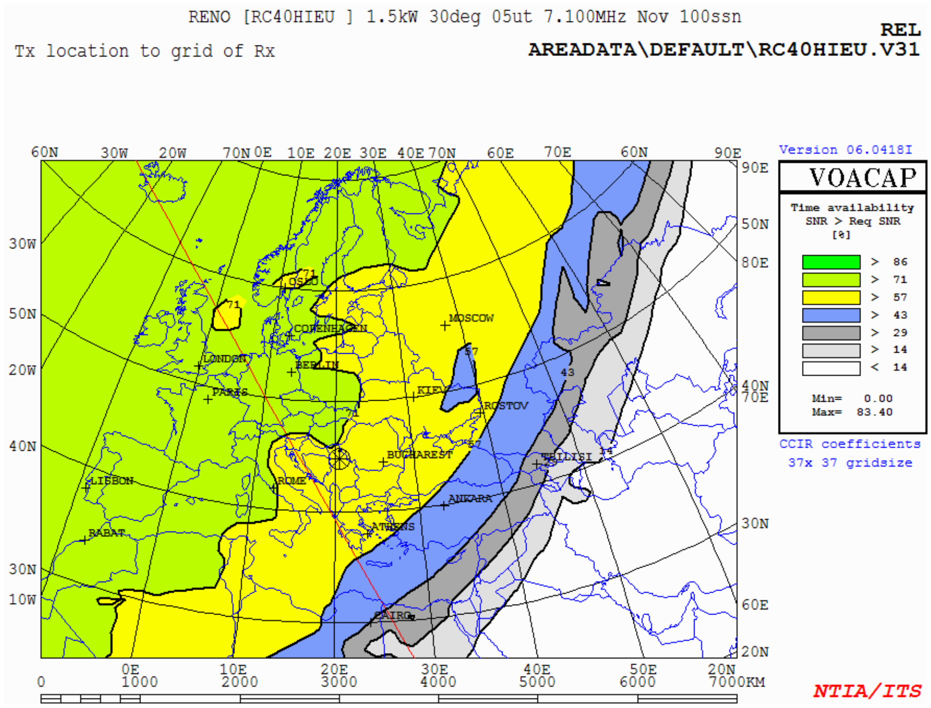


Fig 10 — 40-meter coverage of Europe with High antenna array. Almost all of Europe is covered with this antenna for the required 57% of the time.

Fig 11 shows the reliability coverage of Europe from Reno for a Low Yagi antenna at 45 feet in height. Only Western Europe can be adequately covered with this lower antenna. The coverage of Eastern Europe is missing at the 57% (yellow) standard reliability goal.

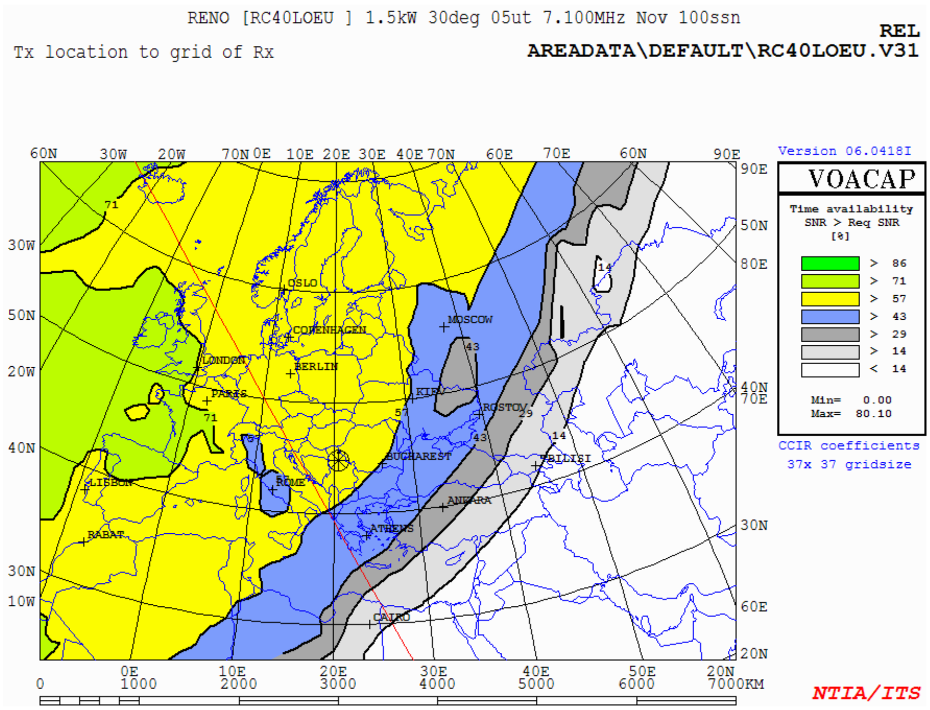


Fig 11 — 40-meter reliability coverage of Europe with single Low (45') antenna. Only Western Europe can be adequately covered at the 57% contour, missing all of Eastern Europe.

Local Terrain Effect on VHF/UHF Communications

The local terrain at the Taormina residence presents a significant challenge for both VHF and UHF amateur radio communication because of the rugged, mountainous terrain.

VHF AND UHF COMMUNICATIONS RELIABILITY

Figs 12 and **13** are included to give a visual representation of the increased coverage expected from moving the 441.625-MHz repeater antenna from its current location at 70 feet on the 80-meter support structure to the top of the replacement 195-foot structure that is already permitted. These plots are called Longley-Rice signal computations.

To simplify the interpretation of them, the lighter the color, the greater the relative signal strength on transmit and receive. At 70 feet, the repeater has a useful coverage of 256 square km. With the antenna at 195 feet, it has a useful coverage area of 405 square km, or a 58% increase in exposure. This is a huge increase in performance, especially for emergency communications applications.

With respect to the UHF repeater, operating in the 440-MHz band, the analysis shows a 58% improvement in coverage when going from the present height of 70 feet, to the proposed height of 195 feet. If the UHF repeater antenna, designed for use in local emergency situations, including search and rescue, were lowered to 45 feet, performance in the presence of the surrounding terrain would be unacceptable.

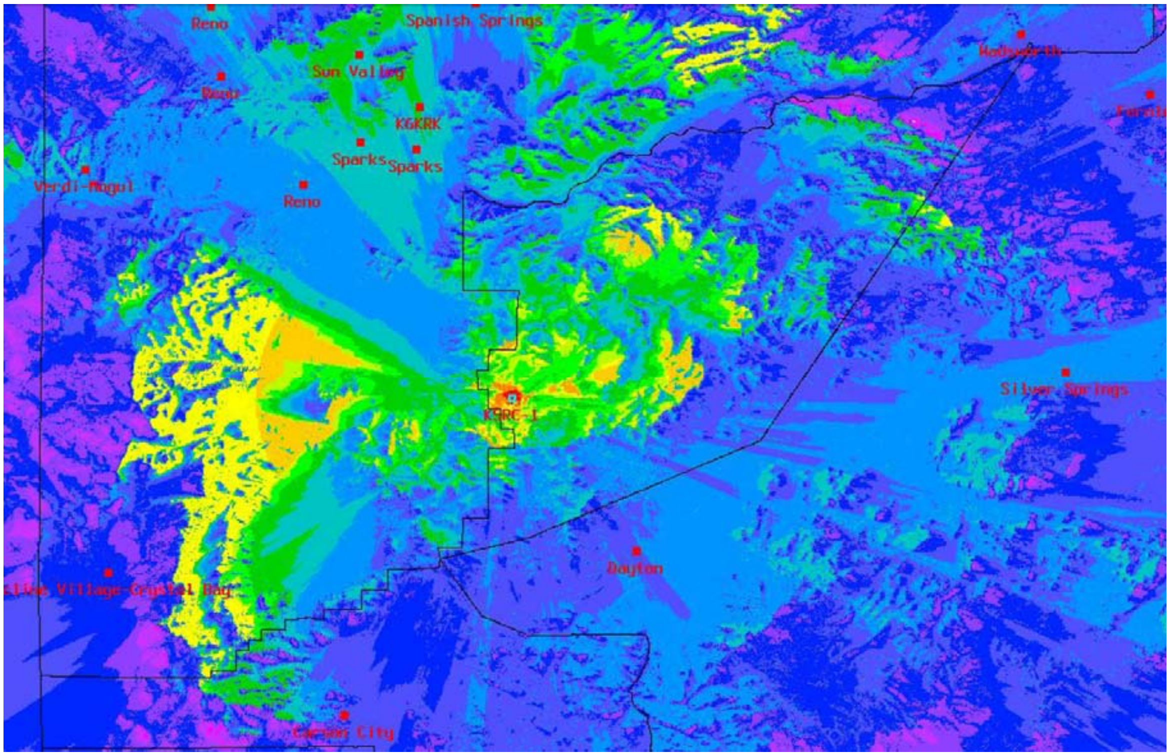


Fig 12 — Longley-Rice plot at 70 feet.

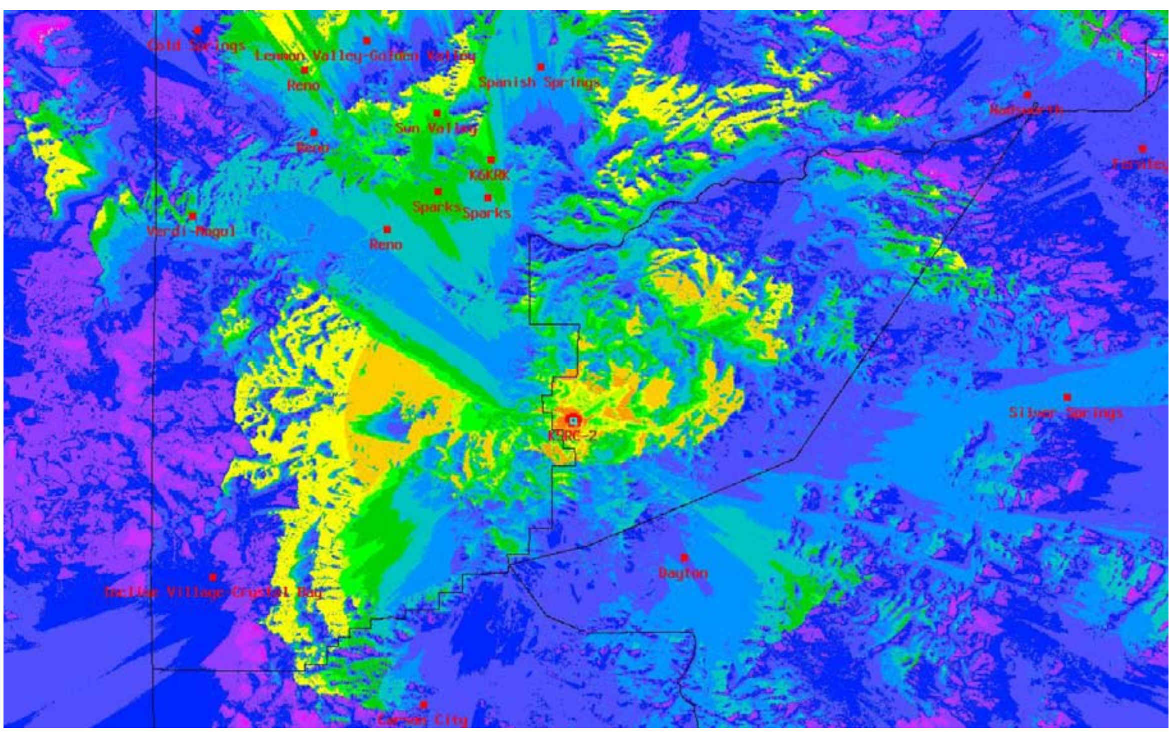


Fig 13 — Longley-Rice plot at 195 feet. Coverage is improved by 58% over the case where the antenna is only 70 feet high.

Communications Analysis, Conclusions

The height of the new proposed antenna support structures and antennas were analyzed for the purpose of determining whether they would meet the need of the two Amateur-Radio operators. Commonly used engineering metrics were employed to determine the effectiveness of communications.

The new 80-meter structure, which will support the 3.8-MHz antennas and the 450-MHz UHF antenna, only marginally meets the need for reliable HF communications to portions of Western Europe. That height also would substantially increase the UHF coverage area for emergency communications. Lowering the antennas to 45 feet, however, would not meet the Taorminas' communication needs.

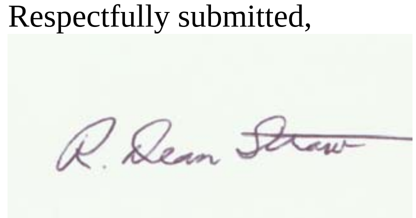
Ideally, a substantially taller structure than 195 feet might be utilized to provide reliable coverage to Eastern Europe and the Middle East on 80 meters. However, Mr. and Mrs. Taormina are willing to live with the proposed 80-meter height structure at 195 feet as an acceptable compromise, despite the limitations it presents in reliable coverage. Again, they do not wish to extend the support structure(s) past 200 feet in height, where they would have to install flashing red lights to meet FAA rules, and they wish to avoid litigation.

The new 40-meter structure, which will support the 7.1-MHz antennas, does meet the requirements to cover all of Europe reliably. Lowering the antenna to 45 feet, however, would not meet the communication needs and does not provide reliable coverage to the desired target geographic areas on 40 meters.

With respect to the UHF repeater, operating in the 440 MHz band, the analysis shows a 58% improvement in coverage when going from the present height of 70 feet, to the proposed height of 195 feet. If the UHF repeater antenna, designed for use in local emergency situations, including search and rescue, were lowered to 45 feet, performance in the presence of the surrounding terrain would be unacceptable.

A height of 45 feet would not provide reliable coverage to the desired target geographic areas at 3.8 or 7.1 MHz (80 meters or 40 meters), nor would reliable coverage be provided on at 440 MHz (UHF) for emergency communications.

Respectfully submitted,



R. Dean Straw
San Francisco
August 13, 2008

Glossary of Terms

(Courtesy, The ARRL Antenna Book)

Antenna—An electrical conductor or array of conductors that radiates signal energy (transmitting) or collects signal energy (receiving).
ARRL—Abbrev. for American Radio Relay League, the national association for Amateur Radio.
BBC—Abbrev. for British Broadcasting Corporation.
Beamwidth—Related to directive antennas. The width, in degrees, of the major lobe between the two directions at which the relative radiated power is equal to one half its value at the peak of the lobe (half power = –3 dB).
Coaxial cable—Any of the coaxial transmission lines that have the outer shield (solid or braided) on the same axis as the inner or center conductor. The insulating material can be air, helium or solid-dielectric compounds.
Counterpoise—A wire or group of wires mounted close to ground, but insulated from ground, to form a low-impedance, high-capacitance path to ground. Used at MF and HF to provide an RF ground for an antenna. Also see ground plane.
CW—Abbrev. for Continuous Wave, an older term denoting communications by means of Morse code.
Decibel—A logarithmic power ratio, abbreviated dB. May also represent a voltage or current ratio if the voltages or currents are measured across (or through) identical impedances. Suffixes to the abbreviation indicate references: dBi, isotropic radiator; dBic, isotropic radiator circular; dBm, milliwatt; dBW, watt.
Dipole—An antenna that is split at the exact center for connection to a feed line, usually a half wavelength long. Also called a “doublet.”
Direct ray—Transmitted signal energy that arrives at the receiving antenna directly rather than being reflected by any object or medium.
Directivity—The property of an antenna that concentrates the radiated energy to form one or more major lobes.
Director—A conductor placed in front of a driven element to cause directivity. Frequently used singly or in multiples with Yagi or cubical-quad beam antennas.
Driven array—An array of antenna elements that are all driven or excited by means of a transmission line, usually to achieve directivity.
Driven element—A radiator element of an antenna system to which the transmission line is connected.
E layer—The ionospheric layer nearest earth from which radio signals can be reflected to a distant point, generally a maximum of 2000 km (1250 miles).
E plane—Related to a linearly polarized antenna, the plane containing the electric field vector of the antenna and its direction of maximum radiation. For terrestrial antenna systems, the direction of the E plane is also taken as the polarization of the antenna. The E plane is at right angles to the H plane.
Efficiency—The ratio of useful output power to input power, determined in antenna systems by losses in the system, including in nearby objects.
EIRP—Effective isotropic radiated power. The power radiated by an antenna in its favored direction, taking the gain of the antenna into account as referenced to isotropic.
Elements—The conductive parts of an antenna system that determine the antenna characteristics. For example, the reflector, driven element and directors of a Yagi antenna.
FAA—Federal Aviation Administration.
F layer—The ionospheric layer that lies above the E layer. Radio waves can be refracted from it to provide communications distances of several thousand miles by means of single- or double-hop skip.
Feed line—Transmission lines of assorted types that are used to route RF power from a transmitter to an antenna, or from an antenna to a receiver.
Field strength—The intensity of a radio wave as measured at a point some distance from the antenna. This measurement is usually made in microvolts per meter.
Front to back—The ratio of the radiated power off the front and back of a directive antenna. For example, a dipole would have a ratio of 1, which is equivalent to 0 dB.
Front to rear—Worst-case rearward lobe in the 180°-wide sector behind an antenna’s main lobe, in dB.
Front to side—The ratio of radiated power between the major lobe and that 90° off the front of a directive antenna.
Gain—The increase in effective radiated power in the desired direction of the major lobe.
Ground plane—A system of conductors placed beneath an elevated antenna to serve as an earth ground. Also see counterpoise.
Ground screen—A wire mesh counterpoise.
Ground wave—Radio waves that travel along the Earth’s surface.

H plane—Related to a linearly polarized antenna. The plane containing the magnetic field vector of an antenna and its direction of maximum radiation. The H plane is at right angles to the E plane.
HAAT—Height above average terrain. A term used mainly in connection with repeater antennas in determining coverage area.
HFTA—Software program High Frequency Terrain Analysis by ARRL.
Impedance—The ohmic value of an antenna feed point, matching section or transmission line. An impedance may contain a reactance as well as a resistance component.
IONCAP—Software program developed by the US government to analyze HF propagation. See *VOACAP*, which is an updated version of *IONCAP*.
Isotropic—An imaginary or hypothetical point-source antenna that radiates equal power in all directions. It is used as a reference for the directive characteristics of actual antennas.
Lambda—Greek symbol (λ) used to represent a wavelength with reference to electrical dimensions in antenna work.
Line loss—The power lost in a transmission line, usually expressed in decibels.
Line of sight—Transmission path of a wave that travels directly from the transmitting antenna to the receiving antenna.
Load—The electrical entity to which power is delivered. The antenna system is a load for the transmitter.
Loading—The process of a transferring power from its source to a load. The effect a load has on a power source.
Lobe—A defined field of energy that radiates from a directive antenna.
Longley-Rice—Standard method used by the FCC for computing coverage for paging systems, FM and TV stations.
MAL—Abbrev. for Minimum Acceptable Level.
MHz—One million hertz, as in a frequency of 14.1 MHz = 14.1 million hertz.
Null—A condition during which an electrical unit is at a minimum. A null in an antenna radiation pattern is a point in the 360-degree pattern where a minima in field intensity is observed. An impedance bridge is said to be “pulled” when it has been brought into balance, with a null in the current flowing through the bridge arm.
Parasitic array—A directive antenna that has a driven element and at least one independent director or reflector, or a combination of both. The directors and reflectors are not connected to the feed line. Except for VHF and UHF arrays with long booms (electrically), more than one reflector is seldom used. A Yagi antenna is one example of a parasitic array.
Polarization—The sense of the wave radiated by an antenna. This can be horizontal, vertical, elliptical or circular (left or right hand circularity), depending on the design and application. (See H plane.)
Radiation pattern—The radiation characteristics of an antenna as a function of space coordinates. Normally, the pattern is measured in the far-field region and is represented graphically.
Radiator—A discrete conductor that radiates RF energy in an antenna system.
Reflected ray—A radio wave that is reflected from the earth, ionosphere or a man-made medium, such as a passive reflector.
Reflector—A parasitic antenna element or a metal assembly that is located behind the driven element to enhance forward directivity. Hillsides and large man-made structures such as buildings and towers may act as reflectors.
Refraction—Process by which a radio wave is bent and returned to earth from an ionospheric layer or other medium after striking the medium.
SDBW—Abbrev. for Signal, in dB referenced to 1 W.
SNR—Abbrev. for Signal-to-Noise Ratio.
SSB—Abbrev. for Single Sideband, an efficient method for voice communications.
SSN—Abbrev. for Smoothed Sunspot Number, an indicator for solar activity.
Stacking—The process of placing similar directive antennas atop or beside one another, forming a “stacked array.” Stacking provides more gain or directivity than a single antenna.
USGS—Abbrev. for United States Geologic Survey.
VHF—Abbrev. for Very High Frequency, ranging from 30 to 300 MHz.
VOA—Abbrev. for Voice of America.
VOAAREA— part of the VOACAP software suite for area-coverage computations.
VOACAP—Software suite by Voice of America for HF propagation analysis.
VSWR—Voltage standing-wave ratio. See SWR.
Wave—A disturbance or variation that is a function of time or space, or both, transferring energy progressively from point to point. A radio wave, for example.
Wave angle—The angle above the horizon of a radio wave as it is launched from or received by an antenna. Also called elevation angle.
Wave front—A surface that is a locus of all the points having the same phase at a given instant in time.

Yagi—A directive, gain type of antenna that utilizes a number of parasitic directors and a reflector. Named after one of the two Japanese inventors (Yagi and Uda).
40 Meters – The amateur band from 7.0 to 7.3 MHz.
80 Meters – The amateur band from 3.5 to 4.0 MHz.

Antenna Height
and
Communications Effectiveness

Second Edition

A Guide for City Planners and Amateur Radio Operators

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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.

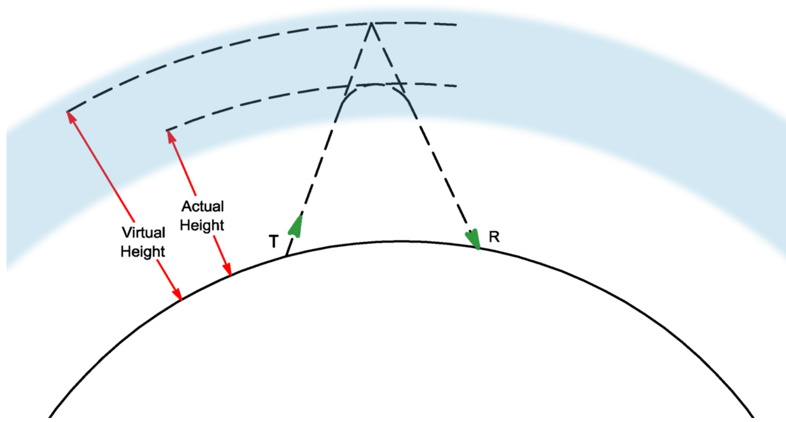

Fig 1—A simplified cross-sectional representation of ionospheric propagation. The simple triangle goes from the Transmitter T up to the virtual height and then back down to the Receiver R. Typically the F layer exists at a height of 150 miles above the Earth at mid-latitudes. The distance between T and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

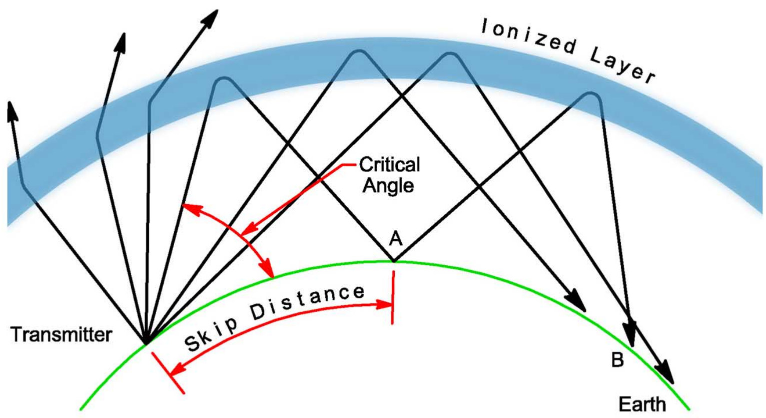

Fig 2—Behavior of radio waves encountering the ionosphere. Rays entering the ionized region at angles above the critical angle are not bent enough to return to Earth and are lost to space. Waves entering at angles below the critical angle reach the Earth at increasingly greater distances as the angle 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 (3^{rd}) hop, and only 1/10 of that 1/10 for the second additional (4^{th}) 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 30º, while the higher antenna has two main lobes, one peaking at 15º and the other at about 50º elevation angle.

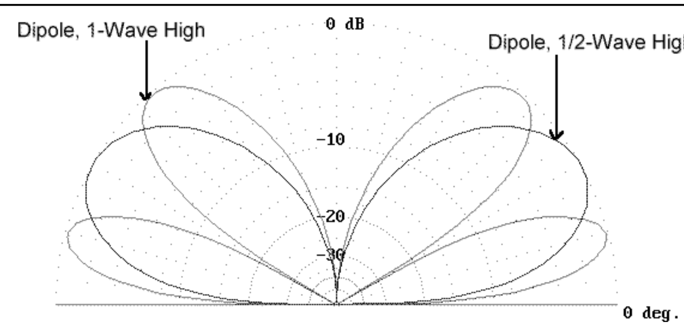

Fig 3–Comparison of elevation responses for two dipoles: one ½-wavelength high, and the other 1-wavelength high.

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 30º. 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 15º. 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 1º to 30º, Fig 4 shows the percentage of time when the 14-MHz band is open at each elevation angle. For example, 5º is the elevation angle that occurs just over 12% of the time when the band is available for communication, while 11º 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 1º to 28º.

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.

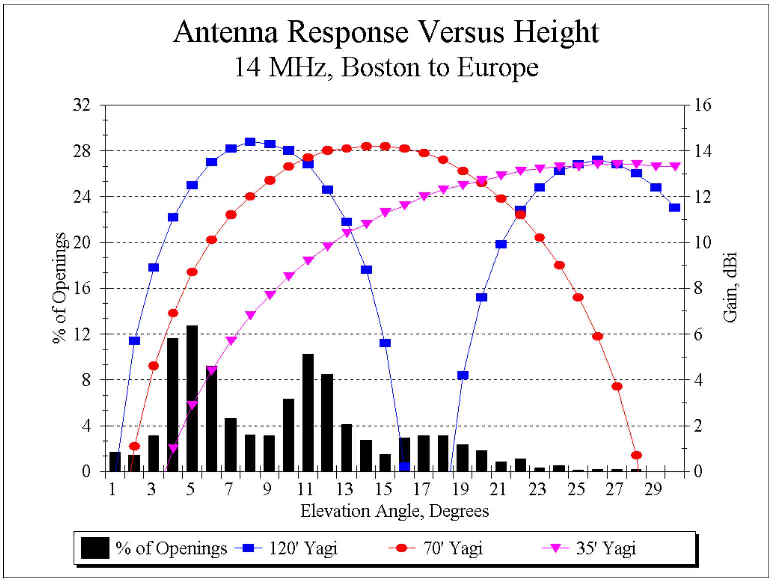

Fig 4—Elevation response patterns of three Yagis at 120, 70 and 35 feet, at 14 MHz over flat ground. The patterns are overlaid with the statistical elevation-angles for the path from Boston to continental Europe over the entire 11-year solar sunspot cycle. Clearly, the 120-foot antenna is the best choice 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 2º, 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.

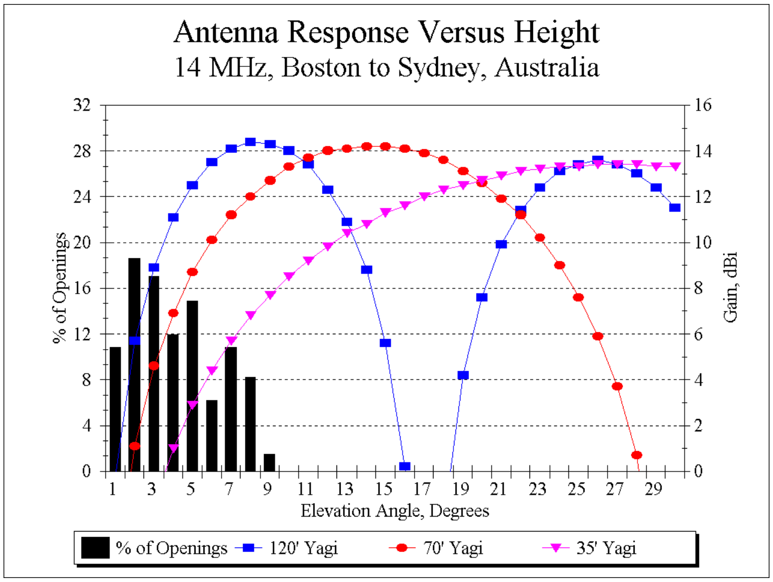

Fig 5—Elevation responses for same antennas as Fig 4, but for a longer-range path from Boston to Sydney, Australia. Note that the prevailing elevation angles are very low.

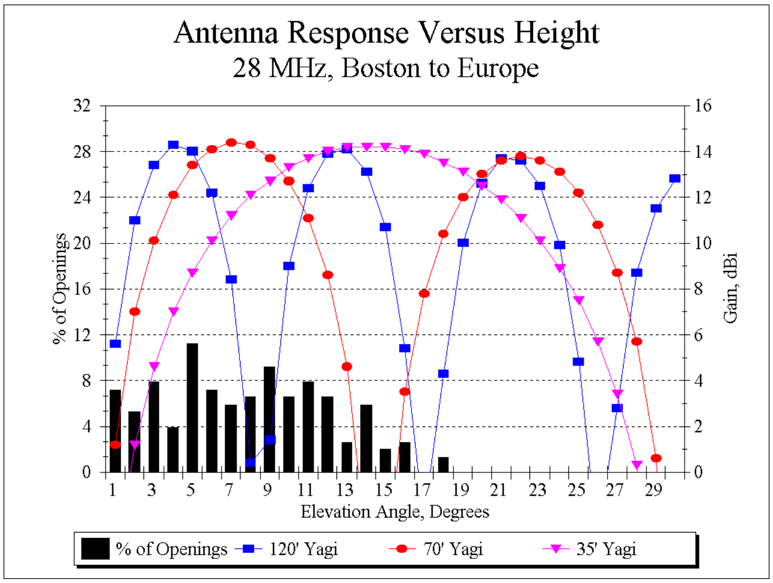

Fig 6—Elevation angles compared to antenna responses for 28-MHz path from Boston to Europe. The 70-foot antenna is probably the best overall choice on this path.

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.

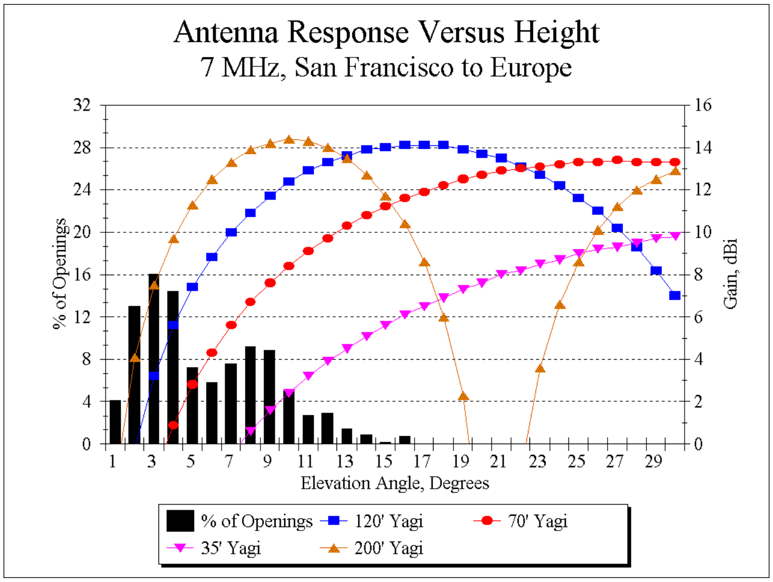

Fig 7—Comparison of antenna responses for another propagation path: from San Francisco to Europe on 7 MHz. Here, even a 120-foot high antenna is hardly optimal for the very low elevation angles required on this very long path. In fact, the 200-foot high antenna is far better suited for this path.

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.

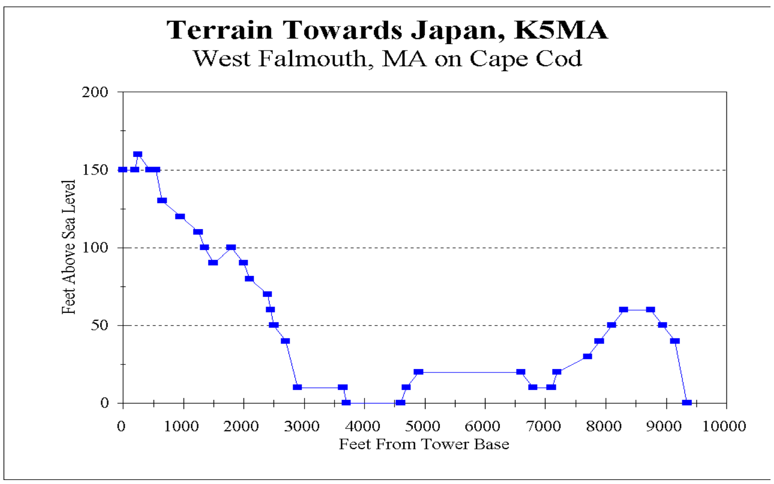

Fig 8—Terrain profile from location of K5MA, Jan Carman, in West Falmouth, MA, towards Japan. This is a moderately complicated real-world terrain on one of the highest hills on Cape Cod.

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.

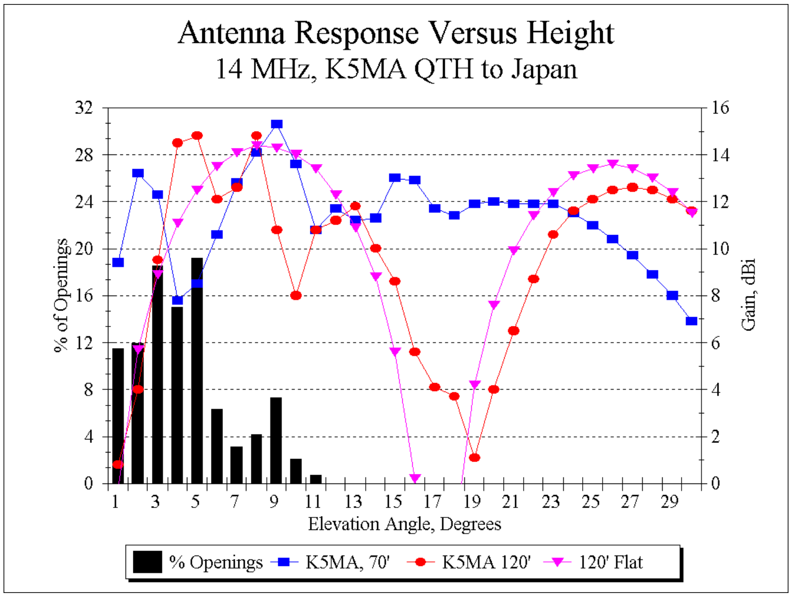

Fig 9—Computed elevation responses of 120- and 70-foot high Yagis, at the K5MA location on Cape Cod, in the direction of Japan and over flat ground, for comparison. The elevation response of the real-world antenna has been significantly modified by the local terrain.

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.

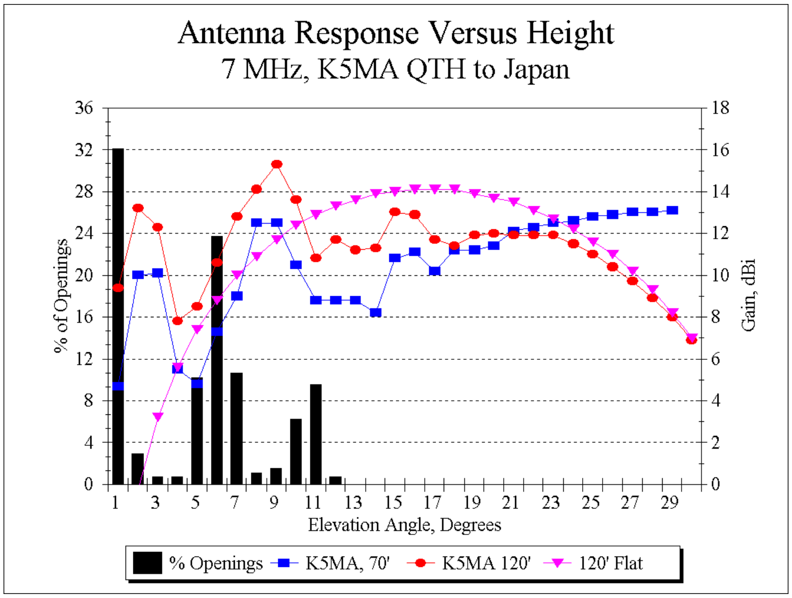

Fig 10—Elevation response on 7 MHz from K5MA location towards Japan on 7 MHz. The 120-foot high Yagi is definitely superior to the one only 70-feet high.

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.**