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Chapter 14 —
CD-ROM Content

Supplemental Articles
- "Station Design for DX, Part I" by Paul Rockwell, W3AFM
- "Station Design for DX, Part II" by Paul Rockwell, W3AFM
- "Station Design for DX, Part III" by Paul Rockwell, W3AFM
- "Station Design for DX, Part IV" by Paul Rockwell, W3AFM
- N6BV and K1VR Stack Feeding and Switching Systems

Chapter 14

HF Antenna System Design

This chapter combines information from previous editions into a condensed discussion of HF antenna system design. An amateur just beginning to build an HF station may be more interested in trying out different types of antennas and gaining experience with selecting, building and installing them. Later on, as experience is gained and specific goals are formed, the process of system design becomes important.

No single book can provide a step-by-step procedure for designing antenna systems — there are too many different needs and operating styles. What can be done, however, is to give an overview of the process by which system-level issues are identified and dealt with. Tools such as propagation prediction and antenna modeling software will be discussed from the antenna system perspective. Methods of using antennas to meet certain goals, such as stacking Yagis and using near vertical incidence skywave propagation (NVIS), will be covered.

By thinking about your "antenna farm" as a system — whether a single antenna in a tree or a multiple-tower contest station — you will be able to make better use of your time and materials and have more success on the air.

We will begin with an overview of the system design process and how to approach it. The next step is a section covering the use of propagation prediction tools as a means of assessing the coverage of an antenna system. Then the effects of local terrain on antenna system planning and performance are covered. The final sections address the use of vertical stacks of Yagi antennas to control elevation angle.

14.1 SYSTEM DESIGN BASICS

The most important time spent in putting together an antenna system is the time spent in planning. Later in this chapter the section on Local Terrain will present steps needed to evaluate how your local terrain can affect HF communications. You will need to compare the patterns resulting from your own terrain to the statistically relevant elevation angles needed for coverage of various geographic areas. (The elevation-angle statistics were discussed in the **Radio Wave Propagation** chapter and are located on the CD-ROM included with this book, as is the terrain-assessment program *HFTA*.)

The implicit assumptions in using propagation data and terrain analysis are (1) that you know where you want to talk to, and (2) that you'd like the most effective system possible. At the start of such a theoretical analysis, cost is no object. Practical matters, like cost or the desires of your spouse, can come later! After all, you're just checking out all the possibilities. If nothing else, you will use the methodology in this chapter to evaluate any property you are considering buying so that you can build your "dream station."

By using the techniques and tools available in this book, you can rationally and logically plan an antenna system that will be best suited for your own particular conditions. Now, however, you have to get practical. Thinking through and planning the installation can save a lot of time, money and frustration.

One often overlooked part of successful antenna system design (and station design, too) is the keeping of a station notebook. Make sure you save and organize the various computer files and documents associated with your system design. Being able to revisit the steps leading to a decision — successful or unsuccessful — is very important. Important data from measurements or tests should always be clearly labeled and stored so that you can find it later. Think of each page or file as a brick in the grand structure you are building. No one ever regrets having kept good records!

While no one can tell you the exact steps you should take in developing your own master plan, this section, prepared originally by Chuck Hutchinson, K8CH, should help you with some ideas.

14.1.1 DESIRES AND LIMITATIONS

Begin planning by spelling out your communications desires and the limitations placed on them. Engineers call these "requirements" and "constraints" — all successful projects begin with clearly understanding and recording them. What bands are you interested in? Who (or where) do you want to talk to? When do you operate? How much time and money are you willing to spend on an antenna system? What physical limitations affect your master plan?

From the answers to the above questions, begin to formulate goals — short, intermediate and long range. Be realistic about those goals. Remember that there are three station effectiveness factors that are under your control. These are: operator skill, equipment in the shack, and the antenna system. There is no substitute for developing operating skills. Some tradeoffs are possible between shack equipment and antennas. For example, a high-power amplifier can compensate for a less than optimum antenna but only for transmitted signals. By contrast, a better antenna has advantages for receiving as well as for transmitting.

Consider your limitations. Are there regulatory restrictions on antennas in your community? Are there any deed restrictions or covenants that apply to your property? Do other factors (finances, family considerations, other interests, and so forth) limit the type or height of antennas that you can erect? All of these factors must be investigated because they play a major role determining the type of antennas you erect.

Chances are that you won't be able to immediately do all you desire. Think about how you can budget your resources over a period of time. Your resources are your money, your time available to work, materials you may have on hand, friends that are willing to help, etc. One way to budget is to concentrate your initial efforts on a given band or two. If your major interest is in chasing DX, you might want to start with a very good antenna for the 14-MHz band. A simple multiband antenna could initially serve for other frequencies. Later you can add better antennas for those other bands.

14.1.2 SITE PLANNING

A map of your property or proposed antenna site can be of great help as you begin to consider alternative antennas.

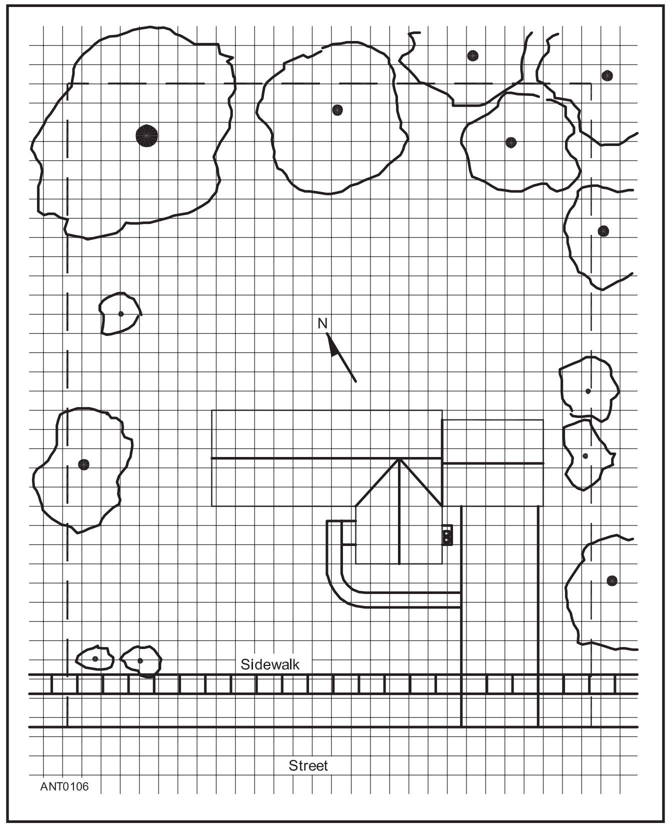

Figure 14.1 — A site map such this one is a useful tool for planning your antenna installation.

You'll need to know the size and location of buildings, trees and other major objects in the area. Be sure to note compass directions on your map. Graph or quadrille paper (or a simple CAD program) can be very useful for this purpose. See **Figure 14.1** for an example. It's a good idea to make a few photocopies of your site map so you can mark on the copies as you work on your plans. If you create a master map with CAD software, you can create and save lots of alternatives for comparisons and evaluations.

Use your map to plan antenna layouts and locations of any supporting towers or masts. If your plan calls for more than one tower or mast, think about using them as supports for wire antennas. As you work on a layout, be sure to think in three dimensions even though the map shows only two.

Be sensitive to your neighbors. A 70-foot guyed tower in the front yard of a house in a residential neighborhood is not a good idea (and probably won't comply with local ordinances!). You probably will want to locate that tower in the back yard.

Be sure to include restrictions and hazards on the map. For example, you may have set-back requirements from property lines for any structure on your property, such as a tower. You may not be allowed to intrude on neighboring "air space" with antenna elements. Power lines and other hazards such as buried utilities should be on your map, as well. It's just as important to identify where antennas can't go as where they can.

As discussed in the **Building Antenna Systems and**

Towers chapter, consider access needs when laying out your system. If you will be putting up towers, consider how a backhoe or concrete truck can get to the location of the tower base. You'll need to allow space for towers that fold over or that are tipped up for installation, too.

14.1.3 INITIAL ANALYSIS

Use the information in this chapter, antenna modeling software and propagation evaluation tools to analyze antenna patterns in both horizontal and vertical planes toward geographic areas of interest. Consider the azimuthal pattern of fixed antennas. You'll want to orient any fixed antennas to favor the directions of greatest interest to you.

Use antenna modeling tools to help you evaluate what type of antenna might be suitable to your own particular style of operating. Do you want a Yagi with a lot of rejection of received signals from the rear? Let's say that terrain analysis shows that you need an antenna at least 50 feet high. Do you really need a steel tower, or would a simple dipole in the trees serve your communication needs just fine? How about a vertical in your backyard? Would that be inconspicuous enough to suit your neighbors and your own family, yet still get you on the air?

If you want to work DX, you'll want antennas that radiate energy at low as well as intermediate angles. An antenna pattern is greatly affected by the presence of ground and by the local topography of the ground. Therefore, be sure to consider what effect ground will have on the antenna pattern at the height you are considering. A 70-foot high antenna is approximately ½, 1, 1½ and 2 wavelengths high on 7, 14, 21 and 28 MHz respectively. Those heights are useful for long-distance communications. The same 70-foot height represents only $\lambda/4$ at 3.5 MHz, however. Most of the radiated energy from a dipole at that height would be concentrated straight up. This condition is not great for long-distance communication, but can still be useful for some DX work and excellent for short-range communications.

Lower antenna heights can be useful for certain types of communications — see the section on NVIS communications later in this chapter, for example. However, for most amateur operation it is generally true that "the higher, the better" as far as communications effectiveness is concerned. This general rule of thumb, of course, should be tempered by an exact analysis of your local terrain. Being located at the top of a steep hill can mean that you can use lower tower heights to achieve good coverage.

There may be cases where it is not possible to install low-frequency dipoles $\lambda/4$ or more above the ground. A vertical antenna with many radials is a good choice for long-distance communications. You may want to install both a dipole and a vertical for the 3.5- or 7-MHz bands. On the 1.8-MHz band, unless extremely tall supports are available, a vertical antenna is likely to be the most useful for DXing. You can then choose the antenna that performs best for a given set of conditions. A low dipole will generally work better for shorter-range communications, while the vertical will generally be the better performer over longer distances.

The performance of ground-mounted monopole antennas depends strongly on a system of ground radials and the characteristics of the ground. Be sure to review this book's chapter **The Effects of Ground** when considering how and where to install the antenna. In particular, Al Christman, K3LC's article on maximizing the effectiveness of ground radials for a fixed amount of wire makes good economic sense for practical system builders.

14.1.4 BUILDING A SYSTEM PLAN

At this point, you will enter a repeated sequence of "design-model-adjust" as you evaluate the plan. You should start with modeling and then compare the results to those "desires" you wrote down at the beginning. With each round of modeling and comparison, your antenna system will be improved.

As you refine your system design, you can also build the long-term plan for construction of the antenna system. Chances are that you can divide the actual construction of your system into a series of phases or steps. By keeping the long-range plan in mind you will be able to make better decisions at every step of the way toward achieving your goals!

Say, for example, that you have lots of room and that your long-range plan calls for a pair of towers, one 100-feet high, and the other 70-feet high, to support monoband Yagi antennas. The towers will also support a horizontal 3.5-MHz dipole, for DX work. On your map you've located them so the 80 meter dipole will be broadside to Europe. You decide to build the 70-foot tower with a triband beam and 80 and 40 meter inverted-V dipoles to begin the project.

In your master plan you design the guys, anchors and all hardware for the 70-foot tower to support the load of stacked 4-element 10 and 15 meter monobanders Yagis. So you make sure you buy a heavy-duty rotator and the stout mast needed for the monoband antennas later because you have a long-range plan for them. Thus you avoid having to buy, and then sell, a medium-duty rotator and lighter weight tower materials later on when you upgrade the station. You could have saved money in the long run by putting up a monoband beam for your favorite band, but you decided that for now it is more important to have a beam on 14, 21 and 28 MHz, so you choose a commercial triband Yagi.

The second step of your plan calls for installing the second tower and stacking a 2-element 40 meter and a 4-element 20 meter monoband Yagi on it. You also plan to replace the tribander on the 70-foot tower with stacked 4-element 10 and 15 meter monoband Yagis. Although this is still a "dream system" you can now apply some of the modeling techniques discussed earlier in this chapter to determine the overall system performance.

14.1.5 MODELING INTERACTIONS

In this next step of analysis we're going to assume that you have sufficient real estate to separate the 70- and 100-foot towers by 150 feet so that you can easily support an 80 meter dipole between them. We'll also assume that you want the 80 meter dipole to have its maximum response

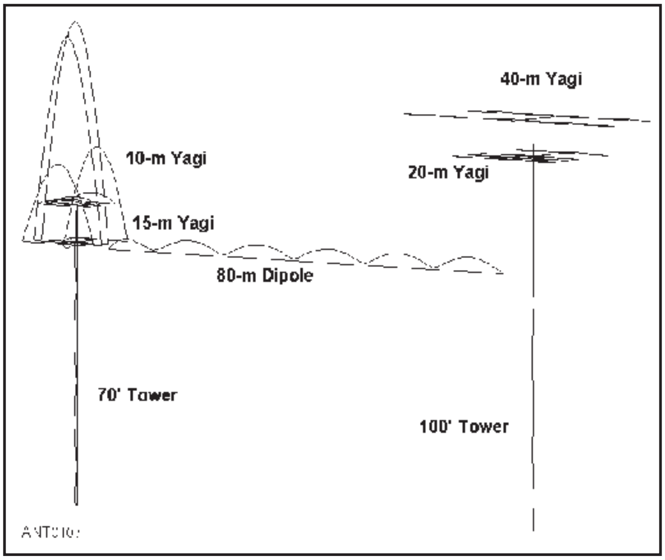

Figure 14.2 — Layout for two-tower antenna system, at 70 and 100 feet high and 150 feet apart. The 70-foot tower has a 4-element 10 meter Yagi at 80 feet on a 10-foot rotating mast and a 4-element 15 meter Yagi at 70 feet. An 80 meter dipole goes from the 70-foot tower to the 100-foot tower, which holds a 2-element 40 meter Yagi at 110 feet and a 4-element 20 meter Yagi at 100 feet. In this figure all the rotatable Yagis are facing the direction of Europe and the currents on the 15 meter Yagi are shown. Note the significant amount of current induced on the nearby 80 meter dipole that will cause a re-radiated signal!

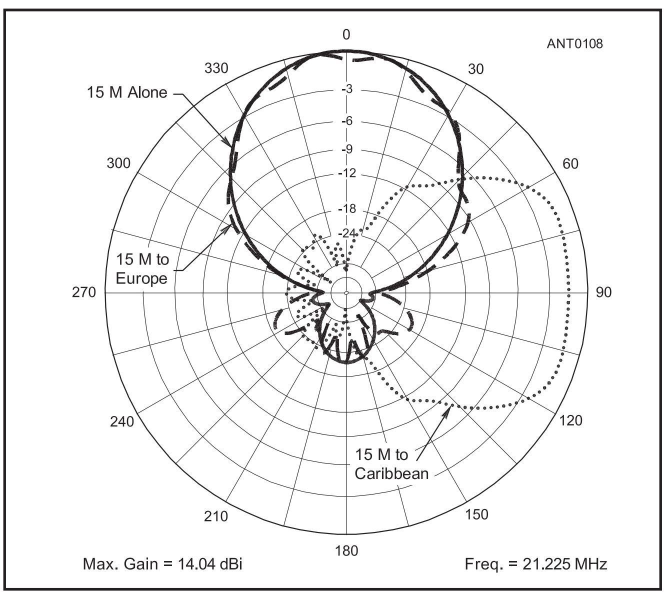

Figure 14.3 — An overlay of azimuth patterns. The solid line is the radiation pattern for the 15 meter Yagi all by itself. The dashed line is the pattern for the 15 meter Yagi, as affected by all the other antennas. The dotted line is the pattern for the 15 meter Yagi when it is pointed toward the Caribbean, with the Yagis on the 100-foot tower pointed toward the 70-foot tower. The peak response of the 15 meter Yagi has dropped by about 1.5 dB.

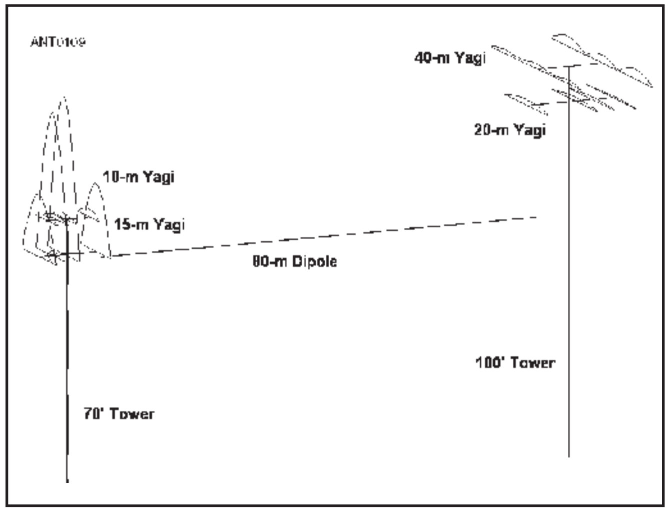

Figure 14.4 — The layout and 15 meter currents when the Yagis on the 100-foot tower are pointed toward the 70-foot tower. The 15 meter Yagi has been rotated to face the direction of the 100-foot tower (toward the Caribbean).

at a heading of 45° into Europe from your location in Newington, Connecticut. The dipole will also have a lobe facing 225° toward the USA and New Zealand, making it a good antenna for both domestic contacts and DX work. Note that it is important to model interactions for the full system even if you don't plan on building all of it right away. This helps avoid "mid-course corrections."

Let's examine the interactions that occur between the rotatable Yagis for 10, 15, 20 and 40 meters. See **Figure 14.2**, which purposely exaggerates the magnitude of the currents on the 4-element 15 meter Yagi mounted at 70 feet. Here, both sets of Yagis have been rotated so that they are pointing into Europe. There is a small amount of current radiated onto the 10 meter antenna but virtually no current is radiated onto the 40 and 20 meter Yagis. This is good.

However, significant current is picked up by the 80 meter dipole. This undesired current and the subsequent reradiated signal affects the radiation pattern of the 15 meter antenna, as shown in **Figure 14.3**, which overlays the pattern of the 4-element 15 meter Yagi by itself with that of the Yagi interacting with the other antennas. You can see "ripples" in the azimuthal response of the 15 meter Yagi due to the effects of the 80 meter dipole's re-radiation. The magnitude of the ripples is about 1 dB at worst, so they don't seriously affect the forward pattern (into Europe), but the rearward lobes are degraded somewhat, to just below 20 dB.

Figure 14.3 also shows the worst-case situation for the 15 meter Yagi. Here, the 15 and 10 meter stack has been turned clockwise 90°, facing the Caribbean, while the 40 and 20 meter Yagis on the 100-foot tower have been turned counter-clockwise 90° (in the direction of Japan) to face the 70-foot tower holding the 10/15 meter Yagis. You can see the layout and the currents in **Figure 14.4**. Now the 40 and 20 meter Yagis re-radiate some 15 meter energy and reduce the maximum gain by about 1.5 dB. Note that in this direction

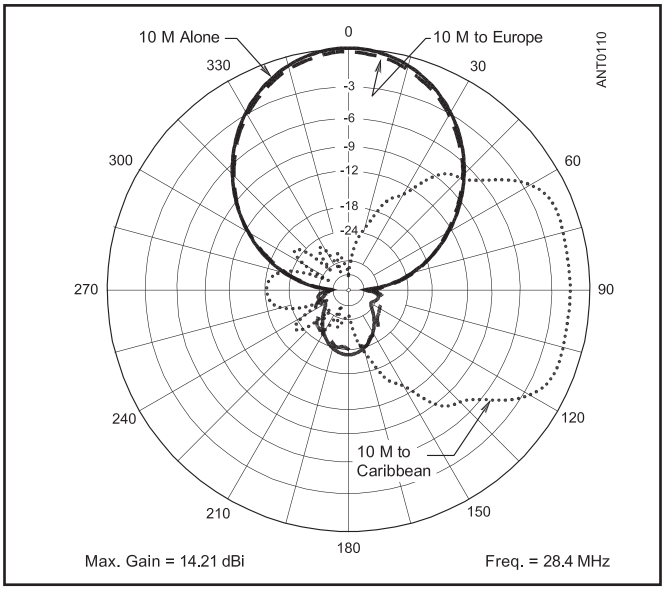

Figure 14.5 — The radiation patterns for the 10 meter Yagi. The solid line is the 10 meter Yagi by itself. The dashed line is for the same Yagi, with all other antenna interactions. The dotted line shows the worst-case pattern, with the stacked Yagis on the 100-foot tower facing the 70-foot tower and the 10 meter Yagi pointed toward the Caribbean. Again, the peak response of the 10 meter Yagi has dropped about 1.5 dB in the worst-case situation.

the 80 meter dipole no longer has 15 meter energy radiated onto it by the 15 meter Yagi.

The shape of the patterns will change depending on whether you specify "current" or "voltage" sources in the models for the other antennas, since this effectively opens up or shorts the feed points at the other antennas so far as 15 meter energy is concerned. In practice, this means that the interaction between antennas will vary somewhat depending on the length of the feed lines going to each antenna and whether each feed line is open-circuited or short-circuited when it is not in use.

You can now see that interactions between various antennas pointing in different directions can be significant in a real-world antenna system. In general, higher frequency antennas are affected by re-radiation from lower-frequency antennas, rather than the other way around. Thus the presence of a 10 or 15 meter stack does not affect the 20 meter Yagi at all.

Modeling can also help determine the minimum stacking distance required between monoband Yagis on the same rotating mast. In this case, stacking the 10 and 15 meter monobanders 10 feet apart holds down interaction between them so that the pattern and gain of the 10 meter Yagi are not impacted adversely. **Figure 14.5** demonstrates this in the European direction, where the patterns for the 10 meter beam by itself looks very clean compared to the same Yagi separated by 10 feet from the 15 meter Yagi below it. The worst-case situation is pointing toward the Caribbean, when the 40 and 20 meter stack is facing the 70-foot tower. This drops the 10 meter gain down about 1.5 dB from maximum, indicating significant interaction is occurring.

In this situation you might find it best to place the 70-foot tower in the direction closest to the Caribbean if this direction is very important to you. Doing so will, however, cause the pattern in the direction of the Far East to be affected on 10 and 15 meters. You have the modeling tools necessary to evaluate various configurations to achieve whatever is most important to you.

14.1.6 COMPROMISES

Because of limitations, most amateurs are never able to build their dream antenna system. This means that some compromises must be made. Do not, under any circumstances, compromise the safety of an antenna installation. Follow the manufacturer's recommendations for tower assembly, installation and accessories. Make sure that all hardware is being used within its ratings. (The ARRL document "Antenna Height and Communications Effectiveness" by Dean Straw, N6BV, and Jerry Hall, K1TD, may be of use in dealing with local regulatory agencies. It is available for downloading at **www.arrl.org/files/file/antplnr.pdf**.)

Guyed towers are frequently used by radio amateurs because they cost less than more complicated unguyed or freestanding towers with similar ratings. (See the chapter **Building Antenna Systems and Towers** for more information.) Guyed towers are fine for those who can climb or those with a friend who is willing to climb. But you may want to consider an antenna tower that folds over or one that cranks up (and down). Some towers crank up (and down) and fold over too. See **Figure 14.6**. That makes for convenient access to antennas for adjustments and maintenance without climbing. Crank-up towers also offer another advantage. They allow antennas to be lowered during periods of no operation, for aesthetic reasons, or during periods of high winds.

A well-designed monoband Yagi should outperform a multiband Yagi. In a monoband design the best adjustments can be made for gain, front-to-rear ratio (F/R) and matching, but only for a single band. In a multiband design, there are always tradeoffs in these properties for the ability to operate on more than one band. Nevertheless, a multiband antenna has many advantages over two or more single band antennas. A multiband antenna requires less heavy-duty hardware, requires only one feed line, takes up less space and it costs less.

Apartment dwellers face much greater limitations in their choice of antennas. For most, the possibility of a tower is only a dream. (One enterprising ham made arrangements to purchase a top-floor condominium from a developer. The arrangements were made before construction began, and the plans were altered to include a roof-top tower installation.) For apartment and condominium dwellers, the situation is still far from hopeless. The chapters **Stealth and Limited Space Antennas** and **Portable Antennas** present ideas for consideration.

14.1.7 SYSTEM DESIGN EXAMPLES

You can plan according to the preceding sections to put together modest or very large antenna systems. The process may sound intimidating but the hardest part is usually just

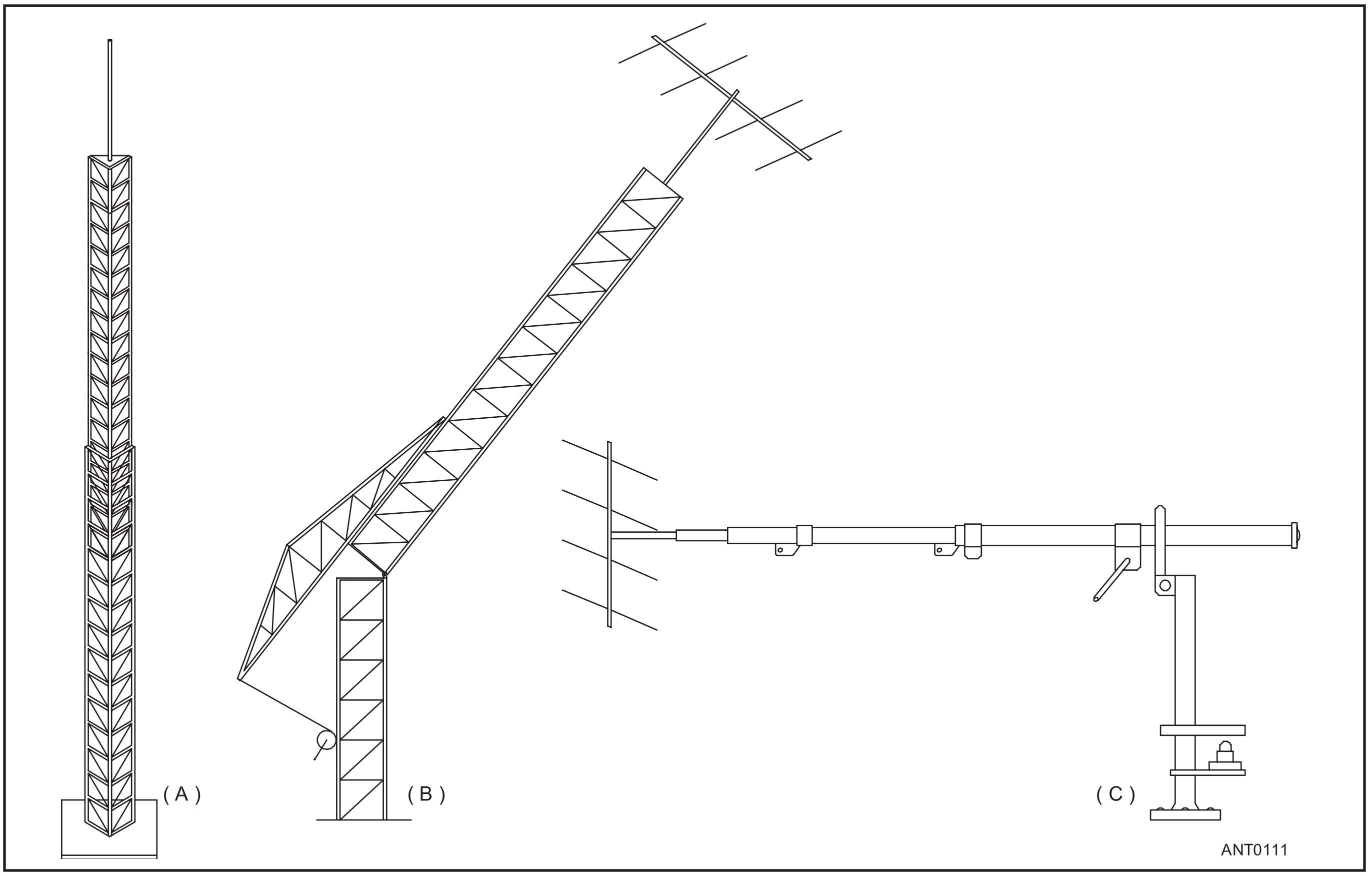

Figure 14.6 — Alternatives to a guyed tower are shown here. At A, the crank-up tower permits working on antennas at reduced height. It also allows antennas to be lowered during periods of no operation. Motor-driven versions are available. The fold-over tower at B and the combination at C permit working on antennas at ground level.

getting started! At this point, some simple examples might be instructive and encourage you to start planning.

Antenna System Example #1

What might a ham put together for antennas when he or she wants to try a little of everything, and has a modest budget? Let's suppose that the goals are (1) low cost, (2) no tower, (3) coverage of all HF bands and the repeater portion of one VHF band and (4) the possibility of working some DX.

After studying the pages of this book, the station owner decides to first put up a 135-foot center-fed antenna. High trees in the back yard will serve as supports to about 50 feet. This antenna will cover all the HF bands by using a balanced feeder and an antenna tuner. It should be good for DX contacts on 10 MHz and above and will probably work okay for DX contacts on the lower bands. However, her plan calls for a ground-mounted vertical and radial system for 3.5 and 7 MHz to enhance the DX possibilities on those bands. For VHF, a chimney-mounted vertical is included.

Antenna System Example #2

A licensed couple has bigger ambitions. Goals for their station are (1) a good setup for DX on 14, 21 and 28 MHz, (2) moderate cost, (3) one tower, (4) ability to work some DX on 1.8, 3.5 and 7 MHz, and (5) no need to cover the CW portion of the bands.

After considering the options, the couple decides to install a 65-foot guyed tower. A large commercial triband Yagi will be mounted on top of the tower. The center of a trap dipole tuned for the phone portion of the 3.5- and 7-MHz bands will be supported by a wooden yardarm installed at the 60-foot level of the tower, with ends drooping down to form an inverted-V. An inverted-L for 1.8 MHz starts near ground level and goes up to a similar yardarm on the opposite side of the tower. The horizontal portion of the inverted L runs away from the tower at right angles to the trap dipole. Later, the husband will experiment with sloping antennas for 3.5 MHz. If those experiments are not successful, a $\lambda/4$ vertical will be used on that band.

14.1.8 EMPIRICAL TESTING

Part of system design is "closing the loop" and evaluating the performance of what you have designed. If the performance is as expected, that validates your planning and design approach. If the performance isn't as expected, find out why and use that as a learning experience to improve your skills.

Unfortunately, many amateurs do not know how to evaluate performance scientifically or compare one antenna with another. Typically, they will put up one antenna and try it out on the air to see how it "gets out" in comparison with a previous antenna. This is obviously a very poor evaluation method because there is no way to know if the better or worse

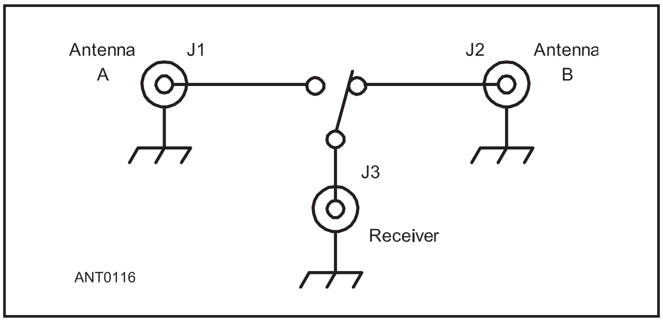

Figure 14.7 — When antennas are compared on fading signals, the time delay involved in disconnecting and reconnecting coaxial cables is too long for accurate measurements. A simple slide switch will do well for switching coaxial lines at HF. The four components can be mounted in a tin can or any small metal box. Leads should be short and direct. J1 through J3 are coaxial connectors.

reports are caused by changing band conditions, different S meter characteristics or any of several other factors that could influence the reports received.

Many times the difference between two antennas or between two different locations for identical antennas amounts to only a few decibels, a difference that is hard to discern unless instantaneous switching between the two is possible. Those few decibels are not important under strong signal conditions, of course, but when the going gets rough a few dB can make the difference between solid copy and no possibility of real communication.

Very little in the way of test equipment is needed for casual antenna evaluation, other than a communications receiver. You can even do a qualitative comparison by ear, if you can switch antennas instantaneously. Differences of less than 2 dB, however, are still hard to discern. The same is true of S meter readings. Signal strength differences of less than a decibel are usually difficult to see. If you want to measure that last fraction of a decibel, you should use a good ac voltmeter at the receiver audio output (with the AGC turned off).

In order to compare two antennas, switching the coaxial transmission line from one to the other is necessary. No elaborate coaxial switch is needed; even a simple double-throw toggle or slide switch will provide more than 40 dB of isolation at HF. See **Figure 14.7**. Switching by means of manually connecting and disconnecting coaxial lines is not recommended because that takes too long. Fading can cause signal-strength changes during the changeover interval.

Whatever difference shows up in the strength of the received signal will be the difference in performance between the two antennas in the direction of that signal. For this test to be valid, both antennas must have nearly the same feed point impedance, a condition that is reasonably well met if the SWR is below 2:1 on both antennas.

On ionospheric propagated signals (sky wave) there will be constant fading, and for a valid comparison it will be necessary to take an average of the difference between the two antennas. Occasionally, the inferior antenna will deliver a stronger signal to the receiver, but in the long run the law of averages will put the better antenna ahead.

Of course with a ground-wave signal, such as that from a station across town, there will be no fading problems. A ground-wave signal will enable the operator to properly evaluate the antenna under test in the direction of the source. The results will be valid for ionospheric-propagated signals at low elevation angles in that direction. On 28 MHz, all sky-wave signals arrive and leave at low angles. But on the lower bands, particularly 3.5 and 7 MHz, we often use signals propagated at high elevation angles, almost up to the zenith. For these angles a ground-wave test between local stations may not provide a proper evaluation of the antenna, and use of sky wave signals becomes necessary.

14.2 PROPAGATION AND COVERAGE

The section "Elevation Angles for HF Communication" in the **Radio Wave Propagation** chapter is an excellent introduction to the use of propagation prediction software such as *IONCAP* and *VOACAP* to assess the coverage of an HF antenna at different frequencies for a wide range of solar conditions. The CD-ROM included with this book includes a set of elevation angle statistics derived from these tools that you can use when designing your antenna system. The author of that elevation angle data and the editor of this book's previous edition, Dean Straw, N6BV, compiled a new and expanded set of data that is available from Radioware (**www.radio-ware.com**) at reasonable cost. The data set has been expanded to more than 240 locations around the world in all 40 CQ zones and covers the five primary HF amateur bands (80 through 10 meters) for 24 hours at six levels of solar activity. These tables show signal strength in S units for easier use by amateurs.

As you plan your antenna system, it is strongly recommended that you become familiar with at least one propagation prediction tool and undertake a study of propagation at your location to the areas of the world with which you want to communicate. Two descriptions of using propagation information are presented as examples of how understanding propagation can inform your antenna system design choices.

14.2.1 ELEVATION ANGLES FOR LOW-BAND DXING

In the chapter **Effects of Ground**, the importance was noted of matching the elevation response of your antennas as closely as possible to the range of elevation angles needed for communication with desired geographic areas. **Figure 14.8** shows the statistical 40 meter elevation angles needed over the entire 11-year solar cycle to cover the path from Boston, Massachusetts, to all of Europe. These angles range from 1° (at 9.6% of the time when the 40 meter band is open to Europe) to 28° (at 0.3% of the time). Creating an antenna

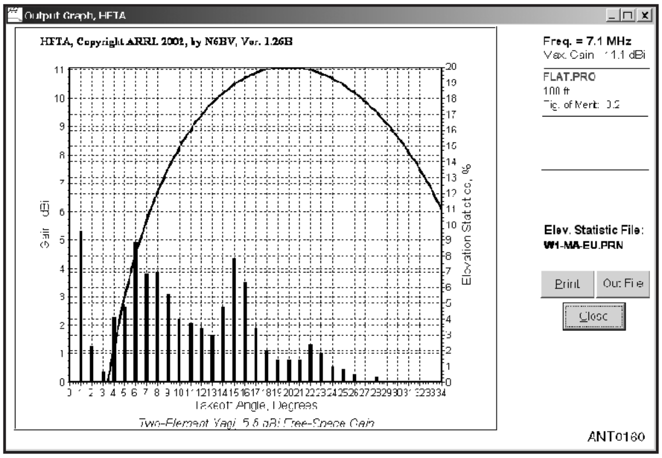

Figure 14.8 — Screen capture from HFTA (HF Terrain Assessment) program showing elevation response for 100-foot high dipole over flat ground on 7.1 MHz, with bar-graph overlay of the statistical elevation angles needed over the whole 11-year solar cycle from New England (Boston) to all of Europe. Even a 100-foot high antenna cannot cover all the necessary angles.

system that concentrates the radiated energy at these low elevation angles is crucial to work DX on the bands below 10 MHz.

Figure 14.8 also overlays the elevation pattern response of a 100-foot high flattop dipole on the elevation-angle statistics, illustrating that even at this height the coverage is hardly optimum to cover all the necessary elevation angles. While Figure 14.8 is dramatic in its own right, the data can be viewed in another way that emphasizes even more the importance of low elevation angles. **Figure 14.9** plots the *cumulative distribution function*, the total percentage of time 40 meters is open from Boston to Europe, at or below each elevation angle. For example, Figure 14.9 says that 40 meters is open to Europe from Boston 50% of the time at an elevation angle of 9° or less. The band is open 90% of the time at an elevation angle of 19° or less.

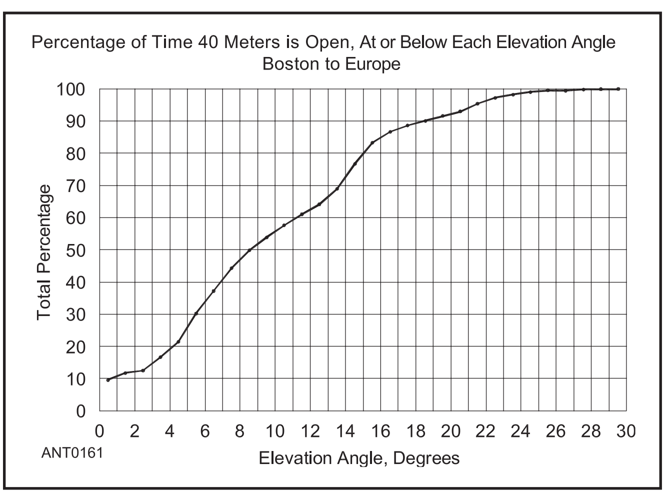

Figure 14.9 — Another way of looking at the elevation statistics from Figure 14.8. This shows the percentage of time the 40 meter band is open, at or below each elevation angle, on the path from Boston to Europe. For example, the band is open 50% of the time at an angle of 9° or lower. It is open 90% of the time at an angle of 19° or lower.

Figure 14.10 plots the 40 meter elevation-angle data for six major geographic areas around the world from Boston. In general, the overall range of elevation angles for far-distant locations is smaller, and the angles are lower than for closer-in areas. For example, from Boston to southern Asia (India), 50% of the time the takeoff angles are 4° or less. On the path to Japan from Boston, the takeoff angles is less than or equal to 6° about 70% of the time. These are low angles indeed.

Figure 14.11 shows similar data for the 40 meter band from San Francisco, California, to the rest of the world. The path to southern Africa from the US West Coast is a very long-distance path, open some 65% of the time it is open at angles of 2° or less! The 40 meter path to Japan involves takeoff angles of 10° or less more than 50% of the time. If you are fortunate enough to have a 100-foot high flattop dipole for 40 meters, at a takeoff angle of 10° the response would be down about 3 dB from its peak level at 20°. At an elevation angle of 5° the response would be about 8 dB down from peak. You can see why the California stations located on mountain tops do best on 40 meters for DXing.

Figure 14.12 shows the same percentage-of-time data for the 80 meter band from Boston to the world. Into Europe from Boston, the 80 meter elevation angle is 13° or less more than 50% of the time. Into Japan from Boston, 90% of the time the band is open is at a takeoff angle of 13° or less. (Note

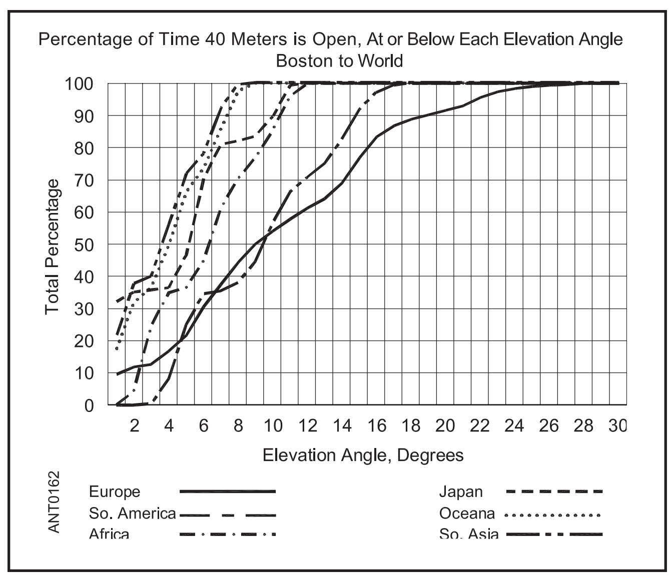

Figure 14.10 — The percentage of time the 40 meter band is open, at or below each elevation angle, for various DX paths from Boston: to Europe, South America, southern Africa, Japan, Oceania and south Asia. The angles are predominantly quite low. For example, on the path from Boston to Japan, 90% of the time when the 40 meter band is open, it is open at elevation angles less than or equal to 10°. Achieving good performance at these low takeoff angles requires very high horizontally polarized antennas, or efficient vertically polarized antennas.

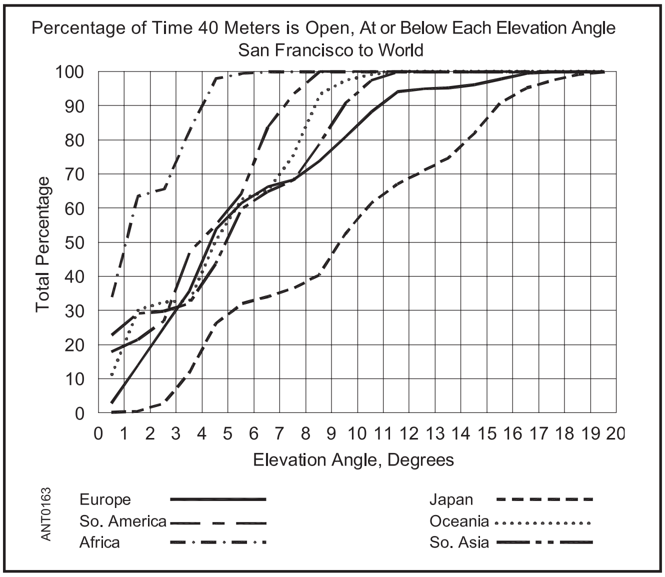

Figure 14.11 — The 40 meter statistics from the West Coast: from San Francisco to the rest of the DX world. Here, 90% of the time the path to Europe is open, it is at takeoff angles less than or equal to 11°. No wonder the hams living on mountain tops do best into Europe from the West Coast.

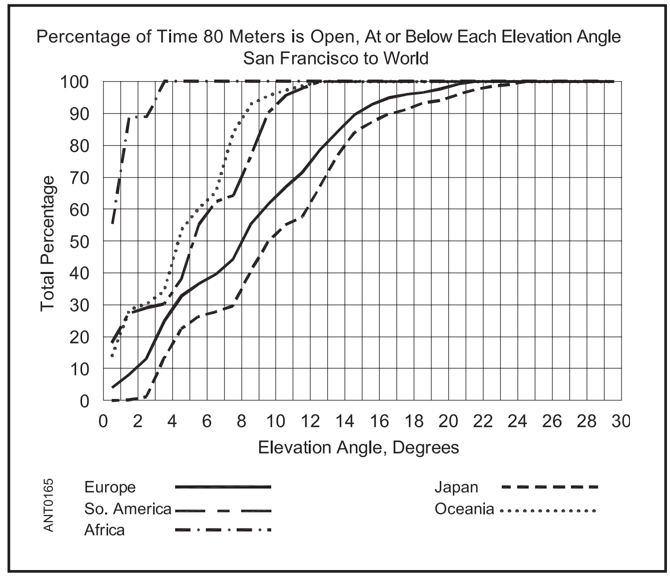

Figure 14.13 — From San Francisco to the rest of the world on 80 meters: 90% of the time on the path to Japan, the take-off angle is less than or equal to 17°; 50% of the time the angle is less than or equal to 10°; 25% of the time the angle is less than or equal to 6°. A horizontally polarized antenna would have to be 600 feet above flat ground to be optimum at 6°!

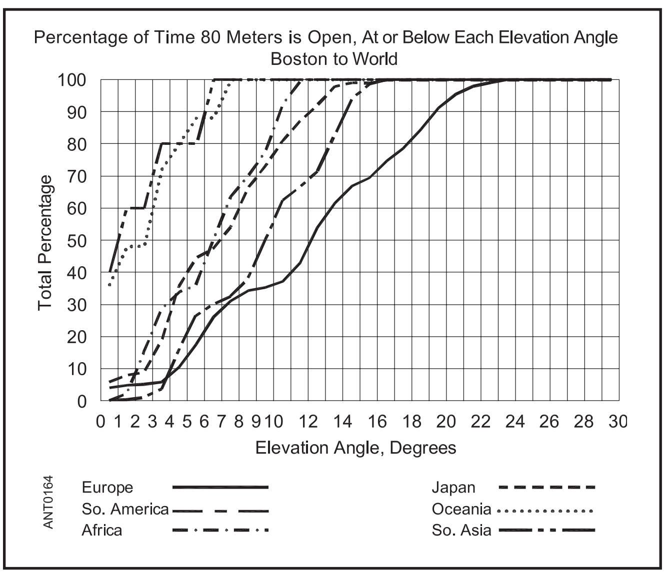

Figure 14.12 — The situation on 80 meters from Boston to the rest of the DX world. Into Europe, 90% of the time the elevation angle is less than or equal to 20°. Into Japan from Boston, 90% of the time the angle is less than or equal to 12°.

that these elevation statistics are computed for "undisturbed" ionospheric conditions. There are times when the incoming angles are affected by geomagnetic storms, and generally speaking the elevation angles rise under these conditions.)

Figure 14.13 shows the 80 meter data from San Francisco to the world. Low elevation angles dominate in this graph and high horizontal antennas would be necessary to optimal coverage. In fact, 50% of the time for all paths, the elevation angle is less than 10°.

14.2.2 NVIS COMMUNICATION

Not all hams are interested in working stations thousands of miles from them. Traffic handlers and rag chewers may, in fact, only be interested in *nearby* communications — perhaps out to 600 miles from their location. In such cases, the low elevation angles needed for effective DXing may be completely ineffective in providing the required short-range coverage.

For example, a ham in Boston may want to talk with his brother-in-law in Cleveland, Ohio, a path that is just over 550 miles away. Or an operator in Buffalo, New York, may be the net control station (NCS) for a regional net involving the states of New York and New Jersey. She needs to cover distances up to about 300 miles away.

Depending on the time of day, the most appropriate ham frequencies needed for nearby communications are the 40 and 80/75 meter bands, with 160 meters also a possibility during the night hours, particularly during low portions of the sunspot cycle. The elevation angles involved in such nearby distances are usually high, even almost directly overhead for distances beyond ground-wave coverage (which may be as short as a few miles on 40 meters). For example, the distance between the Massachusetts cities of Boston and Worcester is about 40 miles. On 40 meters, 40 miles is beyond ground-wave coverage. So you will need sky-wave signals that use the ionosphere to communicate between these two cities, where the elevation angle is 83° — very nearly straight up.

Hams using vertical antennas for communications with nearby stations may well find that their signals will be below the noise level typical on the lower bands, especially if they aren't running maximum legal power. Such relatively short-range paths involve what is called *NVIS*, "Near Vertical Incidence Skywave," a fancy name for HF communication systems covering nearby geographic areas. The US military discusses NVIS out to about 500 miles, encompassing the territory a brigade might cover. Elevation angles needed to cover distances from 0 to 500 miles range from about 40° to 90°. This also covers the circumstances involved in amateur communications, particularly in emergency situations. (An Internet group on NVIS, **groups.yahoo.com/neo/groups/NVIS/info**, focuses on antenna designs and techniques for NVIS communication.)

For the interested reader, a study of the use of NVIS communication is presented in "Near Vertical Incidence Skywave Propagation: Elevation Angles and Optimum Antenna Height for Horizontal Dipole Antennas" in the February 2015 issue of *IEEE Antennas and Propagation Magazine* by Ben Witvliet, PA5BW, and other researchers.

The following section is adapted from the article "What's the Deal About NVIS?" by Dean Straw, N6BV, that appeared in December 2005 *QST*. This article used an example of a hypothetical earthquake in San Francisco to analyze HF emergency communication requirements.

Ham Radio Response in Natural Disasters

One of San Francisco's somewhat less endearing nicknames is "the city that waits to die." When the *Big Earthquake* does come, you can be assured that all the cell phones and the land-line telephones will be totally jammed, making calling in or out of the San Francisco Bay Area virtually impossible. The same thing occurred in Manhattan on September 11, 2001. The Internet will also be severely affected throughout northern California because of its trunking via the facilities of the telephone network. Commercial electricity will be out in wide areas because power lines will be down.

Table 14.1
Average Elevation Angles for Target Destinations from San Francisco

Location	*Distance (Miles)*	*Average Elevation Angle (Degrees)*
San Jose, CA	43	80
Sacramento, CA	75	78
Fresno, CA	160	63
Reno, NV	185	60
Los Angeles	350	44
San Diego	450	42
Portland, OR	530	30
Denver, CO	950	18
Dallas, TX	1500	8

If the repeaters on the hills around the San Francisco Bay Area haven't been damaged by the shaking itself, there will be some ham VHF/UHF voice coverage in the intermediate area, at least until the backup batteries run down. But connecting to the dysfunctional telephone system will be difficult at best through amateur repeaters.

With little or no telephone coverage, an obvious need for ham radio communications to aid disaster relief would be from San Francisco to Sacramento, the state capital. Sacramento is 75 miles northeast of the Bay Area, well outside VHF/UHF coverage, so amateur HF will be required on this radio circuit. On-the-ground communications directly between emergency personnel (including the armed-forces personnel who will be brought into the rescue and rebuilding effort) will often be difficult on VHF/UHF since San Francisco is a hilly place. So HF will probably be needed even for short distance, operator-to-operator or operator-to-communications center work. Throughout the city, portable HF stations will have to be quickly set up and staffed to provide such communications.

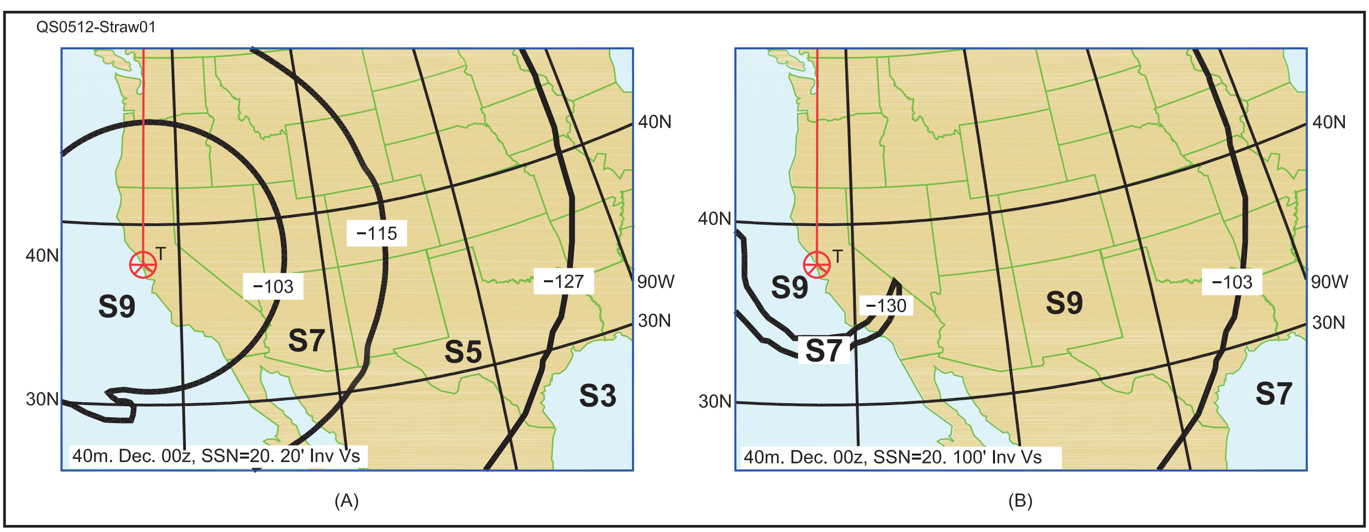

Figure 14.14 — At A, Predicted 40 meter geographic coverage plot for a 100 W transmitter in December at 0000 UTC (near sunset), for a SSN (Smoothed Sunspot Number) of 20. The antennas used are 20-foot-high inverted V dipoles. At B, 40 meter coverage for same date and time, but for 100-foot-high flattop dipoles. Most of California is well covered with S9 signals in both cases, but there is more susceptibility in the higher dipole case to thunderstorm crashes coming from outside California, for example from Arizona or even Texas. Such noise can interfere with communications inside California.

Hams used to half jokingly call short range HF communications on 40 and 80 meters "cloud warming." This is an apt description, because the takeoff angles needed to launch HF signals up into the ionosphere and then down again to a nearby station are almost directly upward. **Table 14.1** lists the distance and takeoff angles from San Francisco to various cities around the western part of the USA. The distance between San Francisco and Sacramento is about 75 miles, and the optimum takeoff angle is about 78°. Launching such a high-angle signal is best done using horizontally polarized antennas mounted relatively close to the ground, such as low dipoles.

Geographic Coverage for NVIS

Figure 14.14A shows the geographic area coverage around San Francisco for a 100-W station on 7.2 MHz using an inverted V dipole. The center of this antenna is 20 feet above flat ground and the ends are 8 feet high. An actual implementation of such an antenna could be as an 80 meter inverted V, fed in parallel with a 40 meter inverted V dipole at a 90° angle. See **Figure 14.15**. The 8-foot height puts the ends high enough to prevent RF burns to humans (or most animals). The low height of the antenna above ground means that the azimuthal pattern is omnidirectional for high elevation angles.

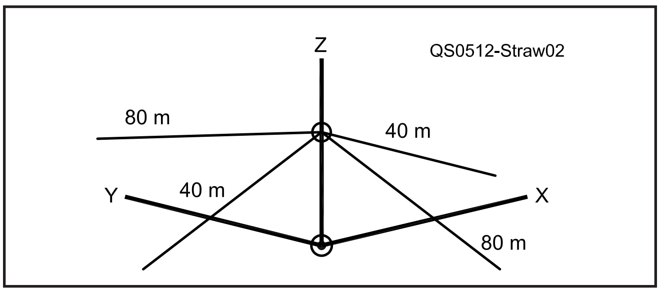

Figure 14.15 — Layout for two band inverted V dipoles for 40 and 80 meters. The two dipoles are fed together at the center and are laid out at right angles to each other to minimize interaction between them. Each end of both dipoles is kept 8 feet above ground for personal safety.

Figure 14.14 was generated using the *VOAAREA* program, part of the *VOACAP* propagation-prediction suite, for the month of December. This was for 0000 UTC, close to sundown, for a low period of solar activity (Smoothed Sunspot Number, SSN of 20). The receiving stations were also assumed to be using identical inverted-V dipoles.

You can see that almost the whole state of California is covered with S9 signals, minus only a thin slice of land near the Mexican border in the southeast portion of the state, where the signal drops to S7. Signals from Texas are predicted to be only S5 or less in strength. Signals (or thunderstorm static) coming from, say, Louisiana would be several S units weaker than signals from central Texas.

Now take a look at Figure 14.14B. Here, the date, time and solar conditions remain the same, but now the antennas are 100-foot high flattop dipoles. California is still blanketed with S9 signals, save for an interesting crescent-shaped slice near Los Angeles, where the signal drops down to S7. Close investigation of this intriguing drop in signal strength reveals that the necessary elevation angle, 44°, from San Francisco to this part of southern California falls in the first null of the 100-foot high antenna's elevation pattern. See **Figure 14.16**, which shows the elevation patterns for five 40 meter antennas at different heights. In the null at a 44° takeoff angle, the 100-foot high dipole is just about equal to a 2-foot high dipole. We'll discuss 2-foot high dipoles in more detail later.

For most of California, the problem with 100-foot high 40 meter antennas is that interfering signals from Texas, Colorado or Washington State will *also* be S9 in San Francisco. So will static crashes coming from thunderstorms

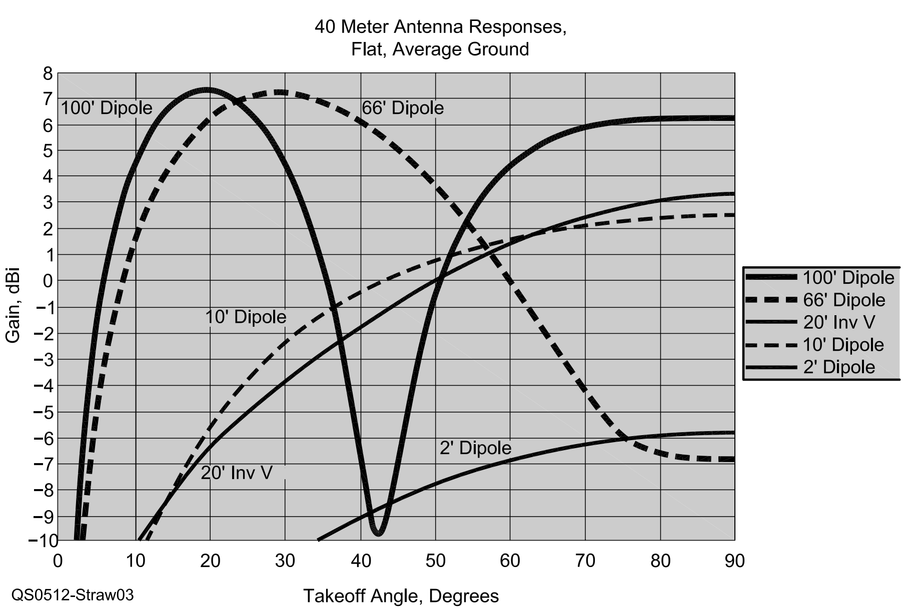

Figure 14.16 — Elevation plots for different 40 meter antennas above flat ground with average ground characteristics (5 mS/m conductivity and dielectric constant of 13). The 10-foot-high flattop dipole and the 20 foot-high inverted V dipoles both have close to the same characteristics. Note that there is a null in the response of the 100-foot-high flattop dipole at a 42° elevation angle. The gain there is roughly that of a 2 foot-high dipole!

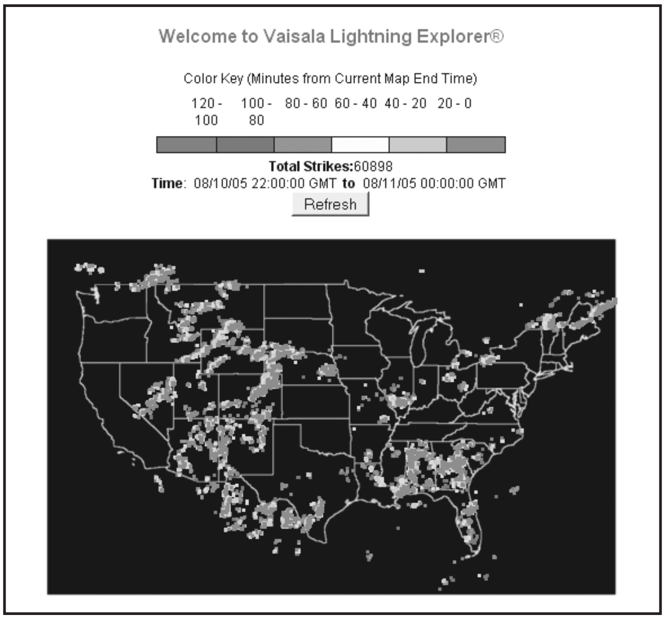

Figure 14.17 — The distribution of lightning strikes across the USA for August 10, 2005 from 2200 to 0000 UTC, in the afternoon California time. There are lots of lightning strikes in the US during the summer — 60,898 of them in this two-hour period! (Courtesy Vaisala Lightning Explorer.)

all over the West and much of the Gulf Coast. See **Figure 14.17**, which shows a typical distribution of thunderstorms across the US in the late afternoon, California time, in mid-August. There certainly are a lot of thunderstorms raging around the country in the summer.

The signal-to-noise and signal-to-interference ratios for a 20-foot high inverted V dipole will be superior for medium-range distances, say out to 500 miles from the center, compared to a 100-foot high antenna. The 20-foot high antenna can discriminate against medium-angle thunderstorm noise in the late afternoon coming from the Arizona desert, although it wouldn't help much for thunderstorms in the Sierra Nevada in central Nevada, which are arriving in San Francisco at high angles, along with the desired NVIS signals.

This is the essence of what NVIS means. NVIS exploits the difference in elevation pattern responses of low horizontally polarized antennas compared to higher horizontal antennas, or even verticals. Over the years, many hams have been lead to believe that higher is always better. This is not quite so true for consistent coverage of medium or short distance signals!

If NVIS only involved putting up a low horizontally polarized antenna on 40 meters the story would end here. However, real cloud warming is more complicated. It also involves the intelligent choice of more than just one operating frequency to achieve reliable all day, all-night communications coverage.

Figure 14.18 shows the signal strength predicted using *VOACAP* for the 350-mile path from San Francisco to Los Angeles for the month of December for a period of low solar activity (SSN of 20). The antennas used in this case are 10-foot high dipoles, just for some variety. These act almost like 20-foot high Inverted V dipoles. December at a low SSN was chosen as a worst-case scenario because the *winter solstice* occurs on December 21. This is the day that has the fewest hours of daylight in the year. (Contrast this with the *summer solstice*, on June 21, which has the most hours of daylight in the year.) Note that the upper signal limit in Figure 14.18 is "S10" — a fictitious quantity that allows easier graphing. S10 is equivalent to S9+, or at least S9+10 dB.

The 40 meter curve in Figure 14.18 shows that the MUF (maximum usable frequency) actually drops below the 7.2 MHz amateur band after sunset. The signal becomes

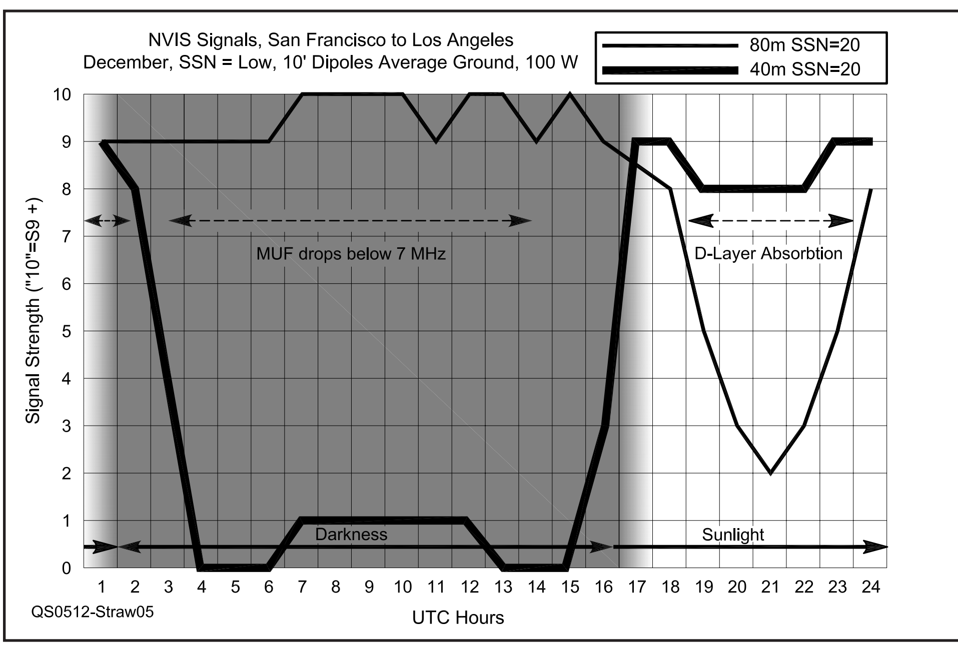

Figure 14.18 — VOACAP calculations for a 350 mile path from San Francisco to Los Angeles, using 10 foot-high flattop dipoles. This plot shows the signal strength in S units ("S10" = S9+10) for a worst-case month/SSN combination — winter solstice, in December, for a low level of solar activity (SSN = 20). The 40 meter signal drops to a very low level during the night because the MUF drops well below 7.2 MHz. The 80 meter signal drops in the afternoon because of D-layer absorption. For 24-hour communications on this path, the rule of thumb is to select 40 meters during the day and 80 meters during the night.

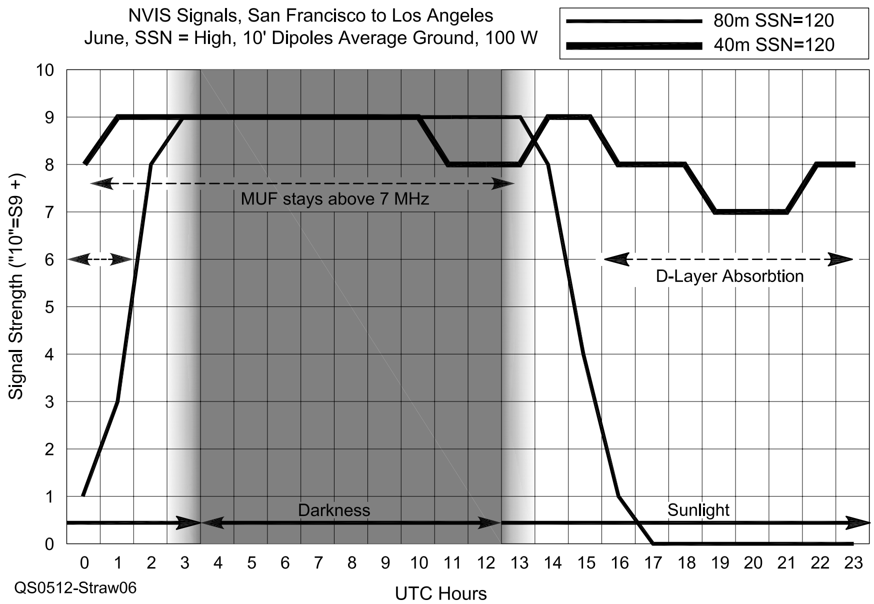

Figure 14.19 — Signal strengths for the San Francisco to Los Angeles path for a worst-case month/SSN combination — summer solstice, in June, for a high level of solar activity (SSN = 120). Now 80 meters drops out more dramatically during the daylight hours, due to increased D-layer absorption. At this high level of solar activity, 40 meters remains open 24 hours with reasonable signal levels. However, the NVIS rule-of-thumb still holds: Use 40 meters during the day; 80 meters at night.

quite weak for about 14 hours during the night, from about 0300 to 1700 UTC. In a period of low solar activity the 40 meter band thus becomes strictly a *daytime band* on this medium-distance path.

The 80 meter curve in Figure 14.18 shows strong signals after dusk, through the night and up until about an hour after sunrise. After sunrise, 80 meters starts to suffer absorption in the D layer of the ionosphere and hence the signal strength drops. Here, 80 meters is a true *nighttime band*.

Let's see what happens from San Francisco to Los Angeles during a period of high solar activity (SSN of 120) during the summer solstice in June. **Figure 14.19** shows that 40 meters now stays open all hours of the day due to the greater number of hours of sunlight in June and because the ionosphere becomes more highly ionized by higher solar activity. Meanwhile, 80 meters still remains a nighttime band during these conditions on this path.

Now, let's look at a shorter-distance path — our 75-mile emergency communications path from San Francisco to Sacramento. We'll again use June during the summer solstice, at a high level of solar activity (SSN of 120) because this represents another worst-case scenario. **Figure 14.20** shows that 40 meters remains open on this path all day, dropping to a lower signal level just before sunrise. At sunrise, the MUF drops close to 7.2 MHz. 80 meters is still mainly a nighttime band to Sacramento, even though it does

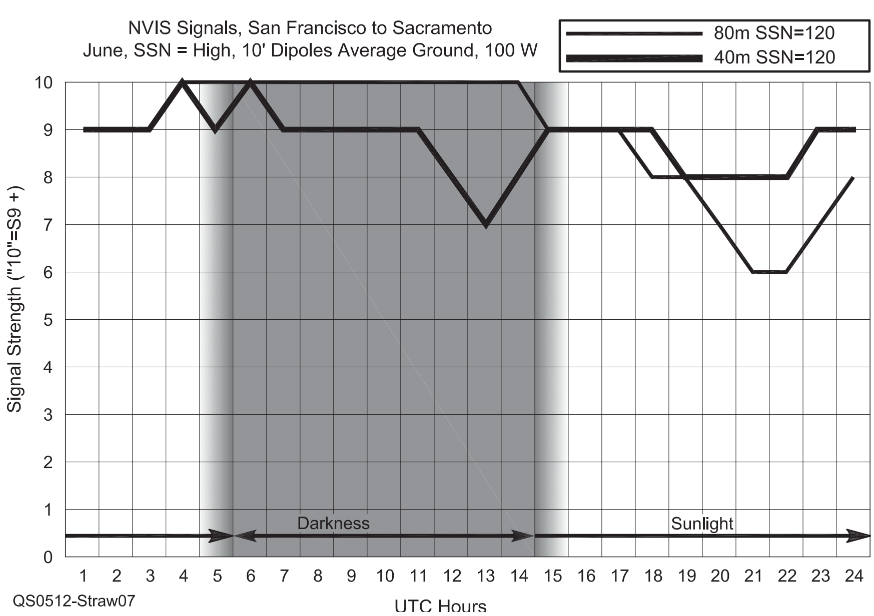

Figure 14.20 — Signal strengths for a 75 mile path — San Francisco to Sacramento. This is for June and SSN = 120. Either band could be used successfully over the full 24-hour period because signal levels are always higher than S6. But the simple NVIS rule-of-thumb still holds: Use 40 meters during the day; 80 meters at night. This simplifies giving instructions to operators unaccustomed to the use of HF.

yield workable signal levels even during the daylight hours. However, 40 meters is better from 1200 to 0400 UTC, so 40 would be still the right daytime band for this path during the day.

Choosing the Right NVIS Frequency

You can see that a pattern is developing here for efficient NVIS short/medium-distance communications out to 500 miles:

- You should pick a frequency on 40 meters during the day.
- You should pick a frequency on 80 meters during the night.
- You should choose an antenna that emphasizes moderate to high elevation angles, from 40° to almost directly overhead at 90°.

"What about 60 meters?" you might ask. The characteristics on 60 meters fall in between 40 and 80 meters, although it resembles 40 meters more closely. With characteristics close to that of 40, but with only five channels available and a 50-W power limit, the 60 meter band is of low utility for serious NVIS use.

What about 160 meters? For 100-W level radios, even at the worst-case month or during low solar activity, the critical frequency doesn't fall below 3.8 MHz often enough to destroy the ability to communicate, even for short distances. That is a relief, considering that installing a 160 meter half-wave dipole involves a 255-foot wingspan, and it would need to be elevated at least 30 feet in the center. A short loaded vertical such as a 160 meter mobile whip would have poor response at the high elevation angles needed for NVIS. You could probably put a monster 160 meter horizontal dipole up at a permanent location, but hauling such a thing around in the field would not be an easy task.

NVIS Strategy

You could pose the question about whether NVIS is an operating *mode* or whether it is actually an operating *strategy*. We maintain that NVIS is a strategy. It involves choosing both appropriate frequencies and then appropriate antennas for those frequencies. Figure 14.20 does show that on short-distance paths, such as between San Francisco and Sacramento, you could stay on 80 meters all day and night. But if you have to give a single rule-of-thumb to operators who are not very experienced at operating HF, we would tell them to operate on the higher frequency band during the day and on the lower frequency band at night.

Antenna Height for NVIS

Some NVIS aficionados have advocated placing dipoles only a few feet over ground, something akin to saying, "If low is good for NVIS, then lower must be even better." Now we are not claiming that a very low antenna *won't* work in specific instances — for example, covering a small state such as Rhode Island or even just the San Francisco Bay Area.

It certainly is convenient to mount a 40 meter dipole on some 2-foot high red traffic cones! You should be very skeptical, however, about the ability of such antennas to cover all of a large state, such as California or Texas, especially on 80 meters. **Figure 14.21** shows the computed elevation responses for a number of 80 meter antennas, including a 2-foot-high dipole. (In addition, ground losses increase dramatically as the antenna height is reduced. Mounting an antenna lower than 10 feet above ground is not recommended for safety reasons, as well — *Ed.*)

Figure 14.22B shows the 80 meter geographic coverage plot for 2-foot-high flattop dipoles, compared with the plot in Figure 14.22A for 20-foot-high inverted V dipoles on both ends of the path. The 2-foot-high dipoles produce about two S-units less signal across all of California than the 20-foot-high inverted V dipoles, at 0300 UTC in December, with an SSN of 20. The reason is that a low dipole will suffer more losses in the ground under it.

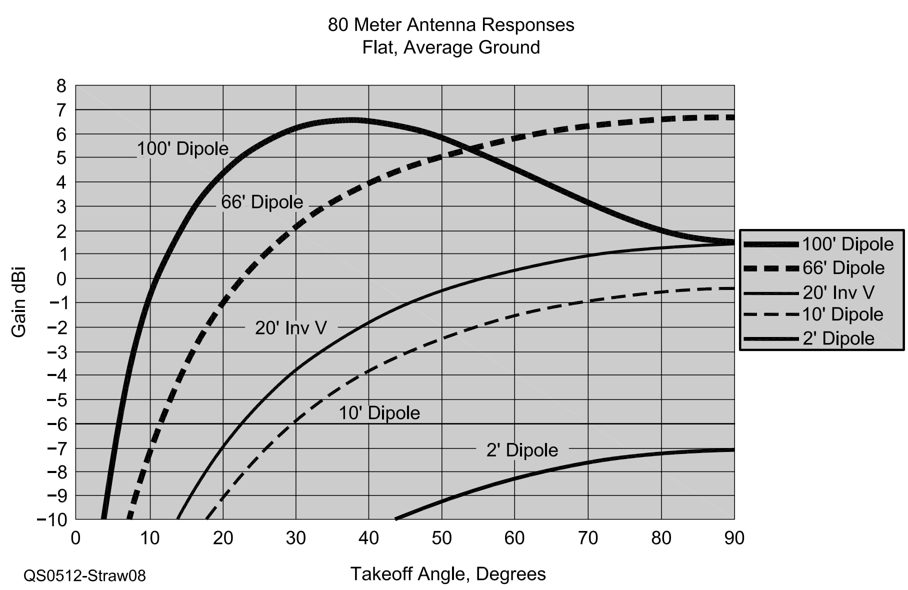

Figure 14.21 — Elevation response patterns for 80 meter antennas over average soil. The shapes track each other rather well, remaining parallel for heights from 2 to 66 feet over flat ground. The 2 foot dipole is substantially down, about 9 dB, from the 20 foot inverted V dipole at all angles.

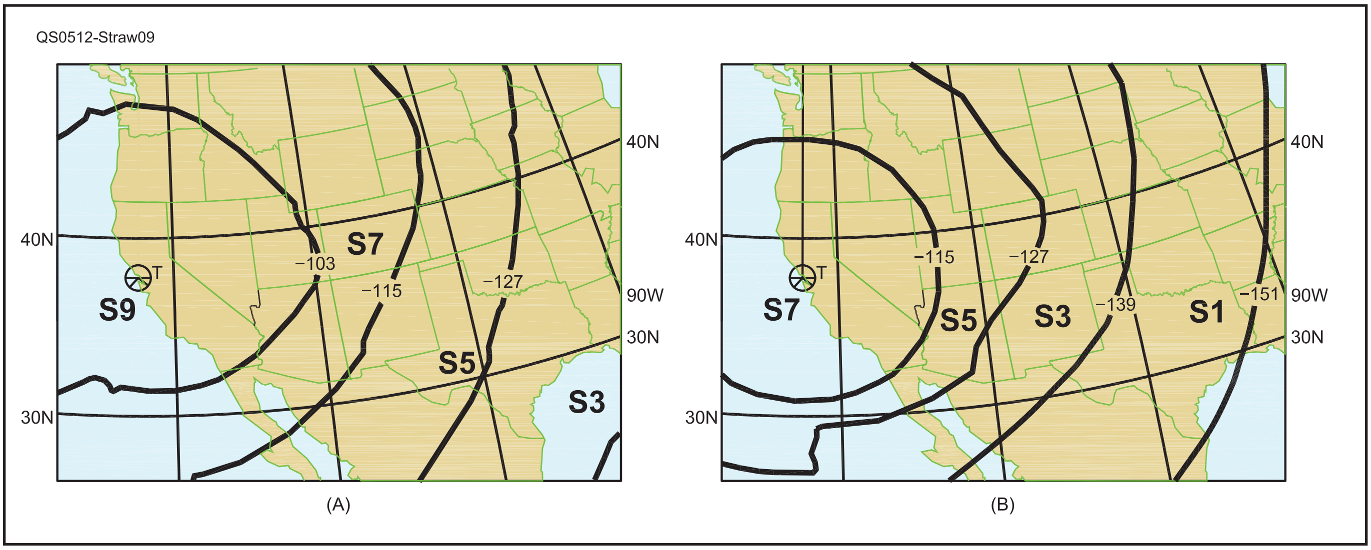

Figure 14.22 — Geographic coverage plots for December, SSN = 20, 0300 UTC. At A, antennas are 20-foot-high inverted V dipoles over Average soil. At B, antennas are 2-foot-high flattop dipoles over Average soil. The response for the 2-foot-high antennas is down about 2 S Units, 8 to 12 dB for a typical communications receiver.

The differential between California signals and possible interfering signals from, say, New Mexico, is predicted to be four S-units, the same as it is for the higher inverted V dipole at 20 feet. Thus there is no real advantage in terms of signal-to-interference ratio or signal-to-noise ratio (for thunderstorm static crashes) for either height. This is because the shape of all the response curves in Figure 14.21 below 20 feet essentially track each other in parallel.

However, the lower the antenna, the lower the transmitted signal strength. Physics remain physics. And if you are in an emergency situation operating on batteries, you could reduce power from 100 W to 10 W with a 20-foot high inverted-V antenna and still maintain the same signal strength as a 2-foot high dipole at 100 W.

Low NVIS Antennas and Local Power Line Noise

Some advocates of really low antennas have stated that the received noise is much lower than that received from higher antennas, and this therefore leads to better signal-to-noise ratios (SNR). How much this is true depends on the source of the noise. If the noise comes from distant thunderstorms, then the SNR advantage going to a 2-foot antenna from a 20-foot-high one is insignificant, as Figure 14.22 indicates.

If noise is from an arcing insulator on a HV power line half a mile away, that noise will arrive at the antenna as a ground-wave signal. We calculate that the 2-foot antenna receives 4.4 dB less noise by ground-wave than a 20-foot-high inverted V dipole. However, at an incoming elevation angle of 45° — suitable for a signal going from Los Angeles to San Francisco — the signal would be down 7.1 dB on the low dipole compared to the higher antenna. The net loss in SNR for the 2-foot-high dipole is thus 7.1– 4.4 or 2.7 dB. Close, but no cigar. Summarizing about really low NVIS antennas:

- A 2-foot-high dipole yields weaker signals, but without an SNR advantage compared to its more elevated brethren.
- A 2-foot-high dipole is a lot easier to trip over at night. We would call this a “knee biter.”
- You (and your dog) can easily get RF burns from an antenna that is only 2 feet off the ground.

This is not a winning strategy to make friends or QSOs, it seems. But still, a really low dipole may serve your short-range communication needs just fine. But remember, that just as “higher is better” isn’t universally true for NVIS (or even longer range) applications, “lower is better” isn’t a panacea either.

Elevation Angles for Moderate Distances on 75/80 Meters

Figure 14.23 shows the elevation angles statistics for a 75 meter, 550-mile path from Boston to Cleveland, together with overlays of the elevation patterns for several different types of antennas. These elevation statistics cover all parts of the 11-year solar cycle for this path. The responses for the popular G5RV antenna (see the **Multiband Antennas** chapter) are shown for two different heights above flat ground: 50 and 100 feet. An 80 meter half-wave sloper (“full sloper”) and an 80 meter ground-plane antenna are also shown. All antenna patterns are for “average ground” constants of 5 mS/m conductivity and a dielectric constant of 13.

At the statistically most significant takeoff angles around 50°, the two horizontally polarized G5RV antennas are about equal. At the second-highest elevation peak near 30°, the 100-foot G5RV has about a 4-dB advantage over its lower counterpart. The full sloper has comparable performance to the 100-foot high G5RV from 1° to about 20° and then gradually rises to its peak at angles higher than 70°. The full sloper is superior to the 50-foot horizontal G5RV at low takeoff elevation angles. The 80 meter ground plane has a deep null directly overhead. At an elevation angle of 70° it is down

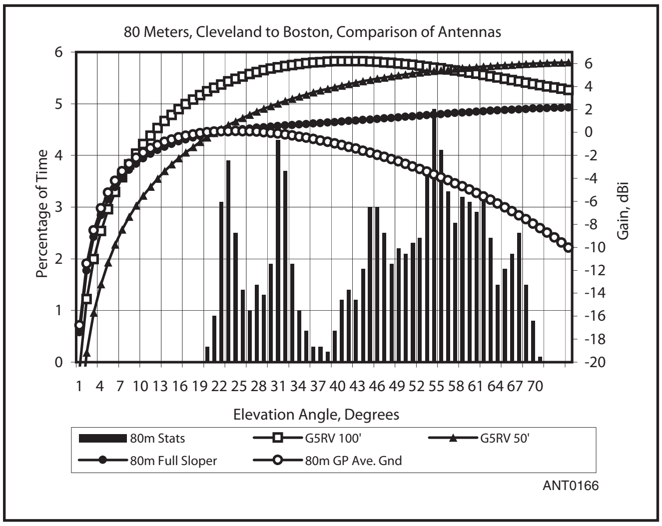

Figure 14.23 — 80/75 meter elevation statistics for all portions of the 11-year solar cycle for the path from Cleveland, Ohio, to Boston, Massachusetts, together with the elevation responses for four different multiband antennas. The 100-foot high horizontally polarized G5RV performs well over the entire range of necessary takeoff elevation angles.

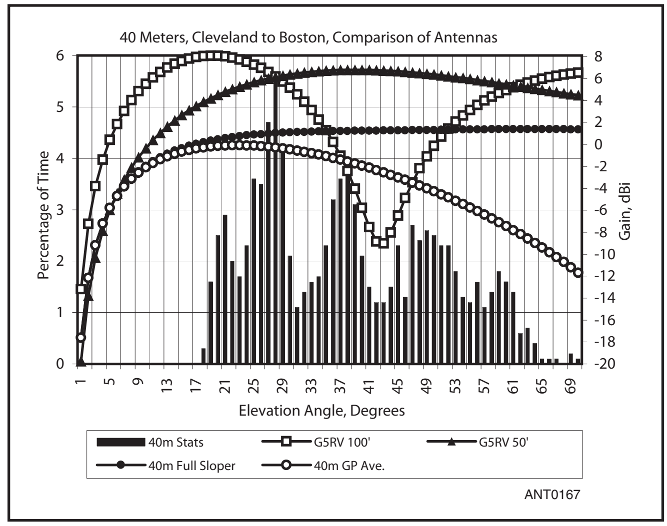

Figure 14.24 — 40 meter elevation statistics for the Cleveland to Boston path, together with elevation patterns for four antennas. Here, the 100-foot high horizontally polarized G5RV would have a null in the middle of the range of elevation angles needed for consistent performance on this path. For multiband use on this path to relatively nearby stations, the 50-foot high horizontal antenna would be a better choice than the 100-foot high antenna.

some 16 dB compared to the 50-foot high horizontal G5RV.

The advantage of antennas suitable for high-angle radiation was vividly demonstrated during a 75 meter QSO one fall evening between N6BV/1 in southern New Hampshire and W1WEF in central Connecticut. This involved a distance of about 100 miles and W1WEF was using his Four Square vertical array. Although W1WEF's signal was S9 on the Four Square, N6BV/1 suggested an experiment. Instead of connecting the so-called "dump power" connector on his Comtek ACB-4 hybrid phasing coupler to a 50-Ω dummy load (the normal configuration), W1WEF switched the dump power to his 100-foot high 80 meter horizontal dipole. W1WEF's signal came up more than 20 dB! The approximately 100-W of power that would otherwise be "wasted" in the dummy load was converted to useful signal.

Elevation Angles for Moderate Distances on 40 Meters

Figure 14.24 shows the situation for the 40 meter band, from Boston to Cleveland, together with the same antennas used for 80 meters in Figure14.23. Note that the 100-foot high horizontally polarized G5RV has about a 16-dB null at an elevation angle of 43°. This doesn't affect things for low elevation angles, but it certainly has a profound effect on signals arriving between about 30° to 60°, especially when compared to the 50-foot high horizontal G5RV. The 40 meter full sloper beats out the high horizontal antenna from about 35° to 50°. And the ground plane is obviously not the antenna of choice for this moderate-range path from Boston to Cleveland, although it is still a good performer on longer-distance paths, with their low takeoff angles.

A 100-foot high multiband dipole is about ⅜-λ high on 75/80 meters. It is an excellent antenna for general-purpose local and DXing operation. But the same dipole used on 40 meters becomes ¾-λ high. At that height, the nulls in its elevation pattern give large holes in coverage for nearby 40 meter contacts. Many operators have found that a 40- to 50-foot high dipole on 40 meters gives them far superior performance for close-in QSOs, when compared to a high dipole, or even a high 2-element 40 meter Yagi.

NVIS Summary

The use of NVIS strategies to cover close-in and intermediate distance communications within about 600 miles involves the intelligent choice of low HF frequencies. As a rule-of-thumb for ham band NVIS, 40 meters is recommended for use during the day; 80 meters during the night.

NVIS involves the choice of antennas suitable for this strategy. Horizontally polarized dual-band 80 and 40 meter flattop dipoles that are mounted higher than about 10 feet high will work adequately for portable operations. Dual-band 80 and 40 meter inverted V dipoles supported 20 feet above the ground at the center can also work well in portable operations.

Single-band 40 meter flattop antennas about 30 feet high and 80 meter flattop antennas about 60 feet high can do a good job for fixed locations.

14.3 EFFECTS OF LOCAL TERRAIN

The following material is condensed from an article by R. Dean Straw, N6BV, in July 1995 *QEX* magazine and updated for this edition. *HFTA* (HF Terrain Assessment) and supporting data files are included on this book's CD-ROM. *HFTA* is the latest version of the *YT* program included with earlier editions of *The ARRL Antenna Book*.

Prior to the introduction of this material, the last major study that appeared in the amateur literature on the subject of local terrain as it affects DX operation appeared in four *QST* "How's DX" columns, by Clarke Greene, K1JX, from October 1980 to January 1981. Greene's work was an update of a landmark series of 1966 *QST* articles entitled "Station Design for DX," by Paul Rockwell, W3AFM. The long-range profiles of several prominent, indeed legendary, stations in Rockwell's articles are fascinating: W3CRA, W4KFC and W6AM. (The articles by Rockwell are included on this book's CD-ROM.)

14.3.1 CHOOSING A QTH FOR DX

The subject of how to choose a QTH for working DX has fascinated hams since the beginning of amateur operations. No doubt, Marconi probably spent a lot of time wandering around Newfoundland looking for a great radio QTH before making the first transatlantic transmission. Putting together a high-performance HF station for contesting or DXing has always followed some pretty simple rules. First, you need the perfect QTH, preferably on a rural mountaintop or at least on top of a hill. Even better yet, you need a mountaintop surrounded by seawater! Then, after you have found your dream QTH, you put up the biggest antennas you possibly can, on the highest towers you can afford. Then you work all sorts of DX — sunspots willing, of course.

The only trouble with this straightforward formula for success is that it doesn't always work. Hams fortunate enough to be located on mountain tops with really spectacular drop-offs often find that their highest antennas don't do very well, especially on 15 or 10 meters, but often even on 20 meters. When they compare their signals with nearby locals in the flatlands, they sometimes (but not always) come out on the losing end, especially when sunspot activity is high.

On the other hand, when the sunspots drop into the cellar, the high antennas on the mountaintop are usually the ones crunching the pileups — but again, not always. So, the really ambitious contest aficionados, the guys with lots of resources and infinite enthusiasm, have resorted to putting up antennas at all possible heights, on a multitude of towers.

There is a more scientific way to figure out where and how high to put your antennas to optimize your signal during all parts of the 11-year solar cycle. We advocate the system approach to HF antenna system design, in which you need to know the following:

1) The range of elevation angles necessary to get from point A to point B

2) The elevation patterns for various types and configurations of antennas

3) The effect of local terrain on elevation patterns for horizontally polarized antennas.

14.3.2 REQUIRED RANGE OF ELEVATION ANGLES

Up until 1994, *The ARRL Antenna Book* contained only a limited amount of information about the elevation angles needed for communication throughout the world. In the 1974 edition, Table 1-1 in the Wave Propagation chapter was captioned: "Measured vertical angles of arrival of signals from England at receiving location in New Jersey."

What the caption didn't say was that Table 1-1 was derived from measurements made during 1934 by Bell Labs. The highest frequency data seemed pretty shaky, considering that 1934 was the low point of Cycle 17. Neither was this data applicable to any other path, other than the one from New Jersey to England. Nonetheless, many amateurs located throughout the US tried to use the sparse information in Table 1-1 as the only rational data they had for determining how high to mount their antennas. (If they lived on hills, they made estimates of the effect of the terrain, assuming that the hill was adequately represented by a long, unbroken slope. More on this later.)

In 1993 ARRL HQ embarked on a major project to tabulate the range of elevation angles from all regions of the US to important DX QTHs around the world. This was accomplished by running many thousands of computations using the *IONCAP* computer program. *IONCAP* has been under development for more than 40 years by various agencies of the US government and is considered the standard of comparison for propagation programs by many agencies, including the Voice of America, Radio Free Europe, and more than 100 foreign governments throughout the world. *IONCAP* is a real pain in the neck to use, but it is the standard of comparison.

The calculations were done for all levels of solar activity, for all months of the year, and for all 24 hours of the day. The results were gathered into some very large databases, from which special custom-written software extracted detailed statistics. The results appeared in summary form in Tables 4 through 13 printed in Chapter 23, Radio Wave Propagation, of the 17th Edition and in more detail on the diskette included with that book. (This book, the 23rd Edition, contains even more statistical data, for more areas of the world, on the accompanying CD-ROM. The author has also made available an expanded set of data through Radioware.)

Figure 14.25 shows the full range of elevation angles (represented as vertical bars) for the 20 meter path from New England (centered on Newington, Connecticut) to all of Europe. This is for all openings, in all months, over the entire 11-year solar cycle. The most likely elevation angle occurs at 5° for about 13% of the times when the 20 meter band is open to Europe from New England. The band is open from 4° to 6° a total of about 34% of the times the band is open. There is a secondary peak between 10° to 12°, occurring for a total of about 25% of the times the band is open.

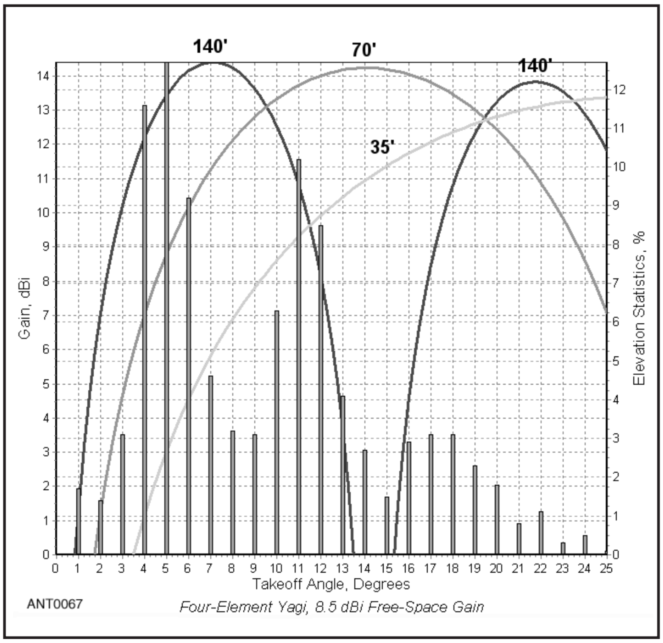

Figure 14.25 — Graph showing 20 meter percentage of all openings from New England to Europe versus elevation angles, together with overlay of elevation patterns over flat ground for three 20 meter antenna systems. The most statistically likely angle at which the band will be open is 5°, although at any particular hour, day, month and year, the actual angle will likely be different. Note the deep null exhibited by the 140-foot high antenna centered at 14°.

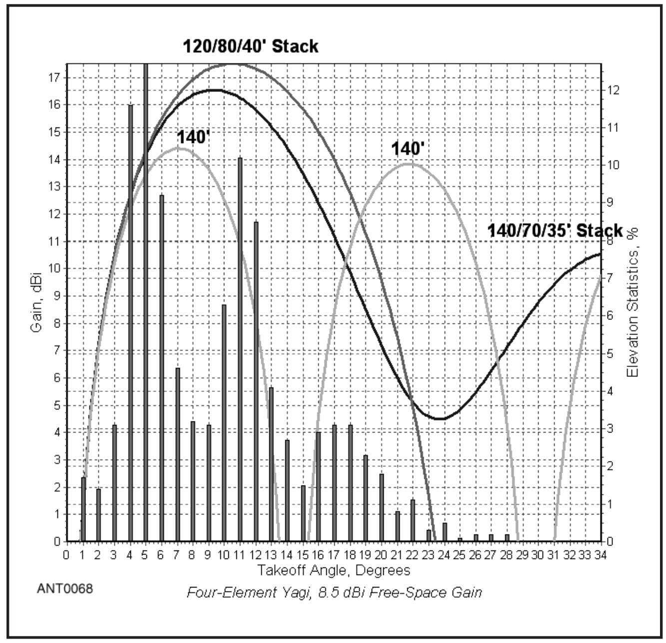

Figure 14.26 — Graph showing results of stacking antennas at different heights on the same tower to cover a wider range of elevation angles, in this case for the path from Connecticut (W1) to all of Europe on 20 meters. The optimized stack at 120/80/40 feet covers the needed range of elevation angles better than the stack at 140/70/35 feet or the single Yagi at 140 feet.

Overlaid on Figure 14.25 along with the elevation-angle statistics are the elevation-plane responses for three different horizontally polarized Yagi beams, all over flat ground. The first is mounted 140 feet high, 2 λ in terms of wavelength. The second Yagi is mounted 70 feet high (at 1 λ) and the third is 35 feet (0.5 λ). The 140-foot high antenna has a deep null at 15°, but it also has the highest response (13.4 dBi) of the three at the statistical peak elevation angle of 5°. However, at 12° — where the band is open some 9% of the time — the 140-foot high Yagi is down 4 dB compared to the 70-foot antenna.

The 70-foot high Yagi arguably covers the overall range best, since it has no disastrous nulls in the 1° to 25° range, where most of the action is occurring on 20 meters. At 5°, however, its response is only 8.8 dBi, 4.6 dB down from the 140-foot high antenna at that angle. The 35-foot antenna peaks above 26° in elevation angle, and is down some 10.4 dB compared to the 140-foot antenna at 5°. Obviously, no single antenna covers the complete range of elevation angles needed.

Note that the highest Yagi has a strong *second lobe* peaking at 22°. Let's say that you could select between two antennas, one at 140 and one at 70 feet, and that the incoming angle for a particular distant station is 22°. You might be fooled into thinking that the incoming angle is around 6°, favoring the first peak of the higher antenna, when in truth the angle is relatively high. The 70-foot antenna's response would be lower at 22° than the higher one, but only because the 140-foot antenna is operating on its second lobe. (What would clinch a determination of the correct incoming angle — 6° or 22° — would be the response of the 35-foot high Yagi, which would be close to its peak at 22°, while it would be very far down at 6°.)

Now, we must emphasize that these elevation angles are *statistical entities* — in other words, just because 5° is the "statistically most likely angle" for the 20 meter path from New England to Europe doesn't mean that the band will be open at 11° at any particular hour, on a particular day, in a particular month, in any particular year. In fact, however, experience agrees with the *IONCAP* computations: the 20 meter path to Europe usually opens at a low angle in the New England morning hours, rising to about 11° during the afternoon, when the signals remain strongest throughout the afternoon until the evening in New England.

What would happen if we were to feed all three Yagis at 140, 70 and 35 feet in-phase as a stack? **Figure 14.26** shows this situation, along with a more highly optimized stack at 120, 80 and 40 feet that better covers the overall range of elevation angles from Connecticut to Europe.

Now see **Figure 14.27**, which uses the same 120/80/40-foot stack of 20 meter antennas as in Figure 14.26, but this time from Seattle, Washington, to Europe. For comparison, the response of a single 4-element Yagi at 100 feet over flat ground is also shown in Figure 14.27. Just because 5° is the

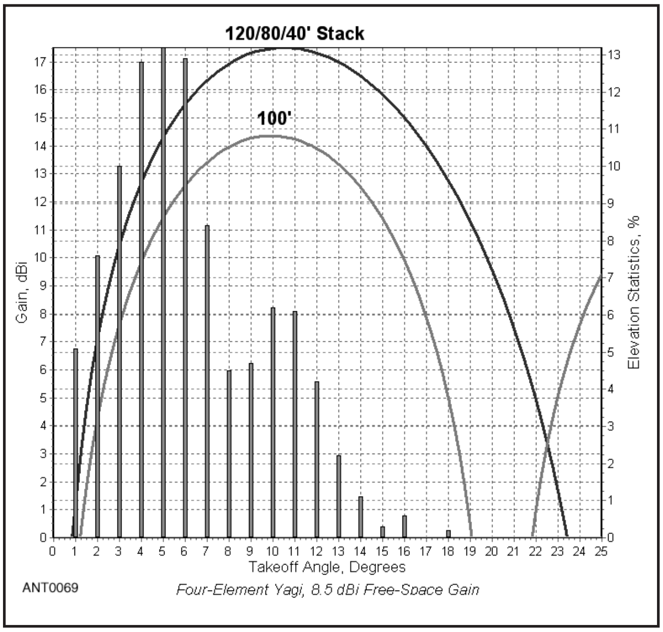

Figure 14.27 — Graph showing 20 meter percentage of all openings, this time from Seattle, WA, to Europe, together with an overlay of elevation patterns over flat ground for two 20 meter antenna systems. The statistically most likely angle on this path is 5°, occurring about 13% of the time when the band is actually open. Higher antennas predominate on this low-angle path.

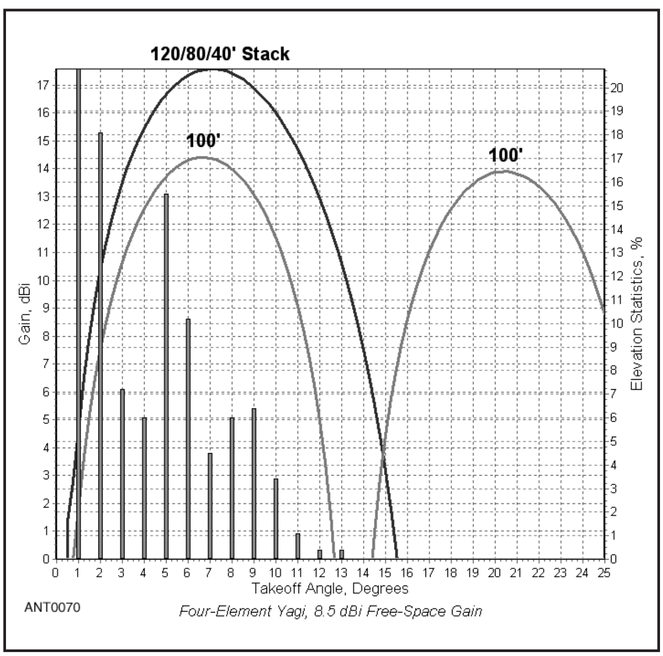

Figure 14.28 — Graph showing 15 meter percentage of all openings from Chicago to Southern Africa, together with overlay of elevation patterns over flat ground for two 15 meter antenna systems. On this long-distance, low-angle path, higher antennas are again most effective.

statistically most prevalent angle (occurring some 13% of the time) from Seattle to Europe on 20 meters, this doesn't mean that the actual angle *at any particular moment in time* might not be 10°, or even 2°. The statistics for W7 to Europe say that 5° is the most likely angle, but 20 meter signals from Europe arrive at angles ranging from 1° to 18°. Note that this range of angles is quite a bit less than from W1 to Europe, which is much closer geographically to Europe than is the Pacific Northwest coast of the US. If you design an antenna system to cover all possible angles needed to talk to Europe from Seattle (or from Seattle to Europe) on 20 meters, you would need to cover the full range from 1° to 18° equally well.

Similarly, if you wish to cover the full range of elevation angles from Chicago to Southern Africa on 15 meters, you would need to cover 1° to 13°, even though the most statistically likely signals arrive at 1°, for 21% of the time when that the band is open for that path. See **Figure 14.28**.

It is important to recognize that Figures 14.25 through 14.28 are for flat ground. When the antennas are mounted over irregular local terrain, things get much more complicated. First, however, we'll discuss general-purpose antenna modeling programs as they try to model real terrain.

14.3.3 DRAWBACKS OF COMPUTER MODELS OVER REAL TERRAIN

Modern general-purpose antenna modeling programs such as *NEC* or *MININEC* (or their commercially upgraded equivalents, such as *NEC-Win Plus* and *EZNEC*) can accurately model almost any type of antenna commonly used by radio amateurs. In addition, there are specialized programs specifically designed to model Yagis efficiently, such as *YW* (Yagi for *Windows*, bundled on the CD-ROM with this book). These programs however are all unable to model antennas accurately over anything other than *purely flat ground*.

While both *NEC* and *MININEC* can simulate irregular ground terrain, they do so in a decidedly crude manner, employing step-like concentric rings of height around an antenna. The documentation for *NEC* and *MININEC* both clearly state that diffraction off these steps is not modeled. Common experience among serious modelers is that the warnings in the manuals are worth heeding.

Although you can analyze and even optimize antenna designs using free-space or flat-earth ground models, it is *diffraction* that makes the real world a very, very complicated place. This should be clarified — diffraction is hard, even tortuous, to analyze properly, but it makes analysis of real world results far more believable than a flat-world reflection model does.

14.3.4 RAY-TRACING OVER UNEVEN LOCAL TERRAIN

The Ray-Tracing Technique

First, let's look at a simple ray-tracing procedure involving only horizontally polarized reflections, with no diffractions. From a specified height on the tower, an antenna shoots "rays" (just as though they were bullets) in 0.25° increments from +35° above the horizon to –35° below the horizon. Each ray is traced over the foreground terrain to see if it hits the ground at any point on its travels in the direction of interest. If it does hit the ground, the ray is reflected following the classical law of reflection. That is, the outgoing angle equals the incoming angle, reflected through the normal to the slope of the surface. Once the rays exit into the ionosphere, the individual contributions are vector-summed to create the overall far-field elevation pattern.

The next step in terrain modeling involves adding *diffractions* as well as reflections. At the Dayton antenna forum in 1994, Jim Breakall, WA3FET, gave a fascinating and tantalizing lecture on the effect of foreground terrain. Later Breakall, Dick Adler, K3CXZ, Joel Young and a group of other researchers published an extremely interesting paper entitled "The Modeling and Measurement of HF Antenna Skywave Radiation Patterns in Irregular Terrain" in the July 1994 *IEEE Transactions on Antennas and Propagation*. They described in rather general terms the modifications they made to the *NEC-BSC* program. They showed how the addition of a ray-tracing reflection and diffraction model to the simplistic stair-stepped reflection model in regular *NEC* gave far more realistic results. For validation, they compared actual pattern measurements made on a site in Utah (with an overflying helicopter) to computed patterns made using the modified *NEC* software. However, because the US Navy funded this work the software remained for a long time a military secret.

Thumbnail History of the Uniform Theory of Diffraction

It is instructive to look briefly at the history of how *Geometric Optics* (GO) evolved (and still continues to evolve) into the *Uniform Theory of Diffraction* (UTD). The following is summarized from the historical overview in one book found to be particularly useful and comprehensive on the subject of UTD: *Introduction to the Uniform Geometrical Theory of Diffraction*, by McNamara, Pistorius, and Malherbe.

Many years before the time of Christ, the ancient Greeks studied optics. Euclid is credited with deriving the law of reflection about 300 BC. Other Greeks, such as Ptolemy, were also fascinated with optical phenomena. In the 1600s, a Dutchman named Snell finally figured out the law of refraction, resulting in *Snell's law*. By the early 1800s, the basic world of classical optics was pretty well described from a mathematical point of view, based on the work of a number of individuals.

As its name implies, classical geometric optical theory deals strictly with geometric shapes. Of course, the importance of geometry in optics shouldn't be minimized — after all, we wouldn't have eyeglasses without geometric optics. Mathematical analysis of shapes utilizes a methodology that traces the paths of straight-line *rays* of light. (Note that the paths of rays can also be likened to the straight-line paths of particles.) In classical geometric optics, however, there is no mention of three important quantities: phase, intensity and polarization. Indeed, without phase, intensity or polarization, there is no way to deal properly with the phenomenon of *interference*, or its cousin, *diffraction*. These phenomena require theories that deal with *waves* rather than rays.

Wave theory has also been around for a long time, although not as long as geometry. Workers like Hooke and Grimaldi had recorded their observations of interference and diffraction in the mid 1600s. Huygens had used elements of wave theory in the late 1600s to help explain refraction. By the late 1800s, the work of Lord Rayleigh, Sommerfeld, Fresnel, Maxwell and many others led to the full mathematic characterization of all electromagnetic phenomena, light included.

Unfortunately, ray theory doesn't work for many problems, at least ray theory in the classical optical form. The real world is a lot more jagged, pointy and fuzzy in shape than can be described in a totally rigorous mathematic fashion. Some properties of the real world are most easily explained on the micro level using electrons and protons as conceptual objects, while other macro phenomena (like resonance, for example) are more easily explained in terms of waves. To get a handle on a typical real-world physical situation, a combination of classical ray theory and wave theory was needed.

The breakthrough in the combination of classical

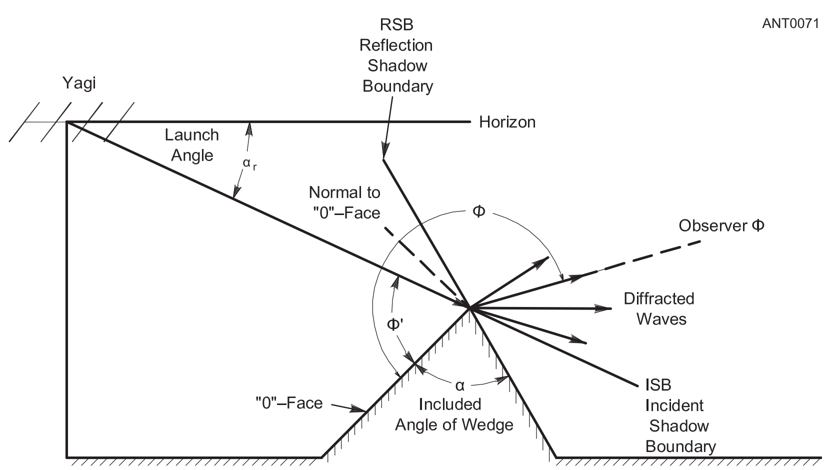

Figure 14.29 — Diagram showing diffraction mechanism of ray launched at angle α_r below the horizon at a diffraction wedge, whose included angle is α. Referenced to the incident face (the o-face as it is called in UTD terminology), the incoming angle is ϕ' (phi prime). The wedge creates an infinite number of diffracted waves. Shown is one whose angle referenced to the o-face is ϕ, the so-called observation angle in UTD terminology.

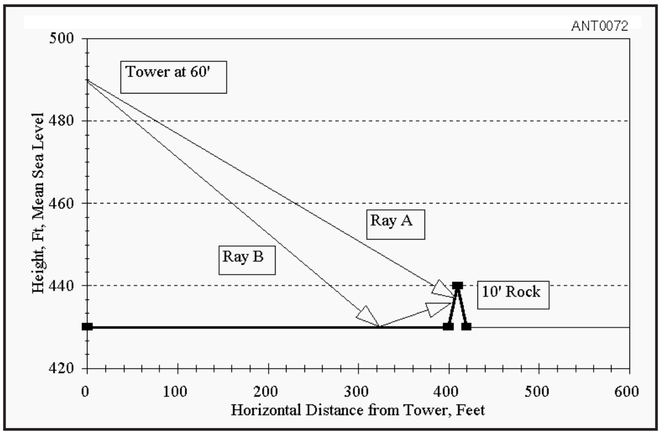

Figure 14.30 — Hypothetical terrain exhibiting so-called "10-foot rock effect." The terrain is flat from the tower base out to 400 feet, where a 10-foot high rock is placed. Note that this forms a diffraction wedge, but that it also blocks direct waves trying to shoot through it to the flat surface beyond, as shown by Ray A. Ray B reflects off the flat surface before it reaches the 10-foot rock, but it is blocked by the rock from proceeding further. A simple Geometric Optics (GO) analysis of this terrain without taking diffraction into account will result in the elevation response shown in Figure 14.31.

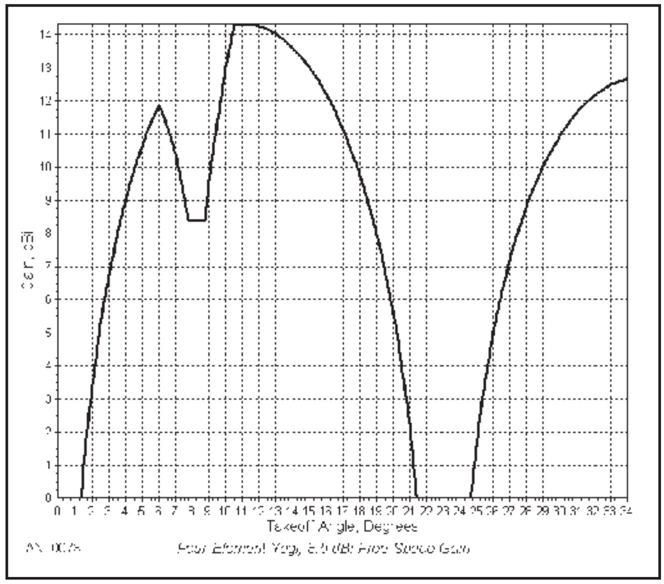

Figure 14.31 — Elevation response for rays launched at terrain in Figure 14.30 from a height of 60 feet using a 4-element Yagi. This was computed using a simple Geometrical Optics (GO) reflection-only analysis. Note the hole in the response between 6° to 10° in elevation. It is not reasonable for a 10-foot high rock to create such a disturbance at 21 MHz!

geometric optics and wave concepts came from J. B. Keller of Bell Labs in 1953, although he published his work in the early 1960s. In the very simplest of terms, Keller introduced the notion that shooting a ray at a diffraction *wedge* causes wave interference at the tip, with an infinite number of diffracted waves emanating from the diffraction point. Each diffracted wave can be considered to be a point source radiator at the place of generation, the diffraction point. Thereafter, the paths of individual waves can be traced as though they were individual classical optic rays again. What Keller came up with was a reasonable mathematical description of what happens at the tip of the diffraction wedge.

Figure 14.29 is a picture of a simple diffraction wedge, with an incoming ray launched at an angle of α_r, referenced to the horizon, impinging on it. The diffraction wedge here is considered to be perfectly conducting, and hence impenetrable by the ray. The wedge generates an infinite number of diffracted waves, going in all directions not blocked by the wedge itself. The amplitudes and phases of the diffracted waves are determined by the interaction at the wedge tip, and this in turn is governed by the various angles associated with the wedge. Shown in Figure 14.29 are the included angle α of the wedge, the angle ϕ' of the incoming ray (referenced to the incoming surface of the wedge), and the observed angle ϕ of one of the outgoing diffracted waves, also referenced to the wedge surface.

The so-called *shadow boundaries* are also shown in Figure 14.29. The Reflection-Shadow Boundary (RSB) is the angle beyond which no further reflections can take place for a given incoming angle. The Incident-Shadow Boundary (ISB) is that angle beyond which the wedge's face blocks any incident rays from illuminating the observation point.

Keller derived the amplitude and phase terms by comparing the classical Geometric Optics (GO) solution with the exact mathematical solution calculated by Sommerfeld for a particular case where the boundary conditions were well known — an infinitely long, perfectly conducting wedge illuminated by a plane wave. Simply speaking, whatever was left over had to be diffraction terms. Keller combined these diffraction terms with GO terms to yield the total field everywhere.

Keller's new theory became known as the *Geometric Theory of Diffraction* (abbreviated henceforth as GTD). The beauty of GTD was that in the regions where classical GO predicted zero fields, the GTD "filled in the blanks," so to speak. For example, see **Figure 14.30**, showing the terrain for a hypothetical case, where a 60-foot high 4-element 15 meter Yagi illuminates a wide, perfectly flat piece of ground. A 10-foot high rock has been placed 400 feet away from the tower base in the direction of outgoing rays. **Figure 14.31** shows the elevation pattern predicted using reflection-only GO techniques. Due to blockage of the direct wave (A) trying to shoot past the 10-foot high rock, and due to blockage of (B) reflections from the flat ground in front of the rock by the rock, there is a *hole* in the smooth elevation pattern.

Now, doesn't it defy common sense to imagine that a single 10-foot high rock will really have such an effect on a 15 meter signal? Keller's GTD took diffraction effects into account to show that waves do indeed sneak past and over the rock to fill in the pattern. The whole GTD scheme is very clever indeed.

However, GTD wasn't perfect. Keller's GTD predicts some big spikes in the pattern, even though the overall shape of the elevation pattern is much closer to reality than a simple GO reflection analysis would indicate. The region right at the RSB and ISB shadow boundaries is where problems are found. The GO terms go to zero at these points because of blockage by the wedge, while Keller's diffraction terms tend to go to infinity at these very spots. In mathematical terms this is referred to as a *caustic problem*. Nevertheless, despite these nasty problems at the ISB and RSB, the GTD provided a remarkably better solution to diffraction problems than did classical GO.

In the early 1970s, a group at Ohio State University under R. G. Kouyoumjian and P. H. Pathak did some pivotal work to resolve this caustic problem, introducing what amounts to a clever "fudge factor" to compensate for the tendency of the diffraction terms at the shadow boundaries to go to infinity. They introduced what is known as a *transition function*, using a form of Fresnel integral. Most importantly, the Ohio State researchers also created several *FORTRAN* computer programs to compute the amplitude and phase of diffraction components. Now computer hackers could get to work!

The ARRL program that finally resulted is called *HFTA*, standing for "HF Terrain Assessment," written by Dean Straw, N6BV. (An earlier DOS version of *HFTA* was known as *YT*, standing for "Yagi Terrain.") As the name suggests, *HFTA* analyzes the effect of local terrain on HF propagation through the ionosphere. It is designed for horizontally polarized Yagis at various heights, although it will model the effects of a simple flattop dipole also. The accurate appraisal of the effect of terrain on vertically polarized signals is a far more complex problem than for horizontally polarized waves, and *HFTA* doesn't do verticals. (*HFTA* is included on this book's CD-ROM.)

There are a set of help files available with *HFTA* that will be invaluable for first-time users. In addition the tutorial, "A Beginner's Guide to *HFTA* High Frequency Terrain Assessment" by John White, VA7JW is available online at **www.orcadxcc.org/content/VA7JW_HFTA_Manual.pdf**.

14.3.5 SIMULATION EXAMPLES

We want to focus first on some simple results, to show that the computations do make some sense by presenting some simulations over simple terrains. We've already described the "10-foot rock at 400 feet" situation, and showed where a simple GO reflection analysis is inadequate to the task without taking diffraction effects into account.

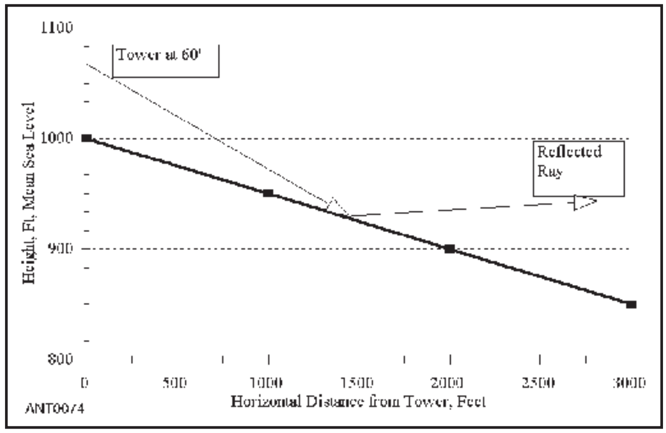

Figure 14.32 — A long, gentle downward-sloping terrain. This terrain has no explicit diffraction points and can be analyzed using simple GO reflection techniques.

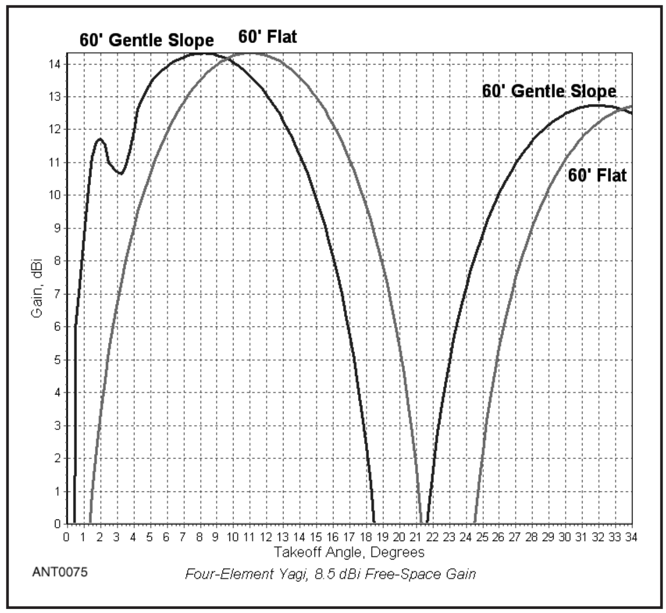

Figure 14.33 — Elevation response for terrain shown in Figure 14.32, using a 4-element 15 meter Yagi, 60 feet high. Note that the shape of the response is essentially shifted toward the left, toward lower elevation angles, by the angle of the sloping ground. For reference, the response for an identical Yagi placed over flat ground is also shown.

Simple Terrain Examples

Now look at the simple case shown in **Figure 14.32**, where a very long, continuous down-slope from the tower base is shown. Note that the scales used for the X- and Y-axes are different: the Y-axis changes 300 feet in height (from 800 to 1100 feet), while the X-axis goes from 0 to 3000 feet. This exaggerates the apparent steepness of the downward slope, which is actually a rather gentle slope, at $\tan^{-1}(1000 - 850) / (3000 - 0) = -2.86°$. In other words, the terrain falls 150 feet in height over a range of 3000 feet from the base of the tower.

Figure 14.33 shows the computed elevation response for this terrain profile, for a 4-element horizontally polarized Yagi on a 60-foot tower. The response is compared to that of an identical Yagi placed 60 feet above flat ground. Compared to the "flatland" antenna, the hilltop antenna has an elevation response shifted over by almost 3° toward the lower elevation angles. In fact, this shift is directly due to the –2.86° slope of the hill. Reflections off the slope are tilted by the slope. In this situation there is a single diffraction at the bottom of the gentle slope at 3000 feet, where the program assumes that the terrain becomes flat.

Look at **Figure 14.34**, which shows another simple terrain profile, called a "Hill-Valley" scenario. Here, the 60-foot high tower stands on the edge of a gentle hill overlooking a long valley. Once again the slope of the hill is exaggerated by

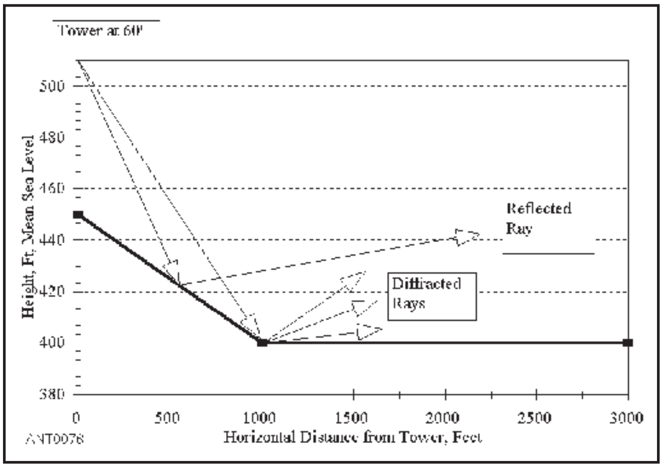

Figure 14.34 — "Hill-Valley" terrain, with reflected and diffracted rays.

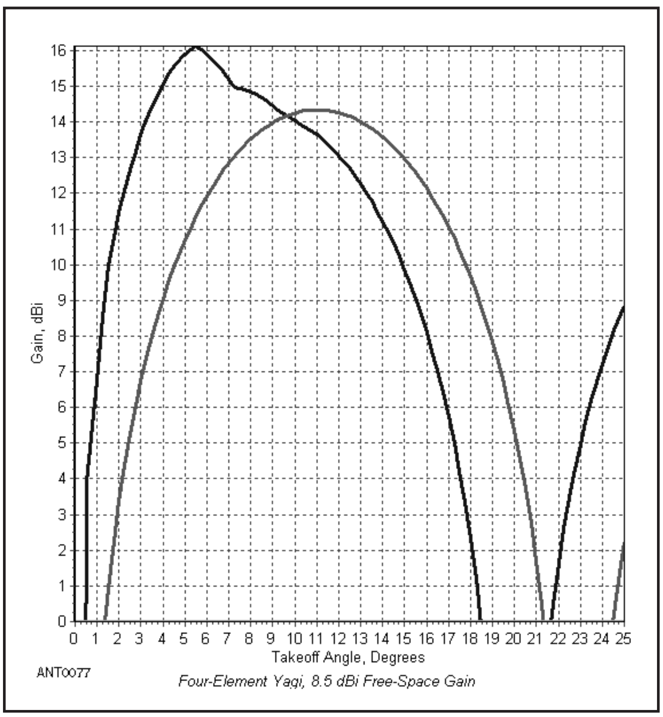

Figure 14.35 — Elevation response computed by HFTA program for single 4-element 15 meter Yagi at 60 feet above "Hill-Valley" terrain shown in Figure 14.34. Note that the slope has caused the response in general to be shifted toward lower elevation angles. At 5° elevation, the diffraction components add up to increase the gain slightly above the amount a GO-only analysis would indicate.

the different X and Y-axes. **Figure 14.35** shows the computed elevation response at 21.2 MHz for a 4-element Yagi on a 60-foot high tower at the edge of the slope.

Once again, the pattern is overlaid with that of an identical 60-foot-high Yagi over flat ground. Compared to the flatland antenna, the hilltop antenna's response above 9° in elevation is shifted by almost 3° toward the lower elevation angles. Again, this is due to reflections off the downward slope. From 1° to 9°, the hilltop pattern is enhanced even more compared to the flatland antenna, this time by diffraction occurring at the bottom of the hill.

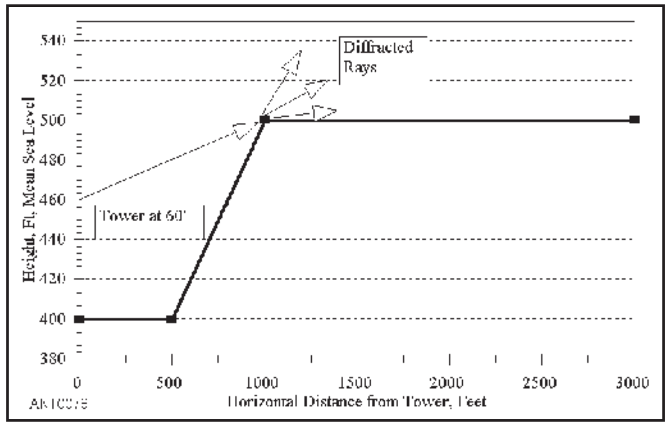

Figure 14.36 — "Hill-Ahead" terrain, shown with diffracted rays created by illumination of the edge of the plateau at the top of the hill.

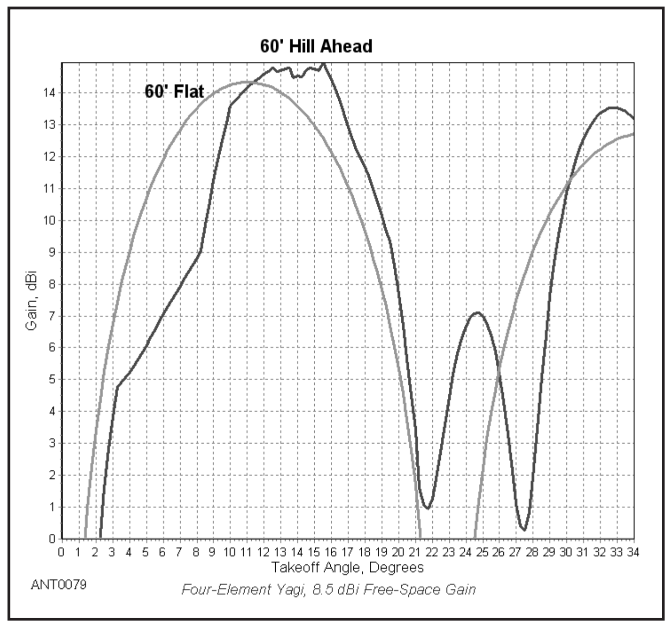

Figure 14.37 — Elevation response computed by HFTA for "Hill-Ahead" terrain shown in Figure 14.36. Now the hill blocks direct rays and also precludes possibility of any constructive reflections. Above 10°, diffraction components add up together with direct rays to create the response shown.

Now let's see what happens when there is a hill ahead in the direction of interest. **Figure 14.36** depicts such a situation, labeled "Hill-Ahead." Here, at a height of 400 feet above mean sea level, the land is flat in front of the tower, out to a distance 500 feet, where the hill begins. The hill then rises 100 feet over the range 500 to 1000 feet away from the tower base. After that, the terrain is a plateau, at a constant 500 feet elevation.

Figure 14.37 shows the computed elevation pattern for a 4-element 21-MHz Yagi 60-feet high on the tower, compared again with an overlay for an identical 60-foot high antenna over flat ground. The hill blocks low-angle waves directly radiated from the antenna from 0° to 2.3°. In addition, waves that would normally be reflected from the ground, and that would normally add in phase from about 2.3° to 12°, are blocked by the hill also. Thus the signal at 8° is down almost 5 dB from the signal over flat ground, all due to the effect of the hill. Diffracted waves start kicking in once the direct wave rises enough above the horizon to illuminate the top edge of the hill. These diffracted waves tend to augment elevation angles above about 12°, which reflected waves can't reach.

Is there is any hope for someone in such a lousy QTH for DXing? **Figure 14.38** shows the elevation response for a truly heroic solution. This involves a stack of four 4-element Yagis, mounted at 120, 90, 60 and 30 feet on the tower. Now, the total gain at low angles is just about comparable to that from a single 4-element Yagi mounted over flat ground. Where there's a ham, there is a way!

At 5° elevation, four diffraction components add up (there are zero reflection components) to achieve the far-field pattern. This seems reasonable, because each of the four antennas is illuminating the diffraction point separately and we know that none of the four antennas can *see over* the hill directly to produce a reflection at a low launch angle.

At an elevation angle of 5°, 15 meter signals arrive from Europe to New England about 13% of the total time when the band is actually open. We can look at this another way. For about two-thirds of the times when the band is open on this path, the incoming angle is between 3° to 12°. For about one-third of the time, signals arrive above 10°, where the "heroic" four-stack is really beginning to come into its own.

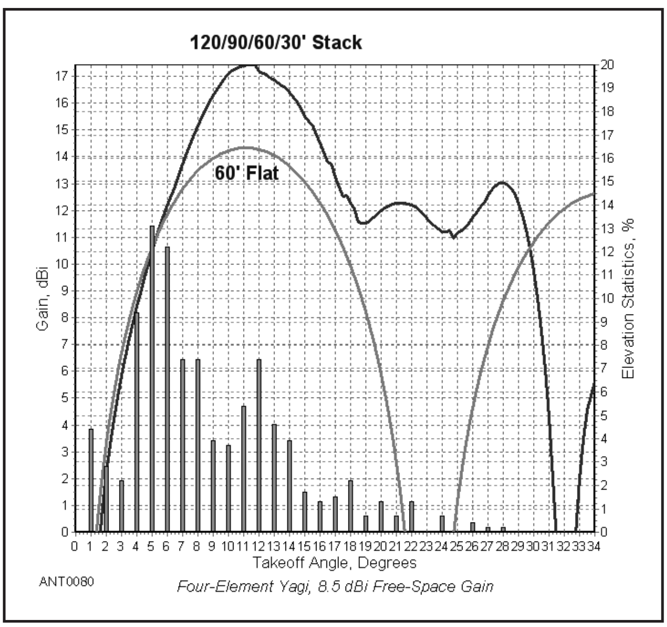

Figure 14.38 — Elevation response of "heroic effort" to surmount the difficulties imposed by hill in Figure 14.36. This effort involves a stack of four 4-element Yagis in a stack starting at 120 feet and spaced at 30-foot increments on the tower. The response is roughly equivalent to a single 4-element Yagi at 60 feet above flat ground, hence the characterization as being a "heroic effort." The elevation-angle statistics from New England to Europe are overlaid on the graph for reference.

Complex Terrain Example

The results for simple terrains look reasonable; let's try a more complicated real-world situation. **Figure 14.39** shows the terrain from the New Hampshire N6BV/1 QTH toward Japan. The terrain was complex, with 52 different points *HFTA* identifies as diffraction points. **Figure 14.40** shows a labeled *HFTA* output for three different types of antennas on 20 meters: a stack at 120 and 60 feet, the 120-foot antenna by itself, and then a 120/60-foot stack over flat ground, for reference. The elevation-angle statistics for New England to Japan are overlaid on the graph also, making for a very complicated looking picture — it is a *lot* easier to decipher the lines on the color monitor, by the way, than on a black-and-white printer.

Comparison of the same 120/60-foot stacks over irregular terrain and flat ground is useful to show where the terrain itself is affecting the elevation response. The flatland stack has more gain in the region of 3° to 7° than the same stack over the N6BV/1 local terrain toward Japan. On the other hand, the N6BV/1 local terrain boosts signals in the range of 8° to about 12°. This demonstrates the conservation of energy — you may gain a stronger signal at certain elevation angles, but you will lose gain at others. In this case, the N6BV/1 station always felt "weak" toward Japan on 20 meters, because the dominant angles are low.

Examination of the detailed data output from *HFTA* shows that at an elevation angle of 5°, there are 6159 diffraction components. There are many, many signals bouncing around off the terrain on their trip to Japan! Note that because

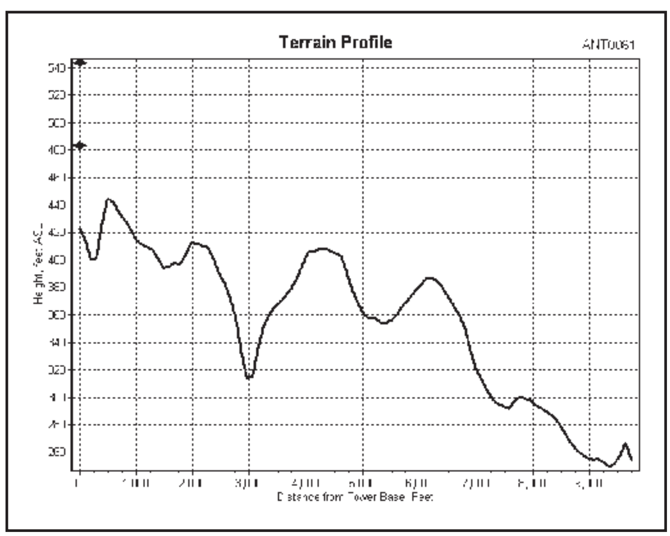

Figure 14.39 — Terrain of N6BV/1 in Windham, NH, toward Japan. HFTA identifies 52 different points where diffraction can occur.

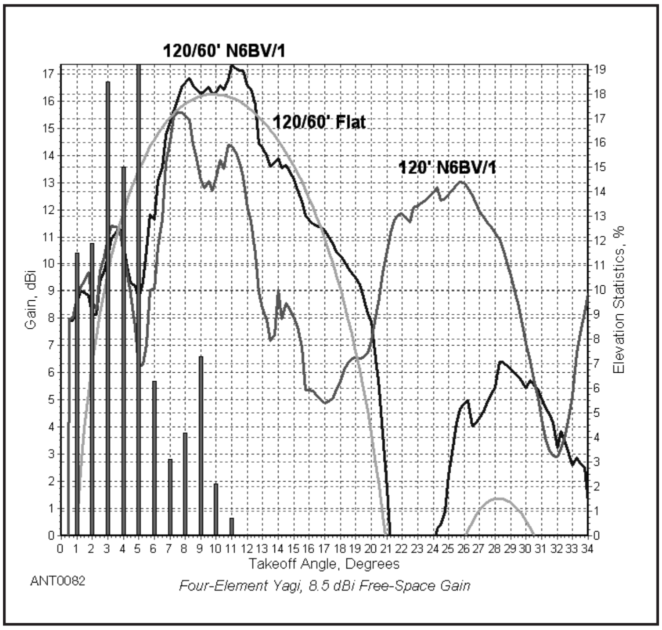

Figure 14.40 — Elevation responses computed by HFTA for N6BV/1 terrain shown in Figure 14.39, for a stack of two 4-element 20 meter Yagis at 120 and 60 feet, together with the response for a single Yagi at 120 feet and a 120/60-foot stack over flat ground for reference. Due to the response, many diffraction and reflection components is quite complicated!

of blockage of some parts of the terrain, the 60-foot high Yagi cannot illuminate all the diffraction points, while the higher 120-foot Yagi is able to see these diffraction points.

It is fascinating to reflect on the thought that received signals coming down from the ionosphere to the receiver are having encounters with the terrain, but from the opposite direction. It's not surprising, given these kinds of interactions, that transmitting and receiving might not be totally reciprocal.

The 120/60-foot stack in Figure 14.40 achieves its peak gain of 17.3 dBi at 11° elevation, where it is about 3 dB stronger than the single Yagi at 120 feet. It maintains this 3-dB advantage over most of the range of incoming signals from Japan. This difference in performance between the stack and each antenna by itself was observed many times on the air. Much of the time when comparisons are being made, however, the small differences in signal are difficult to measure meaningfully, especially when the fading varies signals by 20 dB or so during a typical QSO. It should be noted that the stack usually exhibited less fading compared to each antenna by itself.

14.3.6 USING *HFTA*

Manually Generating a Terrain Profile

The *HFTA* program uses two distinct algorithms to generate the far-field elevation pattern. The first is a simple reflection-only Geometric Optics (GO) algorithm. The second is the diffraction algorithm using the Uniform Theory of Diffraction (UTD). These algorithms work with a digitized representation of the terrain profile for a single azimuthal direction — for example, toward Japan or toward Europe.

You can generate a terrain file manually using a topographic map and a ruler or a pair of dividers. The HFTA.PDF file (accessed by clicking on the HELP button) and on the accompanying CD-ROM gives complete instructions on how to create a terrain file manually (or automatically). The manual process is simple enough in concept. Mark on your US Geological Survey 7.5-minute map the exact location of your tower. You will find 7.5-minute maps available from some local sources, such as large hardware stores, but the main contact point is the U.S. Geological Survey (**nationalmap.gov**). Many countries outside the USA have topographic charts also. Most are calibrated in meters. To use these with *HFTA*, you will have to convert meters to feet by multiplying meters by 3.28 or else inserting a single line at the very beginning of the disk file, saying "meters" for *HFTA* to recognize meters automatically.

Mark off a pencil line from the tower base, in the azimuthal direction of interest, perhaps 45° from New England to Europe, or 335° to Japan. Then measure the distance from the tower base to each height contour crossed by the pencil line. Enter the data at each distance/height into an ASCII computer file, whose filename extension is "PRO," standing for *profile*.

Figure 14.41 shows a portion of the USGS paper map for the N6BV/1 QTH in Windham, NH, along with lines scribed in several directions toward various parts of Europe and the Far East. Note that the elevation heights of the intermediate contour lines are labeled manually in pencil in order to make sense of things. It is very easy to get confused unless you do this!

The terrain model used by *HFTA* assumes that the terrain is represented by flat *plates* connecting the elevation points in the *.PRO file with straight lines. The model is two dimensional, meaning that range and elevation are the only data for a particular azimuth. In effect, *HFTA* assumes that the width of a terrain plate is wide relative to its length. Obviously, the world is three-dimensional. If your shot in a particular direction involves aiming your Yagi down a canyon with steep walls, then it's pretty likely that your actual elevation pattern will be different from what *HFTA* tells you. The signals must careen horizontally from wall to wall, in addition to being affected by the height changes of the terrain. *HFTA* isn't designed to do canyons.

To get a true 3-D picture of the full effects of terrain, a terrain model would have to show azimuth, along with range and elevation, point-by-point for about two miles in every direction around the base of the tower. After you go through the pain of creating a profile for a single azimuth, you'll appreciate the immensity of the process if you were to try to create a full 360° 3D profile manually.

Terrain Data from the Internet

At one time digitized terrain data commonly available from the Internet didn't have sufficient resolution to be accurate enough for *HFTA*. Nowadays, the complete, accurate set of USGS topographic 7.5-minute maps are available at no cost on the Internet (**nationalmap.gov**). You can use a

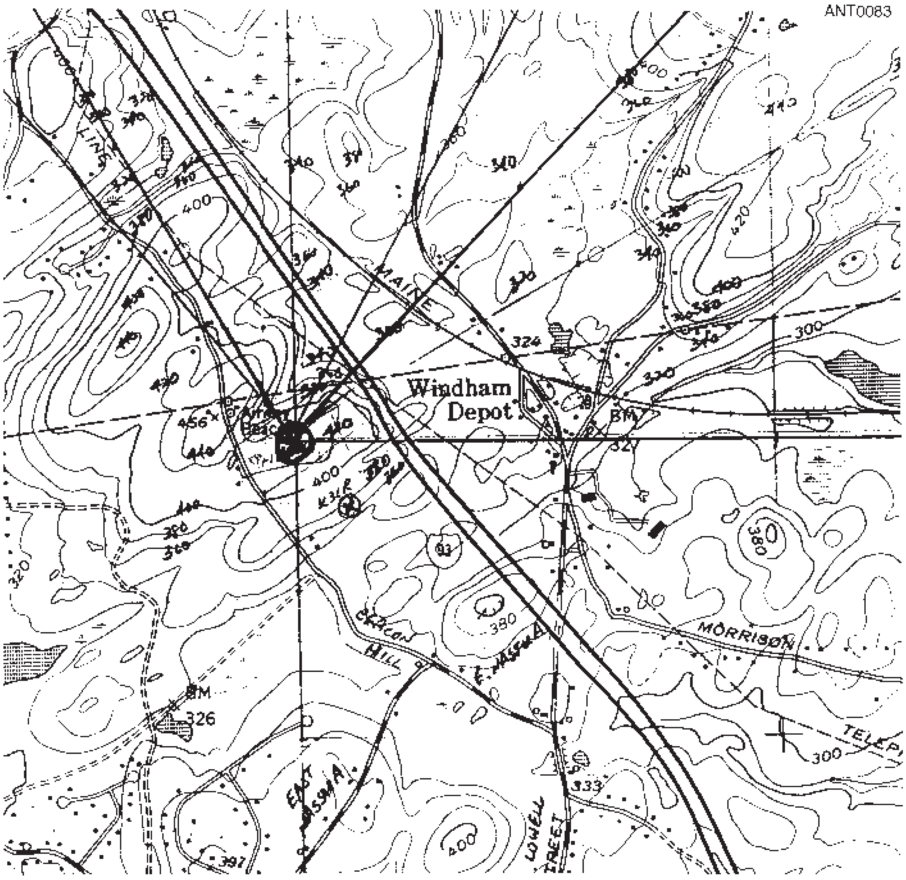

Figure 14.41 — A portion of USGS 7.5-minute topographic map, showing N6BV/1 QTH, together with marks in direction of Europe and Japan from tower base. Note that the elevation contours were marked by hand to help eliminate confusion. This required a magnifying glass and a steady hand!

program called *MicroDEM*, written by Professor Peter Guth at the US Naval Academy, to quickly and easily produce terrain data files suitable for *HFTA* from topographic data files. Dr Guth and the US Naval Academy have published *MicroDEM* for downloading at no cost at **www.usna.edu/User/oceano/pguth/website/microdem/microdem.htm**. It should be noted that besides automatically creating terrain profiles for *HFTA*, *MicroDEM* is a full-featured mapping program on its own.

There are presently three on-line sources of digital elevation data:

- DEM (USGS Digital Elevation Model, corresponding to the 7.5-minute "quadrangle" printed topographic maps used for years by hams and hikers).
- NED (USGS "seamless") topographic data that doesn't require "merging" together different 7.5-minute maps in order to cover sufficient geography for a 4400-meter radius around a tower.
- SRTM (Shuttle Radar Topology Mission). USGS/NOAA SRTM data covers about 80% of the world, but for security reasons has been limited to a resolution of about 30 meters.

Detailed instructions for using *MicroDEM* with these three digital-map data sources are in the Help file for *HFTA* (HFTA.PDF), which you can access from the *HFTA* main window by clicking on the HELP button. **Figure 14.42** shows a screen capture for a recent version of the *MicroDEM* program showing the N6BV/1 location in New Hampshire for an azimuth of 45° into Europe. The black/white rendering of the screen capture doesn't do justice to the same information in color. The computed terrain profile is plotted in the window at the right of Figure 14.42 and the data file is shown in the inset window at the top right.

Using *MicroDEM* and on-line USGS topographic map data, you can also automatically create up to 360 terrain profiles with as little as 1° spacing of azimuths in a few seconds. (Specifying a 1° spacing is really overkill; most operators choose to create 72 profiles with 5° spacing.) On a topographic DEM (digital elevation model) map that covers the geographic area of interest, you simply specify the latitude and longitude of a tower's location — found using a GPS receiver — and then ask *MicroDEM* for a VIEWSHED. See the *HFTA* HELP file for the details.

Compare this automated several-second *MicroDEM* process to creating manual profiles on a paper topographic map. It can take up to an hour of meticulous measurements to manually create a single terrain profile.

Creating DEM files from Downloaded USGS Data

The instructions for *HFTA* include directions for obtaining elevation data files in the TAR.GZ file format. *MicroDEM*,

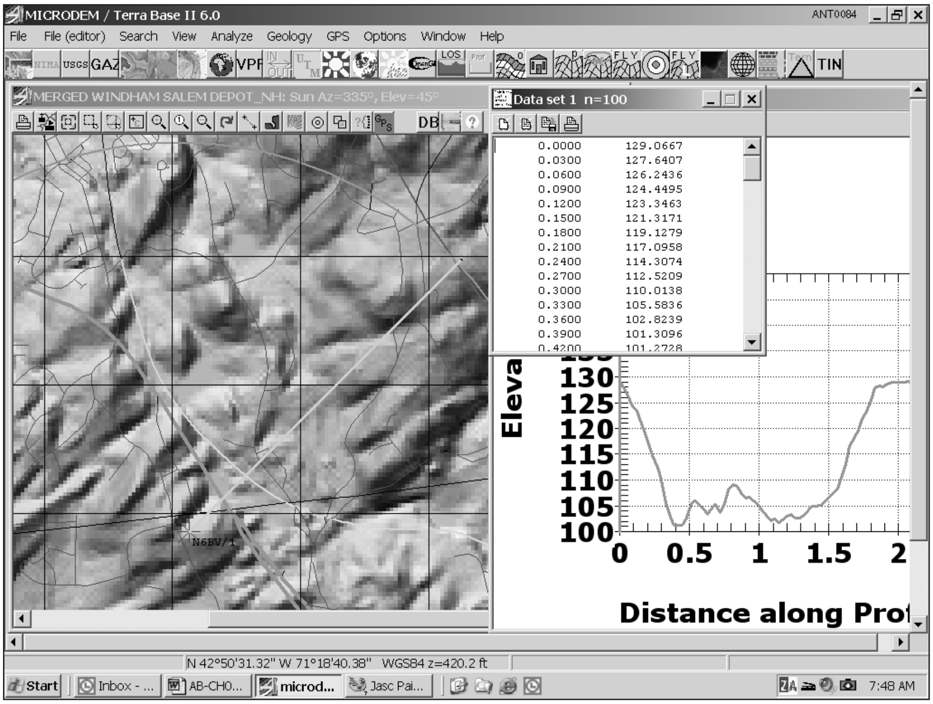

Figure 14.42 — A screen-capture of the *MicroDEM* program, showing the topographic map for the same terrain shown in Figure 14.41, together with the computed terrain profile along an azimuth of 45° on the path toward Europe from the N6BV/1 location in Windham, NH.

however, requires elevation data in the .DEM file format. Users may not be familiar with the process or tools required to convert the US Geological Survey files obtained from Geocomm to the .DEM files required by *MicroDEM*. The following draft procedure is suggested for converting the data for use by *HFTA*. (Be aware that all software in this section is occasionally revised and may invalidate these instructions. This procedure was devised by Tom Ferguson, WBØDHB, in early 2015 but is not guaranteed to be compatible with the latest versions of the data source access interfaces or file formats.) There is an active user's group for *MicroDEM* on the Delphi system at **forums.delphiforums.com/microdem/start**. Note that this includes many non-amateur users and is not dedicated to Amateur Radio use.

The renamed file **Windham_NH.SDTS.TAR.GZ** is a *packed* file that is *compressed*; the GZ extension indicates compression, while the TAR extension indicates packing. To obtain DEM files, you will need to first unzip the compressed TAR.GZ file to a packed TAR file, and then unpack the TAR file. Unpacking the TAR file reveals a number of DDF files that then must be converted into DEM files. These are the steps:

• Save the downloaded TAR.GZ file into the folder c:\mapdata\DEMs

• Right-click on this TAR.GZ file and unzip; Choose the EXTRACT HERE option when unzipping to keep the new unzipped file in the same folder.

• Once unzipped, verify that a similar TAR file (without the GZ extension) now exists in your mapdata\DEMs folder

• Before unpacking the TAR file, review the c:\mapdata\DEMs folder and delete all existing DDF files (or move them into a subfolder). DDF files from several USGS maps can produce files with the same leading four digits, and that creates confusion when taking the final step of creating DEM files.

• Unpack the TAR file by again using an unzipping tool to extract the enclosed DDF files.

• Right-click the TAR file, select the zip program, and select EXTRACT HERE. Verify that a number of DDF files (close to 20) and a README file exist in the DEMS folder.

• The final conversion, from DDF to DEM, requires the download of some conversion software, such as **sdts2dem.exe**, available at **data.geocomm.com/dem/sdts2dem.html**. More information on this application can be found at **www.cs.arizona.edu/projects/topovista/sdts2dem**.

• The **sdts2dem.exe** file should appear in the Downloads folder or wherever the web browser has been directed to save downloaded files. Consider moving the file into the DEMs folder for ease of access.

• Now that **sdts2dem.exe** is downloaded, execute the program by double clicking. When asked, enter the first four characters of the base file name as the first four digits of the DDF files that resulted from unpacking the TAR file. Select Enter.

• The routine now asks for an output file name (without any extension). Assign a name that describes the USGS quad map (with the TAR.GZ extension) that was downloaded earlier. Select ENTER.

• A new file should have been created in the DEMs folder, having an extension of ".dem". This is the file that will be used within *MicroDEM* to create terrain profiles.

You may skip ahead to the section entitled "Creating Azimuth Terrain Files for HFTA in MicroDEM." The following procedure is used for creating terrain profiles along radials emanating from your QTH which form the basis for HFTA's calculations.

Automated HFTA Data Service from K6TU

After manually obtaining and converting terrain data for his location, Stu Phillips, K6TU decided there had to be a simpler way and so automated the complete process on **k6tu.net**. The service is available at no charge to any registered user (sign up process is free and gives on-going access to both the OnDemand propagation predictions of the site as well as generating Terrain Profiles). Stu obtained the complete 0.5 Tbyte database from USGS and for non-US locations, uses the Shuttle Radar Topography Mission dataset.

Fill in a simple form, click on Generate Terrain Profile and you will get an email when the Terrain Profile files are available for download. It typically takes 15 – 45 seconds to generate the profile files depending on how many tiles have to be merged.

Before skipping to this section, start *MicroDEM* and pull up your newly-created digital elevation model.

• Once *MicroDEM* has initialized, you can close the information box in the center of the screen.

• Select your DEM file with FILE > OPEN > OPEN DEM. You should see a folder and file directory window for "mapdata\DEMs".

• Scroll down to desired DEM file (look for the name you assigned to the file when you used sdts2dem.exe, and make sure the file has the extension ".dem". Double-click this file. The elevation map should appear in *MicroDEM*.

One last item to check before creating azimuth files: Scroll over your elevation map and observe the elevations listed at the bottom of the *MicroDEM* window. If they appear consistent with your QTH, you are ready for terrain files.

If the elevations are *not* accurate, some additional work is necessary before proceeding. I discovered that, when merging several DEM files into a larger DEM file, the elevation in meters was 3.28 times the elevation shown in the single quad DEM file! Sounds suspiciously like the conversion between feet and meters! In this instance, my QTH was shown at an elevation that was 3.28 times higher than its actual elevation. The detailed *MicroDEM* Help document contains the procedure for correcting this, but it is not easy to find. A condensed version of correcting elevation issues is as follows:

• You will need to edit the DEM Header to correct the situation — it isn't intuitive that a header would be involved, but it is.

• Close, and then re-start MicroDEM. Immediately select the IN/OUT icon, which appears just under the menu bar about a third of the way to the right. A "Data Manipulation" window appears.

• Select EDIT, then DEM HEADER.

• A File Explorer window appears, probably showing your DEMs folder. If not, navigate to that folder (or to a different folder that contains your DEM files if so configured). Select the DEM file to be edited; double click.

• Another window appears with various options. Under "Z Units", change METERS to FEET, and select OK. Answer YES to REWRITE DEM?, unless you want to retain the original file and save the corrected file under a different name.

• Close the Data Manipulation window.

• On the *MicroDEM* menu bar, go to FILE > OPEN > OPEN DEM to select the modified (and hopefully corrected) DEM file. Hover over the map again with your mouse to check the elevation for accuracy.

Some DEM files may contain erroneous elevations that will throw off *HFTA* runs as well as other actions within *MicroDEM*, such as plotting path profiles. The errors are evident when running *HFTA* using a selected Terrain File. Terrain Files have a .PRO file extension.

If the result of running *HFTA* looks suspicious, look at the contents of the .PRO file within mapdata\MD-PROJ\fans. Right-click the .PRO file and use a text editor such as *Notepad* or a similar application to view the contents. Only two columns of data appear — one for the distance along the radial from your QTH and the other for the elevation. Scroll completely through the file and look for inconsistent elevations. Simple interpolation is the easiest method for replacing bad data points. Re-save the file, and try *HFTA* again.

Algorithm for Ray-Tracing the Terrain

Once a terrain profile is created, there are a number of mechanisms that *HFTA* takes into account as a ray travels over that terrain:

1) Classical ray reflection, with Fresnel ground coefficients.

2) Direct diffraction, where a diffraction point is illuminated directly by an antenna, with no intervening terrain features blocking the direct illumination.

3) When a diffracted ray is subsequently reflected off the terrain.

4) When a reflected ray encounters a diffraction point and causes another series of diffracted rays to be generated.

5) When a diffracted ray hits another diffraction point, generating another whole series of diffractions.

Certain unusual, bowl-shaped terrain profiles, with sheer vertical faces, can conceivably cause signals to reflect or diffract in a backward direction, only to be reflected back again in the forward direction by the sheer-walled terrain to the rear. *HFTA* does not accommodate these interactions, mainly because to do so would increase the computation time too much. It only evaluates terrain in the forward direction along one azimuth of interest.

Figure 14.43 shows a portion of an *HFTA* screen capture in the direction toward Europe from the N6BV/1 location in New Hampshire on 21.2 MHz. It compares the results for a 90/60/30-foot stack of TH7DX tribanders to the same stack over flat land, and to a single antenna at 70 feet over flat ground. The 70-foot single antenna represents a pretty typical station on 15 meters. The terrain produces excellent gain at lower elevation angles compared to the same stack over flat ground. The stack is very close to or superior to the single

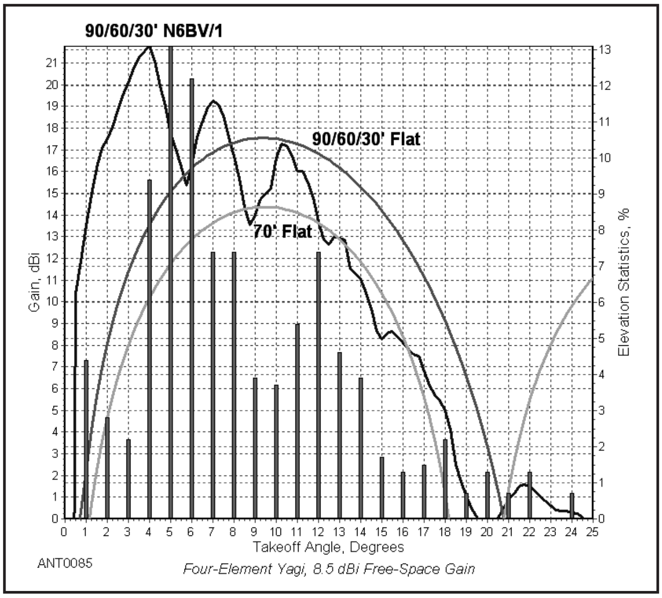

Figure 14.43 — The 21-MHz elevation response for a stack of three TH7DX Yagis mounted on a single tower at 90/60/30 feet, at the N6BV/1 QTH for a 45° azimuth toward Europe. The terrain focuses the energy at low elevation angles compared to the same stack over flat ground. This illustrates once again the conservation of energy: Energy squeezed down into low elevation angles is stolen from other, higher, angles.

70-foot high Yagi at all useful elevation angles. Terrain can indeed exhibit a profound effect on the launch of signals into the ionosphere — for good or for bad.

HFTA's Internal Antenna Model

The operator selects the antenna used inside *HFTA* to be anything from a dipole to an 8-element Yagi. The default assumes a simple cosine-squared mathematic response, equivalent to a 4-element Yagi in free space. *HFTA* traces rays only in the forward direction from the tower along the azimuth of interest. This keeps the algorithms reasonably simple and saves computing time.

HFTA considers each antenna in a stack as a separate *point source*. The simulation begins to fall apart if a traveling wave type of antenna like a rhombic is used, particularly if the terrain changes under the antenna — that is, the ground is not flat under the entire antenna. For a typical Yagi, even a long-boom one, the point-source assumption is reasonable. The internal antenna model also assumes that the Yagi is horizontally polarized. *HFTA* does not do vertically polarized antennas, as discussed previously. The documentation for *HFTA* also cautions the user to work with practical spacings between stacked Yagis — 0.5 λ or more because *HFTA* doesn't explicitly model mutual coupling between Yagis in a stack.

HFTA compares well with the measurements for the horizontal antennas described earlier by Jim Breakall, WA3FET, using a helicopter in Utah. Breakall's measurements were done with a 15-foot high horizontal dipole.

More About *HFTA* Frequency Coverage

HFTA can be used on frequencies higher than the HF bands, although the graphical resolution is only 0.25°. The patterns above about 100 MHz thus look rather grainy. The UTD is a *high-frequency-asymptotic* solution, so in theory the results become more realistic as the frequency is raised. Keep in mind too that *HFTA* is designed to model launch angles for skywave propagation modes, including E- and F-layer, and even Sporadic-E. Since by definition the ionospheric launch angles include only those above the horizon, direct line-of-sight UHF modes involving negative launch angles are not considered in *HFTA*.

See the HFTA.PDF documentation file for further details on the operation of *HFTA*. This file, as well as sample terrain profiles for some *big-gun* stations, is located on the CD-ROM accompanying this book.

14.4 STACKING YAGIS AND SWITCHING SYSTEMS

The preceding sections illustrate the importance of controlling the elevation angle of an antenna's radiation pattern at HF. In addition, the wide variations also illustrate that a single antenna, no matter how much gain it produces, at a single height is often inadequate in maintaining effective communications over the desired path. For example, during a DX band opening on the upper HF bands the initial signals usually appear at very low elevation angles. Later, as the opening strengthens and spreads, signals at higher elevation angles are the strongest. Finally, as the band closes to that area, signals will again be the strongest at low angles. Being able to select the right elevation angle at the right time is important to sustained success in DXing or contest operation.

In HF amateur stations, the most common arrangement to control elevation angle is a vertical stack of identical Yagis on a single tower. This arrangement is commonly called a *vertical stack*. At VHF and UHF, amateurs sometimes employ collinear stacks, where identical Yagis are stacked side-by-side at the same height. This arrangement is called a *horizontal stack*, and is not usually found at HF, because of the severe mechanical difficulties involved with large, rotatable side-by-side arrays. In addition, whereas on HF a primary goal is being able to control the elevation angle of the radiation pattern for the optimum ionospheric path, on VHF and UHF it is more important to narrow the azimuthal width of the array's main lobe and minimize side lobes to improve the signal-to-noise ratio of very weak signals on both ends of the path.

Figure 14.44 illustrates the two different stacking arrangements. In either case, the individual Yagis making up the stack are generally fed in phase. There are times, however, when individual antennas in a stacked array are purposely fed out of phase in order to emphasize a particular elevation pattern. See the **Repeater Antenna Systems** chapter for such a case where elevation pattern steering is implemented for a repeater station.

Let's look at the reasons hams stack Yagis:

- For more gain
- For a wider elevation footprint in a target geographical area
- For azimuthal diversity — two or more directions at once
- For less fading
- For less precipitation static

14.4.1 STACKS AND GAIN

Figure 14.45 compares the elevation responses for three antenna systems of 4-element 15 meter Yagis. The response for the single Yagi at a height of 120 feet peaks at an elevation of about 5°, with a second peak at 17° and a third at 29°. When operated by itself, the 60-foot high Yagi has its first peak at about 11° and its second peak beyond 34°.

The basic principle of a vertically stacked HF array is that it takes energy from higher-angle lobes and concentrates that energy into the main elevation lobe. The main lobe of the 120/60-foot stack peaks about 7° and is about 2 dB stronger than either the 60- or 120-foot antenna by itself. The shape of the left-hand side of the stack's main lobe is determined mainly by the 120-foot antenna's response. The right-hand side of the stack's main lobe is "stretched" rightward (toward higher angles) mainly by the 60-foot Yagi, while the shape follows the curve of the 120-foot Yagi.

Look at the second and third lobes of the stack, which appear about 18° and 27°. These are about 14 dB down from the stack's peak gain, showing that energy has indeed been extracted from them. By contrast, look at the levels of the second and third lobes for the individual Yagis at 60 and 120 feet. These higher-angle lobes are almost as strong as the first lobes.

The stack squeezes higher-angle energy into its main elevation lobe, while maintaining the frontal lobe azimuth pattern of a single Yagi. This is the reason why many state-of-the-art contest stations are stacking arrays of relatively short-boom antennas, rather than stacking long-boom, higher-gain Yagis. A long-boom HF Yagi narrows the azimuthal pattern (and the elevation pattern too), making pointing the antenna more critical and making it more difficult to spread a signal over a wide azimuthal area, such as all of Europe and Asiatic Russia at one time.

14.4.2 STACKS AND WIDE ELEVATION COVERAGE

Detailed studies using sophisticated computer models of the ionosphere have revealed that coverage of a wide range of elevation angles is necessary to ensure consistent DX or contest coverage on the HF bands. These studies have been conducted over all phases of the 11-year solar cycle, and for numerous transmitting and receiving QTHs throughout the world.

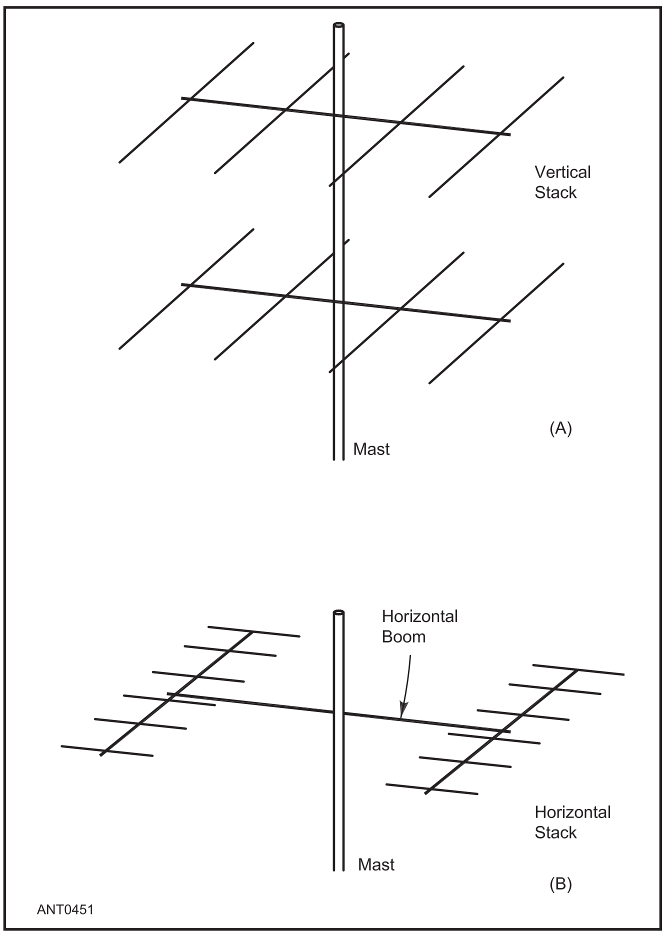

Figure 14.44 — Stacking arrangements. At A, two Yagis are stacked vertically (broadside) on the same mast. At B, two Yagis are stacked horizontally (collinear) side-by-side. At HF the vertical stack is more common because of mechanical difficulties involved with large HF antennas stacked side-by-side, whereas at VHF and UHF the horizontal stack is common.

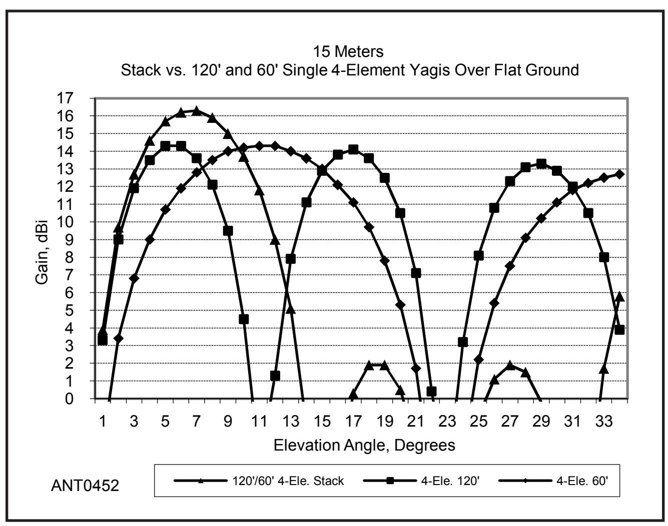

Figure 14.45 — Comparison of elevation patterns on 15 meters for a stack of 4-element Yagis at 120 and 60 feet and individual Yagis at those two heights. The shape of the stack's response is determined mainly by that of the top antenna.

The chapter **Radio Wave Propagation** covers these studies in more detail, and the CD-ROM accompanying this book contains a huge number of elevation-angle statistical tables for locations all around the world. The *HFTA* (HF Terrain Assessment) program on the CD-ROM can not only compute antenna elevation patterns over irregular local terrain, but it can compare them directly to the elevation-angle statistics for a particular target geographic area.

A 10 Meter Example

Figure 14.46 shows the 10 meter elevation-angle statistics for the New England path from Boston, Massachusetts, to all of the continent of Europe. The statistics are overlaid with the computed elevation response for three individual 4-element Yagis, at three heights: 90, 60 and 30 feet above flat ground. In terms of wavelength, these heights are 2.60 λ, 1.73 λ and 0.86 λ high.

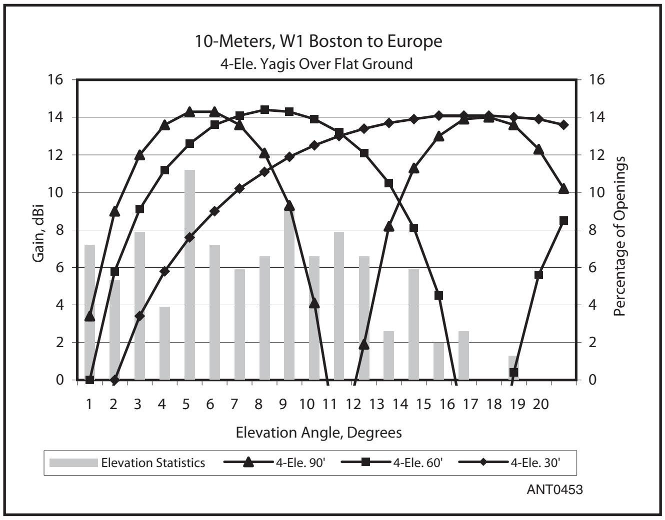

Figure 14.46 — Comparison of elevation patterns and elevation-angle statistics for individual 10-meter TH7DX tribanders mounted over flat ground aiming from New England to Europe. No single antenna can cover the wide range of angles needed — from 1° to 18°.

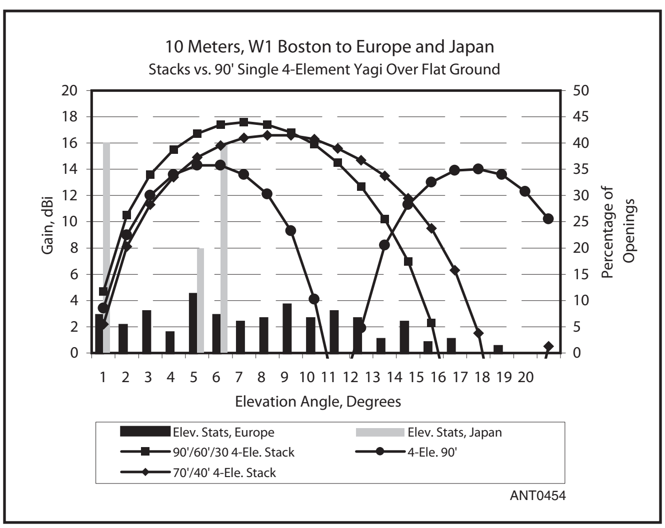

Figure 14.47 — Combinations of 4-element Yagis over flat ground. The elevation-angle statistics into Japan from New England (Boston) are represented by the black vertical bars, while the grey vertical bars represent the elevation-angle statistics to Europe. The 90/60/30-foot stack has the best elevation footprint into Japan, although the 70/40-foot stack performs well also.

You can see that the 90-foot high Yagi covers the lower elevation angles best, but it has a large null in its response centered at about 11°. This null puts a big hole in the coverage for some 22% of all the times the 10 meter band is open to Europe. At those angles where the 90-foot Yagi exhibits a null, the 60-foot Yagi would be effective, and so would the 30-foot Yagi. If that is the only antenna you have, the 90-foot high Yagi would be too high for good coverage of Europe from New England.

The peak statistical elevation angle into Europe is 5°, and this occurs about 11% of all the times the 10 meter band is open to Europe from Boston. At an elevation of 5° the 30-foot high Yagi would be down almost 7 dB compared to the 90-foot high Yagi, but at 11° the 90-foot Yagi would be more than 22 dB down from the 30-foot Yagi. There is no single height at which one Yagi can optimally cover all the necessary elevation angles, especially to a large geographic area such as Europe — although the 60-foot high antenna is arguably the best compromise for a single height. To cover all the possibilities to Europe, however, you need a 10 meter antenna system that can cover equally well the entire range of elevation angles from 1° to 18°.

Figure 14.47 compares elevation-angle statistics for two 10 meter paths from New England to Europe and to Japan. The elevation angles needed for communications with the Far East are very low. Overlaid on Figure 14.47 for comparison are the elevation responses over flat ground for three different antenna systems, using identical 4-element Yagis:

- Three Yagis, stacked at 90, 60 and 30 feet
- Two Yagis, stacked at 70 and 40 feet
- One Yagi at 90 feet.

The best coverage of all the necessary angles on 10 meters to Europe is with the stack of three Yagis at 90/60/30 feet. The two-Yagi stack at 70 and 40 feet comes in a close second to Europe, and for elevation angles higher than about 9° the 70/40-foot stack is actually superior to the 90/60/30-foot stack.

Both of the stacks illustrated here give a wider *elevation footprint* than any single antenna, so that all the angles can be covered automatically without having to switch from higher to lower antennas manually. This is perhaps the major benefit of using stacks, but not the only one, as we'll see.

To Japan, the necessary range of elevation angles is considerably smaller than that needed to a larger geographic target area like Europe. The 90/60/30-foot stack is still best on the basis of having higher gain at low angles, although the two-Yagi stack at 70 and 40 feet is a good choice too. Note that the single 90-foot high Yagi's performance is very close to the 70/40-foot stack of two Yagis at low angles, but the two-Yagi stack is superior to the single 90-foot antenna for angles higher than about 5° on 10 meters.

A 15 Meter Example

The situation is similar on 15 meters from New England to Europe. On 15 meters, the range of angles needed to fully cover Europe is 1° to 28°. This large range of angles makes covering all the angles even more challenging. Ken Wolff, K1EA, a devoted contest operator and the author of the famous *CT* contest logging program, put it very clearly when he wrote in the bulletin for the Yankee Clipper Contest Club:

"Suppose you have 15 meter Yagis at 120 feet and 60 feet, but can feed only one at a time. A 15 meter beam at 120 feet has its first maximum at roughly 5° and the first minimum at 10°. The Yagi at 60 feet has a maximum at 10° and a minimum at 2°. At daybreak, the band is just opening, signals are arriving at 3° or less and the high Yagi outperforms the low one by 5-10 dB. Late in the morning, western Europeans are arriving at angles of 10° or more, while UA6 is still arriving at 4-5°. Western Europe can be 20-30 dB louder on the low antenna than the high! What to do? Stack 'em!"

Figure 14.48 illustrates K1EA's scenario, showing the elevation statistics to Europe from Massachusetts and the elevation responses for a 120- and a 60-foot high, 4-element Yagi, both over flat ground, together with the response for both antennas operated as a vertical stack. The half-power beamwidth of the stack's main lobe is 6.9°, while that for the 120-foot antenna by itself is 5.5° and that for the 60-foot antenna by itself is 11.1°. The half-power beamwidth numbers by themselves can be deceiving, mainly because the stack starts out with a higher gain. A more meaningful observation is that the stack has equal to or more gain than either of the two individual antennas from 1° to about 10°.

Is such a stack of 15 meter Yagis at 120 and 60 feet optimal for the New England to Europe path? No, it isn't, as we'll explore later, but the stack is clearly better than either antenna by itself for the scenario K1EA outlined above.

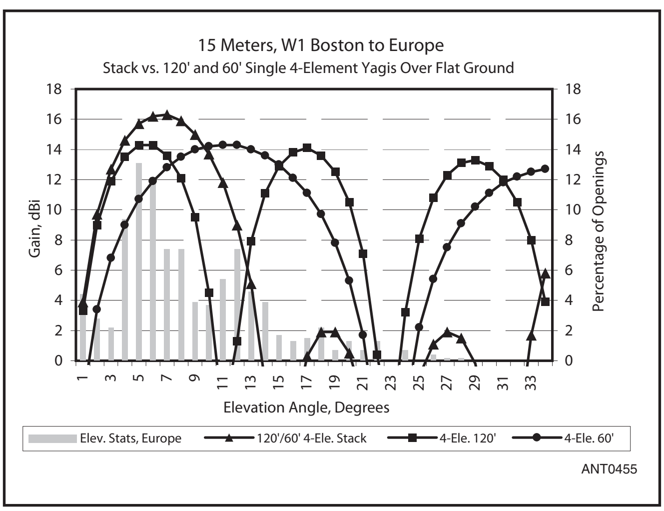

Figure 14.48 — Comparison of elevation patterns for K1EA's illustration about 15 meter Yagis mounted over flat ground, with elevation-angle statistics to Europe added. The stack at 120 and 60 feet yields a better footprint over the range of 3° to 11° at its half-power points, better than either antenna by itself.

A 20 Meter Example

Take a look now at **Figure 14.49**, which overlays elevation-angle statistics for Europe (gray vertical bars) and Japan (black vertical bars) from Boston on 20 meters, plus the elevation responses for four different sets of antennas mounted over flat ground. Just for emphasis, the highest antenna is a 200-foot high 4-element Yagi. It is clearly too high for complete coverage of all the needed angles into Europe. A number of New England operators have verified that this is true — a really high Yagi will open the 20 meter band to Europe in the morning and may shut it down in the afternoon, but during the middle of the day the high antenna gets soundly beaten by lower antennas.

To Japan, however, from New England the range of angles needed narrows considerably on 20 meters, from 1° to only 11°. For these angles, the 200-foot Yagi is the best antenna to work Japan from New England on 20 meters.

This is true provided that the antenna is aiming out over flat ground. The actual, generally irregular, terrain in various directions can profoundly modify the takeoff angles favored by an antenna system, particularly on steep hills. There will be more discussion on this important topic later on.

14.4.3 ELIMINATING DEEP NULLS

Now, let's look closely at some other 20 meter antennas in Figure 14.46, the ones at 120 and 60 feet. At an elevation angle of 8° the difference in elevation response between the 60- and 120-foot high Yagis is just over 3 dB. Can you really notice a change of 3 dB on the air? Signals on the HF bands often rise and fall quickly due to fading, so differences of 2 or 3 dB are difficult to discern. Consequently, the difference between a Yagi at 120 feet and one at 60 feet may be difficult

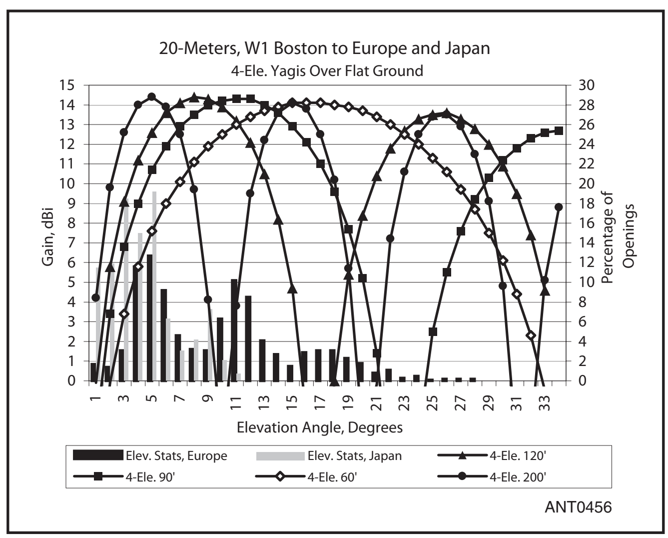

Figure 14.49 — Comparison of elevation patterns for individual 20 meter Yagis over flat ground, compared with the range of elevation angles needed on this band from New England to Europe (gray bars) and to Japan (black bars). For fun, the response of a 200-foot high Yagi is included — this antenna is far too high to cover the needed range of angles to Europe because of its deep nulls at critical angles, like 10°. But the 200 footer is great into Japan!

to detect at elevation angles covered well by both antennas. But a *deep null* in the elevation response is very noticeable.

Back in 1990, when Dean Straw, N6BV, put up his 120-foot tower in Windham, New Hampshire, his first operational antenna was a 5-element triband Yagi, with 3 elements on 40 and 4 elements on both 20 and 15 meters. Just as the sun was going down on a late August day Straw finished connecting the feed line in the shack. The antenna seemed to be playing like it should, with a good SWR curve and a good pattern when it was rotated. So N6BV/1 called a nearby friend, John Dorr, K1AR, on the telephone and asked him to get on the air to make some signal comparisons on 20 meters into Europe.

Straw was shocked that every European they worked that evening said his signal was several S units weaker than K1AR's. Dorr was using a 4-element 20 meter monobander at 90 feet, which at first glance should have been comparable to Straw's 4-element antenna at 120 feet. But N6BV really shouldn't have been so shocked — in New England, the elevation angles from Europe late in the day on 20 meters are almost always higher than 11°, and that is true for the entire solar cycle.

The N6BV/1 station was located on a small hill, while K1AR was located on flat terrain toward Europe. The elevation response for N6BV/1's 120-foot high Yagi fell right into a deep null at 11°. This was later confirmed many times in the following eight years that the N6BV/1 station was operational. During the early morning opening on 20 meters into Europe, the top antenna was always very close to or equal to the stack of three TH7DX tribanders at 90/60/30 feet on the same tower. But in the afternoon the top antenna was *always* decidedly worse than the stack, so much so that Straw often wondered whether something had gone wrong with the top antenna!

So what's the moral to this short tale? It's simple: *The gain you can achieve, while useful, is not so important as the deep nulls you can avoid by using a stack.*

14.4.4 STACKING DISTANCES BETWEEN YAGIS

So far, we've examined stacks as a means of achieving more gain over an individual Yagi, while also matching the antenna system's response to the range of elevation angles needed for particular propagation paths. Most importantly, we seek to avoid nulls in the elevation response. Earlier we asked whether a 120/60-foot stack was optimal for the path from New England to Europe on 15 meters. Let's examine how the stacking distance between individual antennas affects the performance of a stack.

Figure 14.50 shows overlays of various combinations of 15 meter Yagis. Just for reference, a plot for a single 60-foot high Yagi is also included. Let's start by looking at the most widely spaced stack in the group: the 120/30-foot stack. Here, the spacing is obviously too large, since the second lobe is actually stronger than the first lobe. In terms of wavelength, the 90-foot spacing between antennas in this stack is 1.94 λ, a large spacing indeed.

There is a great deal of folklore and superstition among

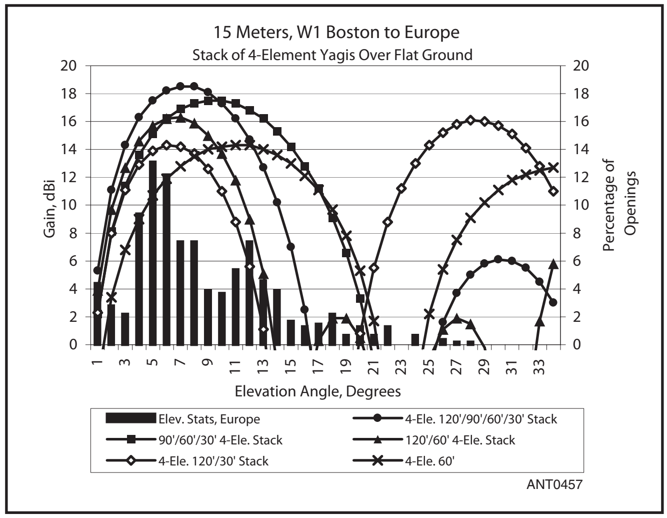

Figure 14.50 — Various stacks toward Europe from New England for 15 meters. The stack at 120 and 30 feet is clearly suboptimal, since the second lobe is higher than the first lobe. The 120/60-foot stack is better in this regard, but is still not as good a performer as the 90/60/30-foot stack. It's debatable whether going to four Yagis in the 120/90/60/30-foot stack is a good idea because it drops below the performance of the 90/60/30-foot stack at about 10° in elevation. The exact distance between practical HF Yagis is not critical to obtain the benefits of stacking. For a stack of tribanders at 90, 60 and 30 feet, the distance in wavelengths between individual antennas is 0.87 λ at 28.5 MHz, 0.65 λ at 21.2 MHz, and 0.43 λ at 14.2 MHz.

amateurs about stacking distances for HF arrays. For years, high-performance stacked Yagi arrays have been used for weak-signal DXing on the VHF and UHF bands. The most extreme example of weak-signal work is EME work (Earth-Moon-Earth, also called *moonbounce*) because of the huge path losses incurred on the way to and from the Moon. The most successful arrays used for moonbounce have low sidelobe levels and very narrow frontal lobes that give huge amounts of gain. The low sidelobes help minimize received noise, since the receive levels for signals that do manage to bounce off the Moon and return to Earth are exceedingly weak.

But HF operation is different from moonbounce in that rigorously trying to minimize high-angle lobes is far less crucial at HF, where we've already shown that the main goal is to achieve gain over a wide elevation-plane footprint without any disastrous nulls in the pattern. The gain gradually increases as spacing in terms of wavelength is increased between individual Yagis in a stack, and then decreases slowly once the spacing is greater than about 1.0 λ. The difference in gain between spacings of 0.5 λ to 1.0 λ for a stack of typical HF Yagis amounts to only a fraction of a decibel. Stacking distances on the order of 0.6 λ to 0.75 λ give best gain commensurate with good patterns.

While the stack at 120/60 feet in Figure 14.50 doesn't have the second-lobe-stronger problem the 120/30-foot stack has — 60 feet between antennas is 1.29 λ, again outside the normal range of HF stack spacings. As a consequence, the

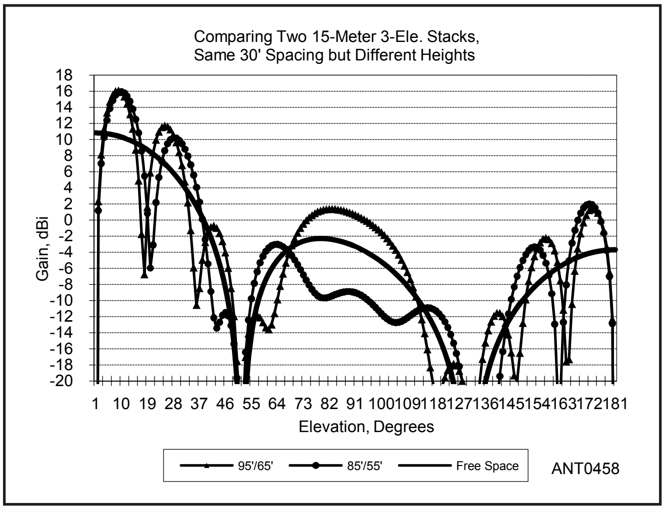

Figure 14.51 — Rectangular plot comparing two 15-meter stacks of 3-element Yagis — each antenna is spaced 30 feet from its partner, but at different heights. The lobes are a complicated function of the antenna height, not the spacing, since that remains constant.

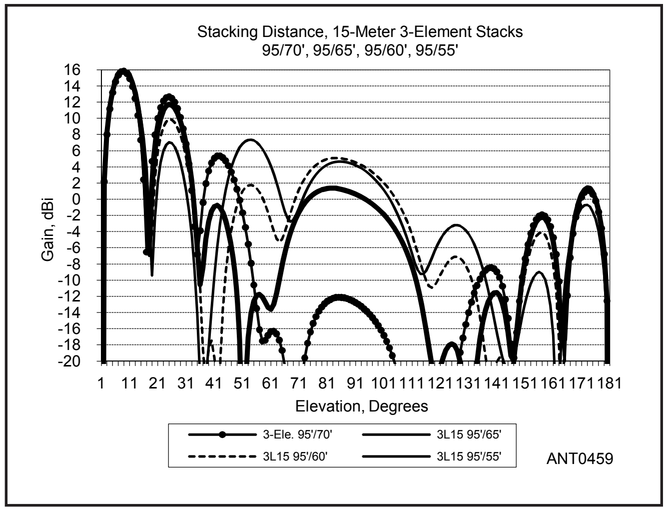

Figure 14.52 — Four spacing scenarios for two 3-element 15-meter Yagis. Things get very complicated. The optimal spacing in terms of stacking gain is 30 feet, which is 0.65 λ. The near-overhead lobes turn out to be ugly looking, but unimportant for skywave propagation.

120/60-foot stack doesn't cover the range of elevation angles as well as it could, and is inferior to both the 90/60/30-foot stack and the 120/90/60/30-foot stack. The 120/60-foot two-Yagi stack needs at least one more antenna placed in-between to spread out the elevation-range coverage and to provide more gain.

It could be debated, but the 90/60/30-foot stack seems optimal for coverage of all the angles into Europe from New England on 15 meters. Note that the 30-foot spacing between Yagis is 0.65 λ on 21.2 MHz, right in the middle of the range of typical stack spacings.

Switching Out Yagis in the Stack

Still, the extra gain that is available at low elevation angles from a 120/90/60/30-foot high, four-Yagi stack in Figure 14.50 is alluring. For those statistically possible, but less likely, occasions when the elevation angle is higher than about 12°, it would be advantageous to switch out the top 120-foot Yagi and operate with only the lower three Yagis in a stack. (This also allows the top antenna to be rotated in another direction, an aspect we'll explore later.) There are even times when the incoming angles are really high and when the top two antennas might be switched out to create a 60/30-foot stack. Later in this chapter we'll present circuitry for such stack switching.

Stacking Distance and Lobes at HF

Let's look a little more closely at how a stack achieves gain and a wide elevation footprint. **Figure 14.51** shows a rectangular X-Y graph of the elevation response from 0° to 180° for two 3-element 15 meter Yagis (with 12-foot booms) spaced 30 feet apart (0.65 λ at 21.2 MHz), but mounted at two different heights: 95/65 and 85/55 feet. The rectangular plot gives more resolution than is possible on a polar plot. Note that the heights shown represent typical stacking heights on 15 meters — there's nothing magic about these choices. The free-space H-Plane pattern for the 30-foot spaced stack is also shown for reference.

The worst-case overhead elevation lobe, which ranges from about 60° to 120° in elevation (±30° from straight overhead at 90°), is about 14.7 dB down for the 95/65-foot stack. The overhead lobe peaks broadly at an elevation angle of about 82°. The overhead lobe for the lower 85/55-foot stack occurs at an elevation of about 64°, where it is 19 dB down.

The F/B for both 3-element sets of heights is about 15 dB, well down from the excellent 32 dB F/B for each Yagi by itself. The degradation of F/B is mainly due to mutual coupling to its neighbor in the stack.

The ground-reflection pattern in effect "modulates" the free-space pattern of the individual Yagi, but in a complex and not always intuitive manner. This is quite evident for the 85/55-foot stack at near-overhead angles. In this region things become complicated indeed, because the fourth and fifth lobes due to ground reflections are interacting with the free-space pattern of the stack.

Because the spacing remains constant at 30 feet for these pairs of antennas, however, the main determinant for the upper-elevation angle lobes is the distance of the horizontally polarized antennas above the ground, not the spacing between them.

Changing the Stack Spacing

Figure 14.52 demonstrates just how complicated things get for four different spacing scenarios. Here, the lower Yagi in the stack is moved down in 5-foot increments from the 95/70 feet level, to 95/65, 95/60 and 95/55 feet. The closest spacing, 25 feet in the 95/70-foot stack, yields nominally the "cleanest" pattern in the overhead region from 60° to 120°. The worst-case overhead lobe for the 95/70-foot stack is down 28 dB from peak. The F/B is again about 15 dB.

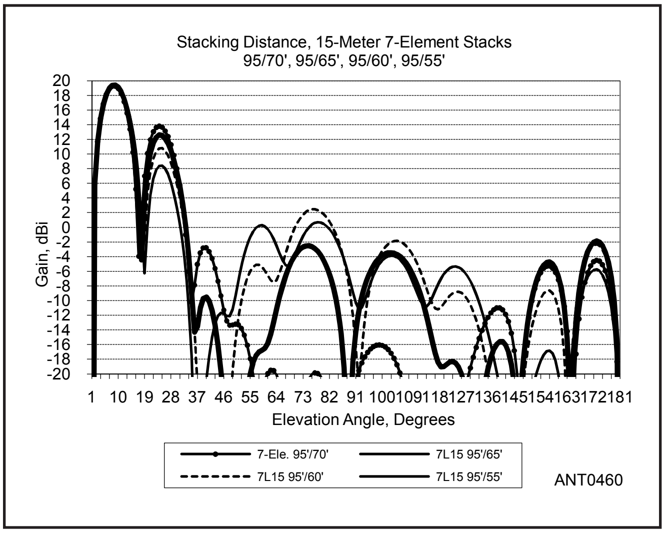

Figure 14.53 — Four spacing scenarios for two large 7-element 15-meter Yagis (on 64-foot booms). Again, a 0.65-λ spacing (30 feet) provides the most stacking gain.

The worst case overhead lobe for the widest spacing, 40 feet in the 95/55-foot stack, is about 11 dB down from peak. The F/B has increased marginally, but is still only about 16 dB. It is difficult to pinpoint directly whether the spacing or the height above ground is the major determinant for the various lobe amplitudes for the 3-element stack. We'll soon look closely at whether the overhead lobe is important or not for HF work.

Longer Boom Length and Stack Spacing

Figure 14.53 shows the same type overlay of elevation plots, but this time for two 7-element 15 meter Yagis on gigantic 64-foot booms. These Yagis are also spaced 30 feet apart (0.65 λ at 21.2 MHz), mounted at the same four sets of heights in Figure 14.52. As you'd expect, the free-space elevation pattern for a stacked pair of 7-element Yagis on 64-foot booms is narrower than that for a stacked pair of 3-element Yagis on 12-foot booms. The intrinsic F/B of the longer Yagi is also better than the F/B of the shorter antenna. As a result, all lobes beyond the main lobe of the stacked 7-element pair are lower for both sets of heights than their 3-element counterparts. The worst-case overhead lobe for the 7-element 95/65-foot pair is about 22 dB down at 76° and the F/B at 172° is greater than 21 dB for all four sets of heights.

Table 14.2 summarizes the main performance characteristics for four sets of stacked Yagis. The first entry for each boom length is for the Yagi by itself at a height of 95 feet. Stacked configurations are next listed in order of gain. The column labeled "Worst lobe, dB re Peak" is the amplitude of the second lobe due to ground reflections, and the elevation angle of that second lobe is listed as well.

Besides the 3- and 7-element designs discussed above, we've also added 4- and 5-element designs in Table 14.2. Over the range of stacking distances between 20 and 40 feet on 15 meters (0.43 λ to 0.86 λ), the peak gain for the 3-element stacks changes less than 0.75 dB, with the 30-foot spacing exhibiting the highest gain. The differences between peak gains versus stacking distance become smaller as the boom length increases. For example, for the 64-foot boom Yagi, the gain varies 19.39 – 19.08 = 0.31 dB for stack spacings from 20 to 40 feet.

In other words, changing the spacing from 20 to 40 feet (0.43 λ to 0.86 λ) doesn't change the gain significantly for boom lengths from 12 to 64 feet (0.26 λ to 1.38 λ). From the point of view of gain,

Table 14.2
Example, Spacing Between 15-Meter Yagis

Antenna	*Peak Gain (dBi)*	*Worst Lobe (dB re Peak)*	*Worst Lobe Angle (°)*	*F/B (dB)*	*Overhead Lobe (dB re Peak)*
3 Elements, 12 Foot Boom					
By itself 95'	13.2	–0.9	21	28.8	–17.5
95'/65' (Δ 30')	16.08	–4.5	25	14.9	–14.7
95'/60' (Δ 35')	16.01	–6.2	24	15.1	–10.9
95'/70' (Δ 25')	15.81	–3.2	24	14.8	–28
95'/55' (Δ 40')	15.71	–8.7	24	16.4	–11
95'/75' (Δ 20')	15.34	–2.3	23	16.3	–17.2
4 Elements, 18 Foot Boom					
By itself 95'	13.92	–1	21	28.3	–20.4
95'/65' (Δ 30')	16.63	–4.5	23	18.5	–17.3
95'/60' (Δ 35')	16.6	–6.2	24	18.2	–13.1
95'/55' (Δ 40')	16.36	–8.7	24	19.8	–13.2
95'/70' (Δ 25')	16.36	–3.3	24	20.4	–31.8
95'/75' (Δ 20')	15.92	–2.5	23	25.9	–19
5 Elements, 23 Foot Boom					
By itself 95'	14.26	–1.1	21	27.9	–22.3
95'/65' (Δ 30')	16.86	–4.6	24	20.8	–19
95'/60' (Δ 35')	16.86	–6.3	24	20.7	–14.4
95'/55' (Δ 40')	16.67	–8.8	24	23.5	–14.4
95'/70' (Δ 25')	16.59	–3.4	24	24.9	–34.4
95'/75' (Δ 20')	16.18	–2.6	23	34.3	–20.2
7 Elements, 64 Foot Boom					
By itself 95'	17.93	–2.2	21	28.9	–17.1
95'/65' (Δ 30')	19.39	–6.9	24.3	21.4	–21.9
95'/60' (Δ 35')	19.38	–8.6	24	21.4	–16.9
95'/55' (Δ 40')	19.29	–10.9	24	25.0	–18.6
95'/70' (Δ 25')	19.26	–5.5	23	24	–35.3
95'/75' (Δ 20')	19.08	–4.6	23	27	–23.4

the vertical spacing between individual antennas in an HF stack is not critical.

The worst-case lobes (generally speaking, the second lobe due to ground reflections) are highest for a Yagi operated by itself. After all, a single Yagi doesn't benefit from the redistribution of energy from higher-angle lobes into the main lobe that a stack gives. Thus, the 3-element, 12-foot boom Yagi by itself at 95 feet would have a second lobe at 21° that is only 0.9 dB down from the main lobe, while the stack of two such antennas with 30-foot (0.65 λ) spacing at 95/65 feet would have a second lobe down 4.5 dB. As the spacing between antennas in a vertical stack increases, the second lobe is suppressed more, up to 8.7 dB with 40-foot (0.86 λ) spacing.

Since the free-space elevation pattern for a 3-element Yagi is wider than that for a 7-element Yagi, the second lobe due to ground reflection will be somewhat reduced. This is true for all longer-boom antennas operating by themselves over ground. Used in stacks, the second lobe's amplitude will vary depending on spacing between antennas, but they range only about 6 dB.

The front-to-back ratio will also tend to increase with longer boom lengths on a properly designed Yagi. Table 14.2 shows that the F/B is somewhat better for closer spacings between antennas in a stack, a rather non-intuitive result, considering that the mutual coupling should be greater for closer antennas. For example, the 5-element Yagi stack with 20-foot spacing has a exceptional F/B of 34.3 dB, compared to a F/B of 21.4 dB with the 30-foot spacing distance that gives nominally the most gain. High values of F/B, however, rarely hold over a wide frequency range because of the very critical phasing relationships necessary to get a deep null, so the difference between 34.3 and 21.4 dB would rarely be noticeable in practice.

The near-overhead lobe structure (between 60° to 120° in elevation) tends also to be lower for smaller stack spacings — for all boom lengths — peaking in this example at a spacing of 25 feet for the boom lengths considered here. Since the peak gain actually occurs with smaller spacing between Yagis in this 7-element stack, even relatively large and messy looking overhead lobes are not subtracting from the stacking gain. In the next section we'll now examine whether this overhead lobe is important or not.

Stacking Distances for Multiband Yagis

By definition, a stack of multiband Yagis (such as a "tribander" covering 20/15/10 meters) has a constant vertical spacing between antennas in terms of feet or meters, but not in terms of wavelength. Tribanders are no different than monobanders in terms of optimal spacing between individual antennas. Again, the difference in gain between spacings of 0.5 λ and 1.0 λ for a stack of triband Yagis amounts to only a fraction of a decibel. Furthermore, the main practical constraint that limits choice of stacking distances between any kind of Yagis, multiband or monoband, is the spacing between guy wire sets on the tower itself.

Summary — Stacking Distances

In short, let us summarize that there is nothing magical about stacking distances for practical HF Yagis — a good rule-of-thumb is a stacking distance of 0.65 λ. This is 23 feet on 10 meters, 30 feet on 15 meters and 45 feet on 20 meters for monoband stacks. Practically speaking, however, you've only got limited places where you can mount antennas on the tower — mainly where guy wires allow you to place them. This is especially applicable if you wish to rotate lower antennas on the tower, where you must clear the guys from above the antenna.

14.4.5 RADIATION OUTSIDE THE MAIN LOBE

The Importance of Higher-Angle Lobes

We've already shown that the exact spacing between HF Yagis is not critical for stacking gain. Further, the heights (and hence spacing) of the individual Yagis in a stack interact in a complicated fashion to determine higher-angle lobes.

Let's examine the relevance of such higher-angle lobes for stacked HF Yagis, this time in terms of interference reduction on receive. As the **Radio Wave Propagation** chapter points out, few DX signals arrive at elevation angles greater than about 30°. In fact, DX signals only propagate at elevation angles in the range from 1° to 30° on all the bands where operators might reasonably expect to stack Yagis — nominally from 7 to 29.7 MHz.

You should remember that the definition of the *critical frequency* for HF propagation is the highest frequency for which a wave launched directly overhead at 90° elevation is reflected back down to Earth, rather than being lost into outer space. The maximum critical frequency for extremely high levels of solar flux is about 15 MHz. In other words, high overhead angles do not propagate signals on the upper HF bands.

However, some domestic signals do arrive at relatively high elevation angles. Let's look at some scenarios where higher angles might be encountered and how the elevation patterns of typical HF stacks affect these signals. Let's examine a situation where a medium-range interfering station is on the same heading as a more distant target station.

We'll examine a typical scenario involving stations in Atlanta, Boston and Paris. The heading from Atlanta to Paris is 49°, the same heading as Atlanta to Boston. In other words, the Atlanta station would have to transmit over (and listen through) a Boston station for communication with Paris. The distance between Atlanta and Boston is about 940 miles, while the distance from Atlanta to Paris is about 4350 miles. Ground wave signals obviously cannot travel either of these distances at 21 MHz (ground wave coverage is less than about 10 miles at this frequency), and so the propagation between Atlanta to Boston and Atlanta to Paris will be entirely by means of the ionosphere.

Let's evaluate the situation on 15 meters in the month of October. We'll assume a smoothed sunspot number (SSN) of 100 and that each station puts 1500 W of power into

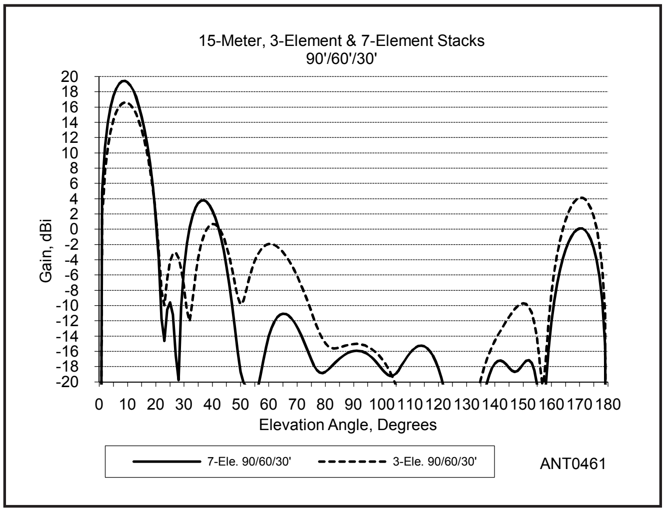

Figure 14.54 — Stacks of three 3-element and 7-element Yagis on 15 meters at 90/60/30 feet heights. The F/B for the 7-element stack is superior to the 3-element stack mainly because the F/B is intrinsically better for the long-boom design.

theoretical isotropic antennas that have +10 dBi of gain at all elevation and azimuth angles. [We use such theoretical isotropic antennas because they make it easier to work in *VOACAP*. We will factor in real-world stacks later.] *VOACAP* predicts that the signal from Boston will be S9 + 8 dB in Atlanta at 1400 UTC, arriving at an elevation angle of 21.3° on a single F2 hop. This elevation angle is higher than commonly encountered angles for DX signals, but it is still far away from near-overhead angles.

The signal from Paris into Atlanta is predicted to be about S6 for the same theoretical isotropic antennas, at an incoming elevation angle of 6.4° on three F2 hops. The S6 level validates the rule-of-thumb that each extra hop loses approximately 10 dB of signal strength, assuming that each S unit is about 4 dB, typical for modern receivers.

Now look at **Figure 14.54**, which shows the response for a stack of 3-element Yagis at 90/60/30 feet over flat ground, along with the response for a similar stack of 7-element Yagis. Again, we'll assume that all three stations are using such 3-element 90/60/30-foot stacks. The stations in Atlanta and Boston point their stacks into Europe and the Parisian station points his stack toward the USA. The gain of the Atlanta array at 6.4° into Paris will be about 16 dBi, or 6 dB more than the isotropic array with its +10 dBi of gain selected for use in *VOACAP*. Similarly, the French station's transmitted signal will enjoy a 6 dB gain advantage over the isotropic array used in the *VOACAP* calculation, and thus the French signal into Atlanta will now be S6 + 12 dB, or about S9.

By comparison, the interfering signal from Boston into Atlanta will be reduced by the rearward pattern of his array, which will launch a signal at 180° – 21.3° = 158.7° in elevation at the single F2 mode from Boston to Atlanta. From Figure 14.51, the Boston station's gain at this rearward elevation is going to drop from the isotropic's +10 dBi of gain down to –11 dBi, a drop of 21 dB. The signal into the Atlanta receiver will also be reduced by the pattern of the Atlanta array on receive, which has a gain of about 0 dBi at 21.3°, compared to the isotropic's +10 dBi gain at 6.4°, a net drop of 10 dB.

Thus, the Boston station's signal will drop by about 21 + 10 = 31 dB, bringing the interfering signal from Boston, which would be S9 + 8 dB for isotropic antennas, down to about S3 due to the combined effects of the arrays. This is a very significant reduction in interference. But you will note that the reduction has nothing to do with the near-overhead lobes, dealing as it does with the trailing edge of the main lobe and the F/B lobe.

Higher Elevation Angles

Now let's evaluate a station that is even closer to Boston, say a station in Philadelphia. The heading from Philadelphia to Paris is 53° and the distance is 3220 miles. On the same day in October as above, *VOACAP* predicts a signal strength of S8 from Paris to Philadelphia, at a 2.7° elevation angle on two F2 hops. Again, the *VOACAP* computations assume isotropic antennas with +10 dBi gain at all three stations. The gain of the 3-element stacks at both ends of the circuit at 2.7° is also about +10 dBi, so the signal level from Paris to Philadelphia would be S8 with the 3-element stacks.

Now *VOACAP* computes the elevation angle from Philadelphia to Boston as 56.3°, on one F_2 hop launched at an azimuth of 53°, well within the azimuthal beamwidth of the stack. *VOACAP* says the predicted signal strength for isotropic antennas with +10 dBi of gain is less than S1!

What's happening here? Boston and Philadelphia are within the "skip" region on 21 MHz and signals are skipping right over Boston from Philadelphia (and vice versa). Actual signals would be much weaker than they would be with theoretical isotropic antennas because of the actual patterns of the transmitting and receiving stacks. At an elevation angle of 56.3° the receiving stack would have a gain of –10 dBi, while at an elevation of 180° – 56.3° = 123.7° the transmitting stack would be down to –10 dBi as well. The net reduction for the stacks compared to isotropics with +10 dBi gain each would be 40 dB, putting the interfering signal well into the receiver noise.

You can safely say that near-overhead angles don't enter into the picture, simply because signals at intermediate distances are in the ionospheric skip zone and interfering signals are very weak in that zone already.

Even in situations where having a poor front-to-back ratio might be beneficial — because it alerts stations tuning across your signal that you are occupying that frequency — the ionosphere doesn't cooperate for intermediate-distance signals that are in the skip zone. Often two stations may be on the same frequency without either knowing that the other is there.

Ground Wave and Stacks

What happens, you might wonder, for ground-wave signals? Let's look at a situation where the interfering station is in the same direction as the desired target, but is only 5 miles away. Unfortunately, his signal is S9 + 50 dB. Even reducing the level by 30 dB, a huge number, is still going to make his signal 20 dB stronger than signals from your desired target location! There is not much you can do about ground-wave signals and fretting about optimizing stack heights to discriminate against local signals is generally futile.

14.4.6 REAL-WORLD TERRAIN AND STACKS

So far, the stacking examples shown have been for flat ground. Things can become a lot more complicated when you deal with real-world irregular terrains! **Figure 14.55** shows the *HFTA*-computed 20 meter elevation responses toward Europe (at an azimuth of 45°) for three antennas at the N6BV/1 location in Windham, New Hampshire. Overlaid as a bar graph are the elevation-angle statistics for the path to all of Europe from New England (Massachusetts). The stack at 90/60/30 feet clearly covers all the angles needed best at 14 MHz. The N6BV/1 120-foot Yagi has a severe null in the region from about 7° to about 20°, with the deepest part of that null occurring at about 13° and is roughly comparable to the 90/60/30-foot stack between 2° to 7°.

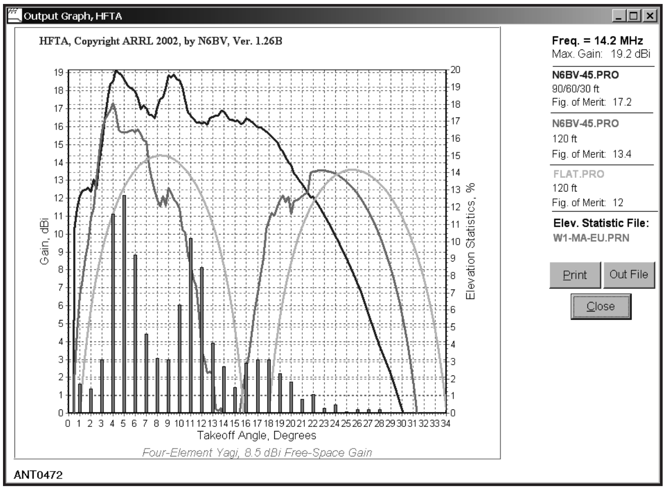

Figure 14.55 — *HFTA* screen shot showing how complicated things become when real-world irregular terrain is analyzed. This is the 20-meter elevation pattern for the N6BV/1 station location in Windham, NH, for the 90/60/30-foot stack of triband TH7DX Yagis and a 4-element Yagi at 120 feet on the same tower. For comparison, the response of a 120-foot Yagi over flat ground is also included.

In practice, the 120-foot Yagi was indeed comparable to the stack during morning openings to Europe on 20 meters, when the elevation angles are typically about 5°. In the New England afternoon, when the elevation angles typically rise to about 11°, the 120-foot Yagi was always distinctly inferior to the stack.

For reference, the response of a single 120-foot high Yagi over flat ground is also shown. Note that the N6BV 120-foot high Yagi has about 3 dB more gain at a 5° takeoff angle than does its flatland counterpart. This additional gain is due to the focusing effects of the local terrain, which had about a 3° downward slope toward Europe.

Figure 14.56 shows the *HFTA*-computed 15 meter elevation responses toward Europe for the 90/60/30-foot stack at 90/60/30 feet at N6BV/1, compared to the same 120-foot high Yagi and a 90/60/30-foot stack, but this time over flat ground. Again, the N6BV/1 terrain toward Europe has a significant effect on the gain of the stack compared to that of an identical stack over flat ground. In fact, the peak gain of 20.1 dBi at a 4° elevation angle is close to moon-bounce levels.

Optimizing Over Local Terrain

There are only a small number of possibilities to optimize an installation over local terrain:

- ■Change the antenna height(s) above ground.
- ■Stack two (or more) Yagis.
- ■Change the spacing between stacked Yagis.
- ■Move the tower back from a cliff (or a hill).
- ■BIP/BOP (Both In Phase/Both Out of Phase).

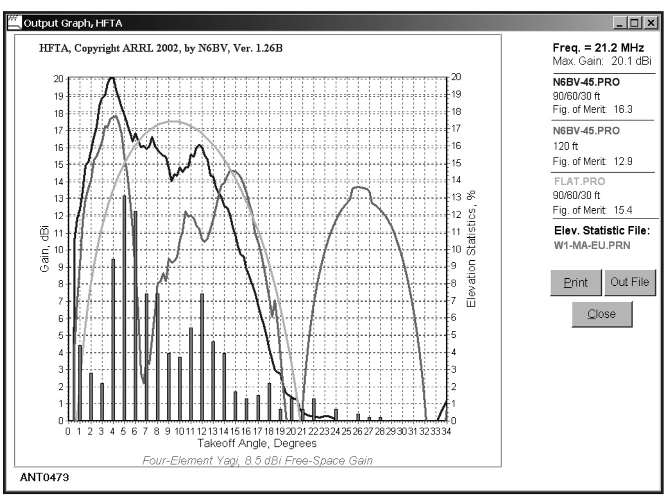

Figure 14.56 — *HFTA* screen shot showing the 15-meter elevation pattern for the N6BV/1 station location in Windham, NH, for the 90/60/30-foot stack of triband TH7DX Yagis and a 4-element Yagi at 120 feet on the same tower. For comparison, the response of a 120-foot Yagi over flat ground is also included.

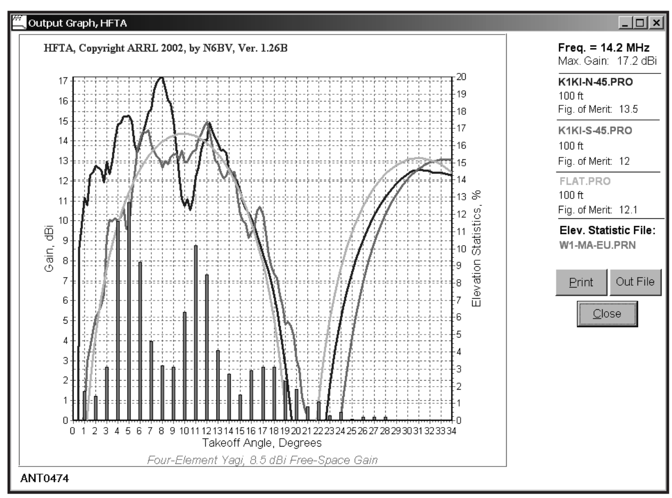

Figure 14.57 — *HFTA* screen shot showing the 20-meter elevation pattern for K1KI's North and South towers, with 100-foot high 4-element Yagis pointing into Europe at an azimuth of 45°. The responses are surprisingly different for two towers separated by only 600 feet.

The *HFTA* program on the CD-ROM accompanying this book can be used, together with Digital Elevation Model (DEM) topographic data available on the Internet, to evaluate all these options.

It is sometimes very surprising to compare elevation responses for different towers located at various points on the same property, particularly when that property is located in the mountains. **Figure 14.57** shows the computed elevation responses for three 100-foot high 14-MHz Yagis over three terrains toward Europe: from the North tower at K1KI's location in West Suffield, Connecticut, from the South tower at K1KI, and over flat ground. The elevation response from the South tower follows that over flat ground well, while the response from the North tower is quite a bit stronger at low elevation angles — about 1.5 dB on average, as the Figure of Merit shows from *HFTA*.

Figure 14.58 shows the reason why this happens — the terrain from the North tower slopes down quickly toward Europe, while the terrain from the South tower goes out almost 900 feet before starting to fall off. These two towers are about 600 feet apart.

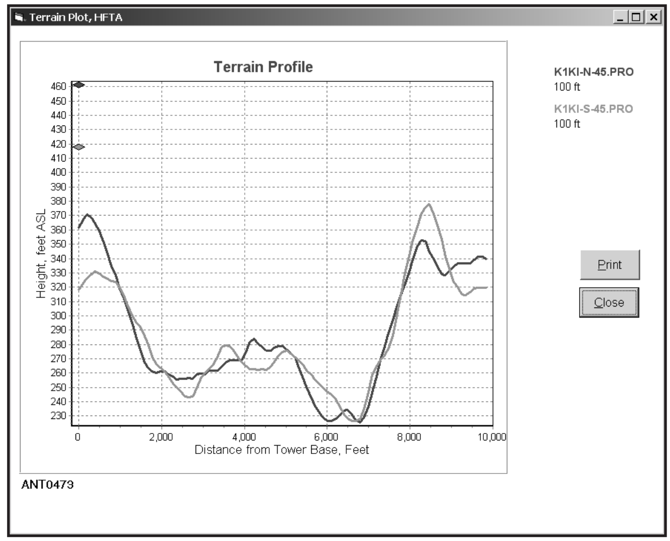

Figure 14.58 — K1KI's terrain profiles for the North and South towers at an azimuth of 45° into Europe.

14.4.7 STACKING TRIBANDERS

Enterprising amateurs have built stacked tribander arrays even with full recognition that they are compromise antennas when compared one-on-one against monoband Yagis. Bob Mitchell, N5RM, is a prominent example, with his so-called "TH28DX" array of four TH7DX tribanders on a 145-foot-high rotating tower. Mitchell employed a rather complex system of relay-selected tuned networks to choose either the upper stacked pair, the lower stacked pair or all four antennas in stack. Others in Texas have also had good results with their tribander stacks. Contester Tom Owens, K7RI, has very successfully used a pair of stacked KT-36XA tribanders for years.

A major reason why tribanders were used is that over the years both amateurs have had good results using TH6DXX or TH7DX antennas. They are ruggedly built, mechanically and electrically, and their 24-foot long booms are long enough to produce significant gain, despite trap-loss compromises. Trap losses estimated at approximately 0.5 dB are not high enough to be of serious concern. A long-boom tribander like the TH6DXX or TH7DX also has enough space to employ elements dedicated to different bands, so the compromises in element spacing usually found on short-boom 3 or 4-element tribanders can be avoided.

Another factor in favor of tribanders is the serious interaction that can result from stacking monoband antennas closely together on one mast in a Christmas Tree configuration. N6BV's worst experience was with the ambitious 10 through 40 meter Christmas Tree at W6OWQ in the early 1980s. This installation used a Tri-Ex SkyNeedle tubular crank-up tower with a rotating 10-foot-long heavy-wall mast. The antenna suffering the greatest degradation was the 5-element 15 meter Yagi, sandwiched 5 feet below the 5-element 10 meter Yagi at the top of the mast, and 5 feet above the full-sized 3-element 40 meter Yagi, which also had five 20 meter elements interlaced on its 50-foot boom.

The front-to-back ratio on 15 meters was at best about 12 dB, down from the 25+ dB measured with the bottom 40/20 meter Yagi removed. No amount of fiddling with element spacing, element tuning or even orientation of the 15 meter boom with respect to the other booms (at 90° or 180°, for example) improved its performance. Further, the 20 meter elements had to be lengthened by almost a foot *on each end of each element* in order to compensate for the effect of the interlaced 40 meter elements. It was a lucky thing that the tower was a motorized crank-up, because it went up and down hundreds of times as various experiments were attempted!

Interaction due to close proximity to other antennas in a short Christmas Tree can definitely destroy carefully optimized patterns of individual Yagis. Nowadays, such interaction can be modeled using a computer program such as *EZNEC* or *NEC*. A gain reduction of as much as 2 to 3 dB can easily result due to close vertical spacing of monobanders, compared to the gain of a single monoband antenna mounted in the clear. Curiously enough, at times such a reduction in gain can be found even when the front-to-back ratio is not drastically degraded, or when the front-to-back occasionally is actually *improved*.

If you plan on stacking monoband Yagis — for example, putting 15 and 20 meter Yagis on a single tower, do make sure you model the system to see if any interactions occur. You may be quite surprised.

Finally, triband antennas make for less mechanical complexity than do an equivalent number of monobanders. There were five Yagis on the N6BV/1 tower, yielding gain from 40 to 10 meters, as opposed to using 12 or 13 monobanders on the tower.

Simple Tribander Stacks

All this discussion of large stacks of many antennas is simply out of the question for most amateurs. However, many hams already have a tribander on top of a moderately tall tower, typically at a height of about 70 feet. It is not terribly difficult to add another, identical tribander at about the 40-foot level on such a tower. The second tribander can be pointed in a fixed direction of particular interest (such as Europe or Japan), or it can be rotated around the tower on a side mount or a Ring Rotor. If guy wires get in the way of rotation, the antenna can usually be arranged so that it is fixed in a single direction.

Insulate the guy wires at intervals to ensure that they don't shroud the lower antenna electrically. A simple feed system consists of equal-length runs of surplus ½-inch 75-Ω hardline (or more expensive 50-Ω hardline, if you are really obsessed by SWR) from the shack up the tower to each antenna. Each tribander is connected to its respective hardline feeder by means of an equal length of flexible coaxial cable, with a ferrite choke balun, so that the antenna can be rotated.

Down in the shack, the two runs of hardline can simply be switched in and out of parallel to select the upper antenna only, the lower antenna only, or the two antennas as a stack. See **Figure 14.59**. Any impedance differences can be handled as stated previously, simply by retuning the linear amplifier, or by means of the internal antenna tuner (included in most modern transceivers) when the transceiver is run barefoot. The extra performance experienced in such a system will be far greater than the extra decibel or two that modeling calculates.

14.4.8 STACKING DISSIMILAR YAGIS

So far we have been discussing vertical stacks of identical Yagis. Less commonly, hams have successfully stacked dissimilar Yagis. For example, consider a case where two 5-element 10 meter Yagis are placed 46 and 25 feet above flat ground, with a 7-element 10 meter Yagi at 68 feet on the same tower. See **Figure 14.60**, which is a schematic of the layout for this stack. Note that the driven element for the top 7-element Yagi is well behind the vertical plane of the driven elements for the two 5-element Yagis. This offset distance must be compensated for with a phase shift in the drive system for the top Yagi.

Figure 14.61 shows the elevation-pattern responses for uncompensated (equal-length feed lines) and the compensated (additional 150° of phase shift to top Yagi) stacks. These patterns were computed using *EZNEC*. Not only is about 1.7 dB of maximum gain lost, but the peak elevation angle is shifted upward by 11° from the optimal takeoff angle of 8° — where some 10 dB of gain is also lost. Without compensation, this is a severe distortion of the stack's elevation pattern.

For RG-213 coax, the extra length needed to provide an additional 150° of phase shift = 150°/360° λ = 0.417 λ = 9.53 feet at 28.4 MHz. This was computed using the program *TLW*

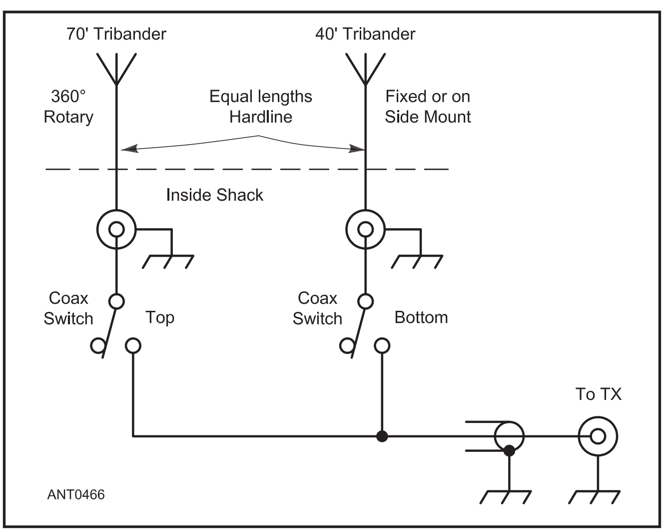

Figure 14.59 — Simple feed system for 70/40-foot stack of tribanders. Each tribander is fed with equal lengths of 0.5-inch 75-Ω Hardline cables (with equal lengths of flexible coax at the antenna to allow rotation), and can be selected singly or in parallel at the operator's position in the shack. Again, no special provision is made in this system to equal SWR for any of the combinations.

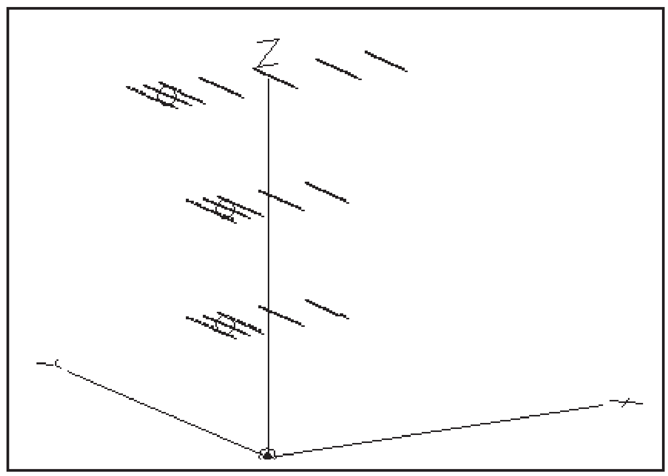

Figure 14.60 — Stacking dissimilar Yagis. In this case a 7-element 10-meter Yagi is stacked over two 5-element Yagis. Note the displacement of the 7-element Yagi's driven element compared to the position of the two 5-element Yagis. This leads to an undesired phase shift for the higher antenna.

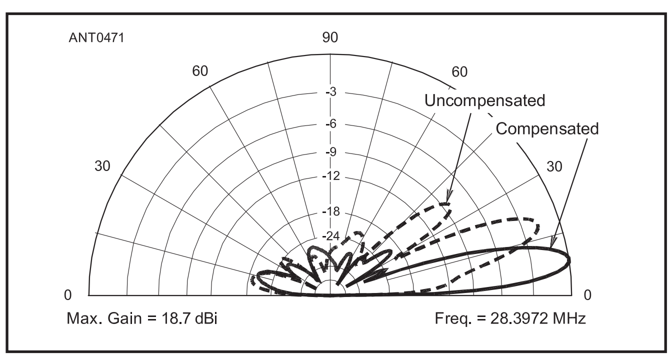

Figure 14.61 — Comparison of elevation responses for 7/5/5-element 10-meter stacks, with and without compensation for driven-element offset.

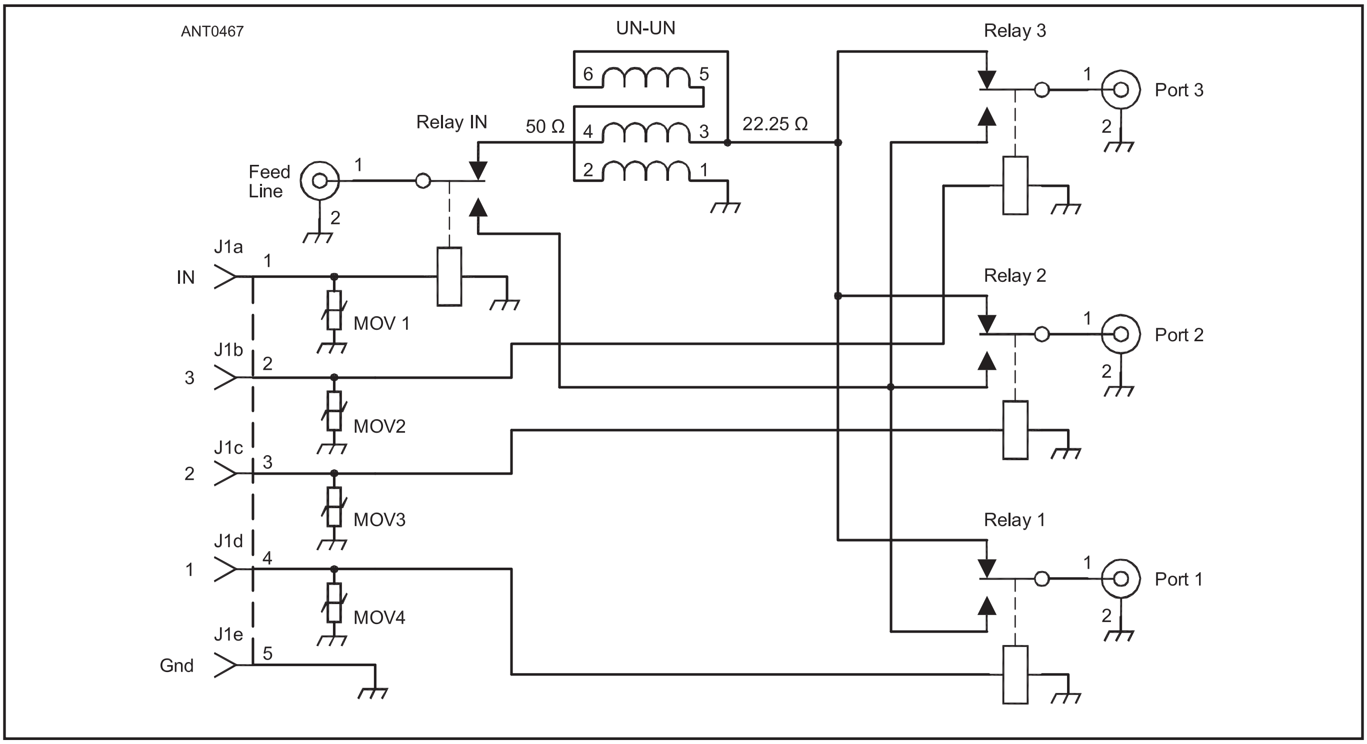

Figure 14.62 — Schematic of WXØB's StackMatch 2000 switchbox, which uses a broadband transmission line transformer using trifilar #12 enamel-insulated wires. (*Courtesy Array Solutions.*)

(Transmission Line for *Windows*) included on the CD-ROM accompanying this book.

It is not always possible to compensate for dissimilar Yagis in a stack with a simple length of extra coax, so you should be sure to model such combinations to make sure that they work properly. A safe alternative, of course, is to stack only identical Yagis, feeding all of them with equal lengths of coax to ensure in-phase operation.

14.4.9 THE WXØB APPROACH TO STACK SWITCHING

Earlier we mentioned how useful it would be to switch various antennas in or out of a stack, depending on the elevation angles that need to be emphasized at that moment. Jay Terleski, WXØB, of Array Solutions (**www.arraysolutions.com**) has designed switchable matching systems, called *StackMatches*, for stacks of monoband or multiband Yagis. This has become the standard method of switching for stacks of Yagi antennas, whether monoband or triband. (A description of two other systems used by N6BV/1 and K1VR is included on this book's CD-ROM.)

The StackMatch uses a 50-Ω to 22.25-Ω broadband transmission-line transformer to match combinations of up to three Yagis in a stack. See **Figure 14.62** for a schematic of the StackMatch. For selection of any 50-Ω Yagi by itself, no matching transformer is needed and Relay IN routes RF directly to the common bus going to Relay 1, 2 and 3. For selection of two Yagis together the parallel impedance is 50/2 = 25 Ω and Relay IN routes RF to the matching transformer. The SWR is 25/22.25 = 1.1:1. For three Yagis used together, the parallel impedance is 50/3 = 16.67 Ω, and the SWR is 22.25/16.67 = 1.3:1.

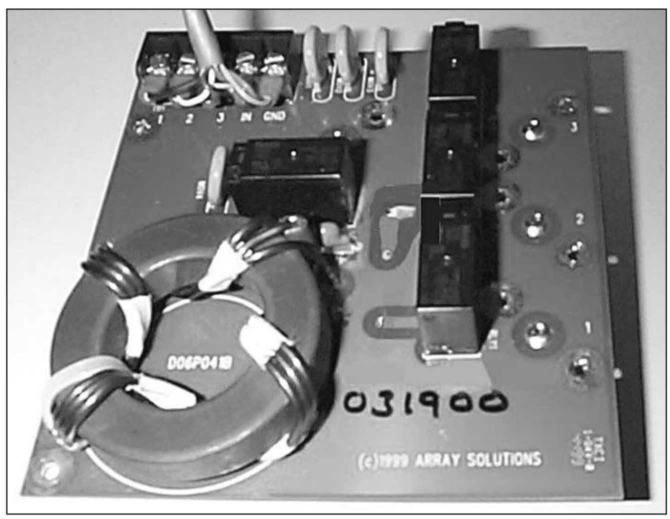

Figure 14.63 — Inside view of StackMatch. (*Photo courtesy Array Solutions.*)

The broadband transformer consists of four trifilar turns of #12 enamel-insulated wire wound on a Ferrite Corporation FT-240 2.4-inch OD core made of #61 material (μ = 125). WXØB uses 10-A relays enclosed in plastic cases to do the RF switching, selected by a control box at the operating position. (10-A relays can theoretically handle 10 $A^2 \times 50\ \Omega$ = 5000 W.) **Figure 14.63** shows a photo of the transmission-line transformer and StackMaster PCB.

The control/indicator box uses a diode matrix to switch various combinations of antennas in/out of the stack. Three LEDs lined up vertically on the front panel indicate which antennas in a stack are selected.

14.4.10 MISCELLANEOUS TOPICS

Stacks and Fading

The following is derived from an article by Fred Hopengarten, K1VR, and Dean Straw, N6BV, in a February 1994 *QST* article. Using stacked Hy-Gain TH7DXs or TH6DXXs at their respective stations, they have solicited a number of reports from stations, mainly in Europe, to compare various combinations of antennas in stacks and as single antennas. The peak gain of the stack is usually just a little bit higher than that for the best of the single antennas, which is not surprising. Even a large stack has no more than about 6 dB of gain over a single Yagi at a height favoring the prevailing elevation angle. Fading on the European path can easily be 20 dB or more, so it is very confusing to try to make definitive comparisons. They have noticed over many tests that the stacks are much less susceptible to fading compared to single Yagis. Even within the confines of a typical SSB bandwidth, frequency-selective fading occasionally causes the tonal quality of a voice to change on both receive and transmit, often dramatically becoming fuller on the stacks, and tinnier on the single antennas. This doesn't happen all the time, but is often seen. They have also observed often that the depth of a fade is less, and the period of fading is longer, on the stacks compared to single antennas.

Exactly *why* stacks exhibit less fading is a fascinating subject, for which there exist a number of speculative ideas, but little hard evidence. Some maintain that stacks outperform single antennas because they can afford *space diversity* effects, where by virtue of the difference in physical placement one antenna will randomly pick up signals that another one in another physical location might not hear.

This is difficult to argue with, and equally difficult to prove scientifically. A more plausible explanation about why stacked Yagis exhibit superior fading performance is that their narrower frontal elevation lobes can discriminate against undesired propagation modes. Even when band conditions favor, for example, a very low 3° elevation angle on 10 or 15 meters from New England to Western Europe, there are signals, albeit weaker ones, that arrive at higher elevation angles. These higher-angle signals have traveled longer distances on their journey through the ionosphere, and thus their signal levels and their phase angles are different from the signals traversing the primary propagation mode. When combined with the dominant mode, the net effect is that there is both destructive and constructive fading. If the elevation response of a stacked antenna can discriminate against signals arriving at higher elevation angles, then in theory the fading will be reduced. Suffice it to say: In practice, stacks do reduce fading.

Stacks and Precipitation Static

The top antenna in a stack is often much more affected by rain or snow precipitation static than is the lower antenna. N6BV and K1VR have observed this phenomenon, where signals on the lower antenna by itself are perfectly readable, while S9+ rain static is rendering reception impossible on the higher antenna or on the stack. This means that the ability to select individual antennas in a stack can sometimes be extremely important for reasons unrelated to elevation angle.

Stacks and Azimuthal Diversity

Azimuthal diversity is a term coined to describe the situation where one of the antennas in a stack is purposely pointed in a direction different from the main direction of the stack. During most of the time in a DX contest from the East Coast, the lower antennas in a stack are pointed into Europe, while the top antenna is often rotated toward the Caribbean or Japan. In a stack of three identical Yagis, the first-order effect of pointing one antenna in a different direction is that one-third of the transmitter power is diverted from the main target area. This means that the peak gain is reduced by 1.8 dB, not a very large amount considering that signals are often 10 to 20 dB over S9 anyway when the band is open from New England to Europe.

Figure 14.64 shows the 3D pattern of a pair of 4-element Yagis fed in-phase at 95 and 65 feet, but where the lower antenna has been rotated 180° to fire in the –X direction. The backwards lobe peaks at a higher elevation angle because the antenna doing the radiating in this direction is lower on the tower. The forward lobe peaks at a lower angle because its main radiator is higher.

"BIP/BOP" Operation

The contraction "BIP" means "both in-phase," while "BOP" means "both out-of-phase." BIP/BOP refer to stacks containing two Yagis, although the term is commonly used for stacks containing more than two Yagis. In theory, feeding

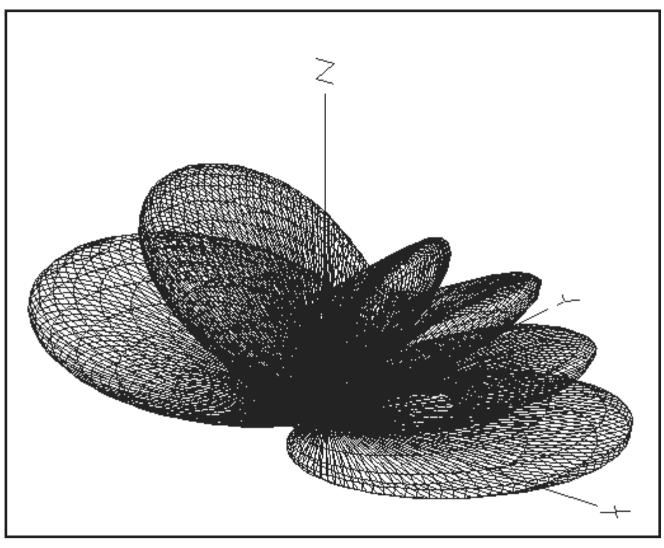

Figure 14.64 — 3D representation of the pattern for two 4-element 15-meter Yagis, with the top antenna at 95 and the bottom at 65 feet, but pointed in the opposite direction.

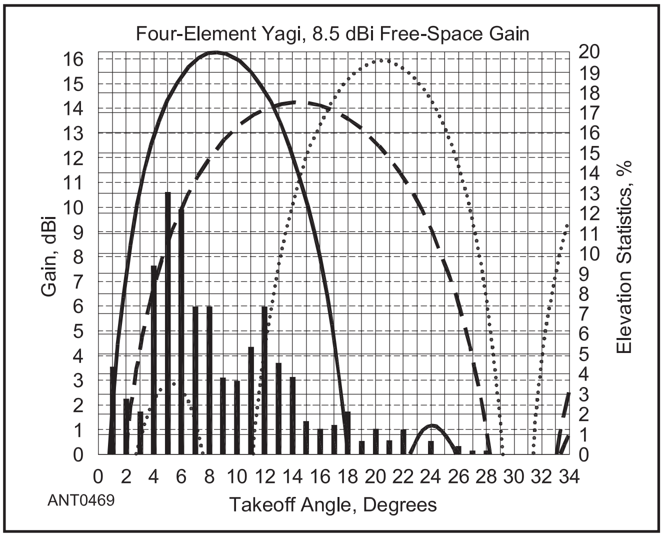

Figure 14.65 — *HFTA* screen shot of "BIP/BOP" operation of two 4-element 15-meter Yagis at 93 and 46 feet above flat ground. The elevation response in BOP (both out-of-phase) operation is shifted higher, peaking at about 21°, compared to the BIP (both in-phase) operation where the peak is at 8°. The dashed line is response of single Yagi at 46 feet.

a stack with the antennas out-of-phase will shift the elevation response higher than in-phase feeding.

Figure 14.65 shows a rectangular plot comparing BIP/BOP operation of two 3-element 15 meter Yagis at heights of 2 λ and 1 λ (93 and 46 feet) over flat ground. The BOP pattern is the higher-angle lobe and the two lobes cross over about 14°. The maximum amplitude of the BOP stack's gain is about ½ dB less than the BIP pair. For reference, the pattern of a single 46-foot high Yagi is overlaid on the pattern for the stacks.

The most common method for feeding one Yagi 180° out-of-phase is to include an extra electrical half wavelength of feed line coax going to one of the antennas. This method obviously works on a single frequency band and thus is not applicable to stacks of multiband Yagis, such as tribanders. For such multiband stacks, feeding only the lower antenna(s) — by switching out higher antenna(s) in the stack — is a practical method for achieving better coverage at medium or high elevation angles.