By L. B. Cebik, W4RNL

A Beginner's Guide to Modeling with *NEC*

Part 1: Getting settled and getting started

Antenna modeling has become a popular engineering and amateur activity. You can see the results in almost any issue of *QST*. Among the modeling products you might encounter are azimuth patterns, such as Figure 1, or elevation patterns, such as Figure 2, or even an SWR graph, such shown in Figure 3. Almost every ham knows that antenna-modeling software is available at reasonable prices. So only two important questions remain:

1. Can I model antennas, too? Can I master the software and produce the same kinds of results that I see in *QST*?

2. Is antenna modeling worth the effort? Does antenna modeling really offer me any information that I cannot easily get elsewhere?

The answer to both questions is a definite "yes." With a little coaching and a little practice, virtually any ham can effectively model many kinds of antennas. The result will be a better understanding of one's own antennas and of antennas in general. The purpose of this 4-part series is to provide the "little coaching" part of the effort. The practice is up to you.

In this first episode, we'll try to understand what antenna modeling is and become oriented to the many parts of a good antenna model. In future episodes, we'll take a closer (but still incomplete) look at crucial details that will make the task smoother and the output more understandable.

In all of our work, we'll focus our attention on the antenna-modeling core known as *NEC*-2. This public domain software is the heart of numerous commercial implementations that provide ways for the user to input data and also that supply tabular and graphical outputs. There is another modeling core called *MININEC*. Rockway and Logan developed it when PCs could not handle the *Fortran* of *NEC*. There are two versions available, a public domain version and a totally revised proprietary version.[1] The nature and limitations of *MININEC* have been covered in past ARRL publications, and so they need not be repeated here.[2]

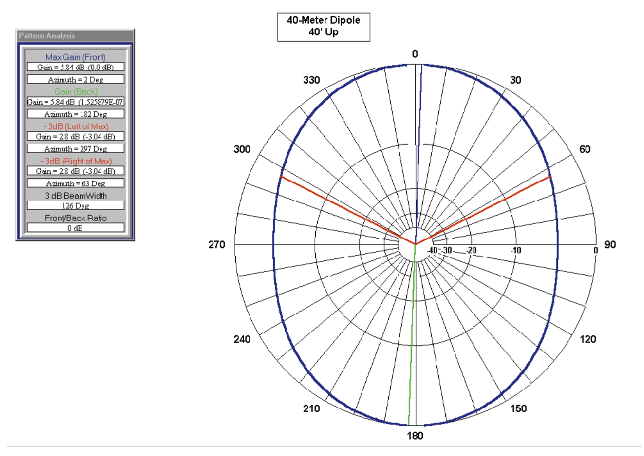

Figure 1—A (*NEC-Win Plus*) azimuth pattern for a dipole at 70 feet above average ground at 7.15 MHz with an elevation angle of 27°.

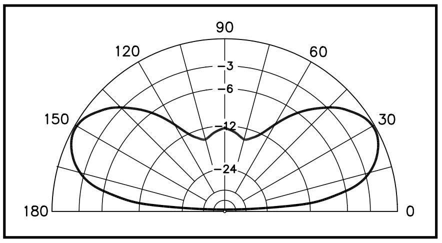

Figure 2—An (*EZNEC*) elevation pattern for a dipole at 70 feet above average ground at 7.15 MHz with an azimuth angle of 0 degrees.

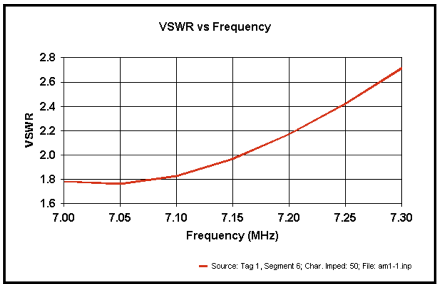

Figure 3—A (*NEC-Win Plus*) SWR graph for a 40-meter dipole at 70 feet above average ground.

Our focal software, *NEC*-2 is neither the newest nor the oldest modeling software.[3] It is the latest public domain core available and appears in several commercial implementations, as well as in "raw" form that one can download from more than one ftp site. For the beginner, one of the commercial versions is recommended, since the raw form requires that the user develop appropriate input and output systems.[4] I happen to have two different commercial versions of *NEC*-2—*EZNEC* 3.0 and *NEC-Win Plus*. Therefore, without prejudice toward or against any version, I shall be illustrating these guidelines by alternating among the programs I have. Figure captions will identify the program used for each graphic.

What is Antenna Modeling?

One common misconception of antenna modeling is that it is similar to making model boats and cars. The result sort of looks like—

[1]Notes appear on page 38.

and may even behave a little like—the real thing. Still, the model is a pretty but pale shadow of reality. Nothing could be further from the truth. So let's start all over again.

If you have ever referred to a formula to cut a dipole, you have done some rudimentary antenna modeling.

$$L_{ft} = \frac{468}{f_{MHz}} \qquad \text{Eq 1}$$

If we choose 7.15 MHz for our design frequency, then we need an antenna wire that is 65.45 feet long. Of course, the basic dipole formula always carries with it the advice to leave some extra wire and trim the length for the best SWR.

The formula does not include the diameter of the wire or the material out of which it is made. Nor does the formula account for the height of the antenna above ground or the properties of the soil that makes up the ground. Suppose we had a formula that would account for all of these factors?

We do. The oversimplified cutting formula for dipoles is just one small extract from a large body of mathematical analysis of antennas. If we place all of the most accurate equations into a single calculating piece of software, we would achieve much higher accuracy with our wire cutting. Not only could we analyze or predict the correct wire length for a resonant dipole, we could also calculate the field strength at any elevation above ground and in any direction from the antenna. This is exactly what *NEC* does. For many antenna types, *NEC*-2 is as accurate as engineering mathematics can make antenna analysis.

The basic antenna analysis used by *NEC*-2 relies on the "method of moments," a mathematical technique that subdivides an antenna element into segments, calculates the correct properties, and then combines the results to provide a set of results for the entire element (or an array of elements).[5] The results can be adjusted using standard engineering equations for material resistance, element loading, and ground effects. For the beginning modeler, two points are important to remember: (1) The method, when used within the limits of the software, is very accurate and (2) we have to think in terms of segments of our

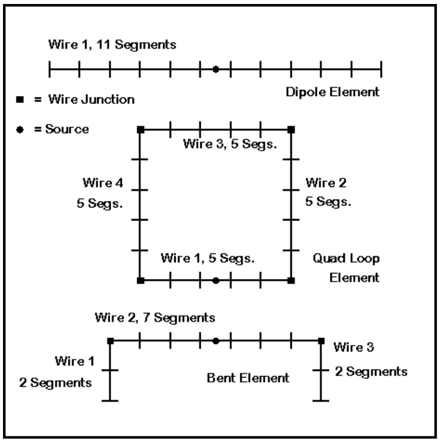

Figure 4—Several types of antenna elements with their segmented wire components.

antenna elements. Instead of dwelling on the math behind the core, let's learn how to think in modeling terms.

The Language of Modeling

Clearly, we'll have to add some new terms to our antenna language in order to get a good grip on antenna modeling. We have already encountered one of them: the *segment*. In fact, we may find it useful to think of three different terms to sort out pieces of an antenna and pieces of an antenna model.

Figure 4 shows several different types of antenna *elements*, a dipole, a quad loop, and a bent element such as might be used in a half square or a Moxon rectangle. *NEC* can only work with individual straight *wires*, although we can form complex geometric shapes by joining straight wires at their ends. In fact, if we needed to form a circle, we would have to approximate it with a collection of straight wires, perhaps an octagon. Whatever the shape, each wire composing each antenna element has the dimensions of that part of the real antenna element. Of course, the single wire dipole element brings together the "wire" and the "element," but we should always keep the ideas of an element and a modeling wire separate.

Next, each wire in an element should be segmented. For beginning modelers, the following two guidelines are useful to stay on the safe side of *NEC* limits for segmentation:

1. A wire should have at least 9 segments per half wavelength. If a wire is only a quarter wavelength long, then perhaps 5 segments is a good minimum number. We'll shortly see why we're using so many odd numbers.

2. The segment length should be at least 4 times larger than the wire diameter. There is a complex equation for figuring the absolute minimum segment length that is reliable, but in the beginning, the 4:1 ratio of segment length to wire diameter is a safe guideline.

Let's add one more guideline:

3. To the degree possible, make all segment lengths equal within a model. If we have a dipole consisting of one wire and specify 11 segments, then the program will automatically make them all the same length. However, for elements consisting of more than one wire, we'll have to look at the number of segments we assign in order to equalize their lengths. Dividing the wire length by the number of segments gives the segment length. If we know the segment length we want, then dividing the wire length by the segment length gives the number of segments.

The next step is to set up a model element. Let's remain with our simple 1-dipole wire. In order to model the element, we must know the orientation of the dipole. For this first model, we shall make it horizontal. In fact, let's play with a 40-meter dipole cut for 7.15 MHz. To determine the wire's length, we'll initially use our traditional formula and arrive at a length of 65.46 feet for our antenna.

In order to place the antenna into the model, we must master the world of 3 dimensions, also called *Cartesian coordinates*. This system is just a way of specifying directions, as shown in Figure 5. Relative to the earth, we can think of the X-axis and the Y-axis as two lines at 90° angles, both of which are parallel to the Earth's surface. Then, the Z-axis becomes another word for height above ground. Since we are going to start with a dipole above the Earth, the Z-value can never be below zero, although—as we shall see—it

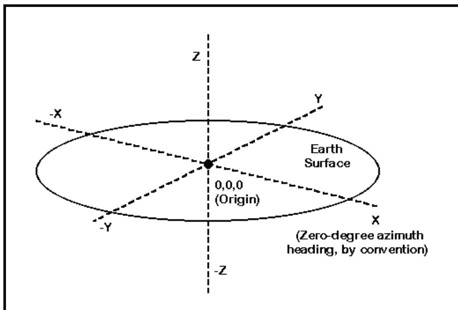

Figure 5—The Cartesian coordinate system with an "earth surface" shown.

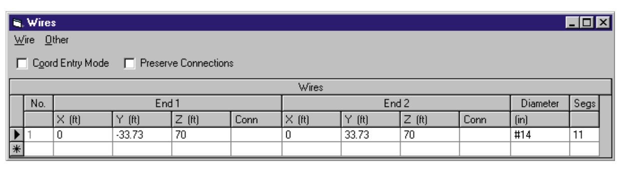

Figure 6—The *EZNEC* wire spreadsheet with 40-meter dipole components.

might be very close to zero.

As we begin to model, we need to begin to think systematically about antenna geometry. One of the most convenient (but not the only workable) systems for setting up a horizontal antenna is to place the ends equal distances along the Y axis. For most horizontal designs based on $^1/_2$-wavelength dipoles, this orientation will result in a pattern of radiation that is strongest along the X-axis, and the pattern value of zero degrees lies along this axis. So let's center the antenna on the X-axis and make the End-1 Y value –33.73 feet with the End-2 Y value +33.73 feet. Since we have only one wire, the X-value at both ends can be zero.

However, we must not neglect Z, the antenna height. Since a fairly common backyard value for the height of a 40-meter dipole is about 70 feet, let's use this value for Z—at both ends of the wire. Figure 6 shows the *EZNEC* wire window with exactly these values plugged in. Note that we have defined the wire by its end coordinates. If we had other wires as part of the same element, we would have added them by using either the End-1 or End-2 coordinates as the coordinates of one end of the extra wire. We shall explore more complex geometries in a future episode. For now, let's focus on mastering the language of the coordinate system of wire entry.

We can check our work for errors by looking at a diagram of the antenna that we have just entered. Most *NEC* programs have a "view antenna" option. Figure 7 shows the *EZNEC* view, with the antenna positioned above ground on the Z-axis and extending along the Y-axis on either side of the "origin," that is, the 0, 0, 0 point of the coordinate system.

Although the elements in all of our figures show feed points as small dots, we haven't yet added them to our model. In modeling language, a feed point is the source. We will have to specify both the position and the electrical conditions of the source. In *NEC*, the source is always the position within a segment, and for simplicity, we take its position to be centered.[6] If we wish to have a feed point or source positioned exactly at the center of an element wire, then we must have an odd number of segments on the wire. *NEC* was designed for voltage sources, so we shall specify a value of 1.0 for the magnitude and 0.0° for the phase for most common antennas having only a single feed point. For these kinds of antennas, changing the values we insert for the source will make no difference to the antenna pattern, gain or source impedance. We might as well keep it simple.

Different commercial implementations of *NEC* handle source setting in slightly different ways. The *NEC-Win Plus* system appears in Figure 8. We "drag and drop" the source symbol onto a picture of the wire that shows all of the segments. For an 11-segment dipole, we drop the symbol on segment 6. We then select the source type and values in a box that automatically appears. (The *EZNEC* system specifies the source position as a percentage of the wire length. For a center feed antenna, we specify 50%.)

The Other Parts of the Model

The work we have just done corresponds to cutting a piece of wire and stringing it up between supports. With a wire in place and having the correct dimensions, we can turn to the other parts of the program that we must set up before running the model. For example, the wire has a diameter that we can express in either the same dimensional units as the wire length (feet, in this case) or as an AWG wire gauge. Figure 9 shows the *NEC-Win Plus* wire diameter window that allows us simply to select a common wire gauge or provide a custom entry.

Not only does the wire have a diameter, it is also composed of a conductive material. We need to specify this material so that the program can account for any resistive losses in it. In Figure 9, we also see the separate *NEC-Win Plus* selection box for common materials. There is a place for entering the conductivity of materials not listed, a topic we shall look at down the line. For now, checking "copper" will get us started. Incidentally, the corresponding materials window in *EZNEC* will allow custom entries in terms of resistivity, which is simply the inverse of conductivity.

Next, let's look at the ground over which our antenna hangs. *NEC* has two "real" ground systems, but for our modern fast PCs, there is no reason not to select the better of the two. It goes under different names in different implementations of *NEC*. You can find it as the "high accuracy" ground, the Sommerfeld-Norton ground, or simply as *SOMNEC*, the name of the calculating module within *NEC*. Whatever the program-matic name, it is the most accurate available system for calculating the behavior of an antenna above ground. While other systems tend to become inaccurate for antennas below 0.1 to 0.2 wavelengths above ground, the Sommerfeld-Norton system is accurate down to a tiny fraction of a wavelength above ground.

Once we have selected the ground type, we need some values for ground conductivity (in Siemens per meter) and for the relative dielectric constant (also called permittivity). We usually derive these values from maps of our local area (available in *The ARRL Antenna Book*). However, the ground quality values do not make a big difference in horizontal dipole performance, so we can initially use the program default numbers. Most programs default to what is called "average" ground, which has a conductivity of 0.005 S/m and a dielectric constant of 13.

We have neglected the test frequency. *EZNEC* is set up for single frequency runs, so we would just click on the frequency button and enter 7.15 MHz in the box that appears. *NEC-Win Plus* is always setup for frequency sweeps, that is, multiple runs defined by start and stop frequencies, plus a frequency interval between runs. For a

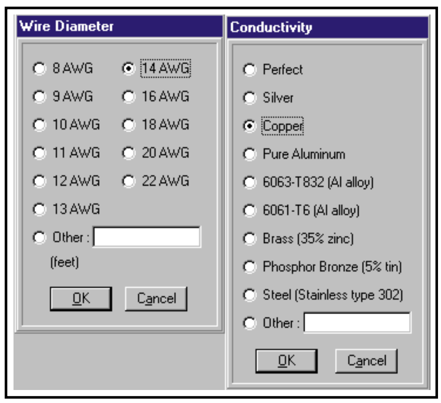

Figure 9—The *NEC-Win Plus* wire-diameter window and wire-material window.

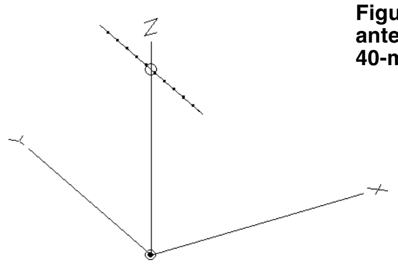

Figure 7—The *EZNEC* antenna-view of the 40-meter dipole model.

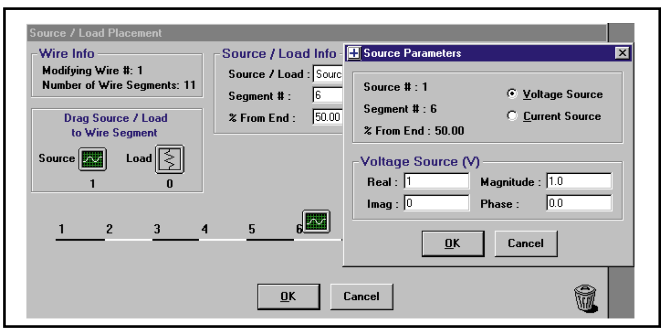

Figure 8—The *NEC-Win Plus* source-placement window.

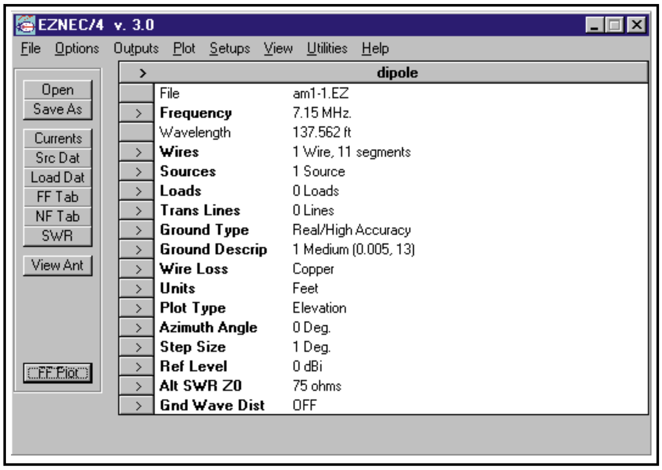

Figure 10—The *EZNEC* elevation pattern data on the main screen.

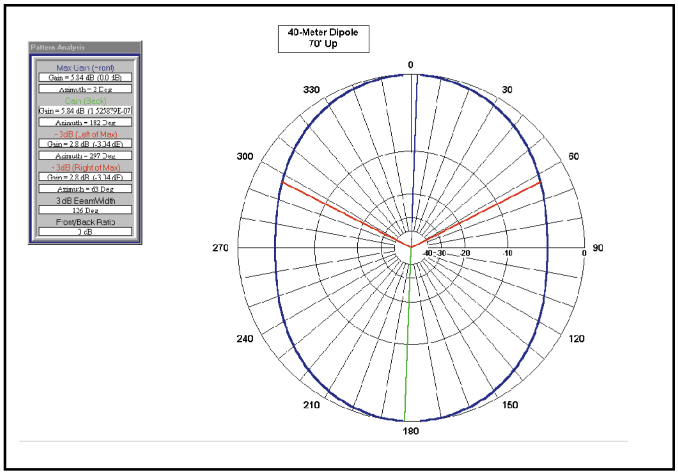

Figure 13—A (*NEC-Win Plus*) azimuth pattern for a dipole at 40 feet above average ground at 7.15 MHz with an elevation angle of 49°.

single run, we just enter the same frequency on both the start and stop lines. The interval or "step" will not matter.

We have now completely specified our model. We created the wire element and gave it an environment. Part of the environment was geometric as we set the coordinates to position the wire. A second part of the environment was electrical as we positioned the source. A further part of the environment was physical as we specified the wire material and the ground beneath the antenna. Essentially, we would go through all of these thinking processes when erecting a real antenna.

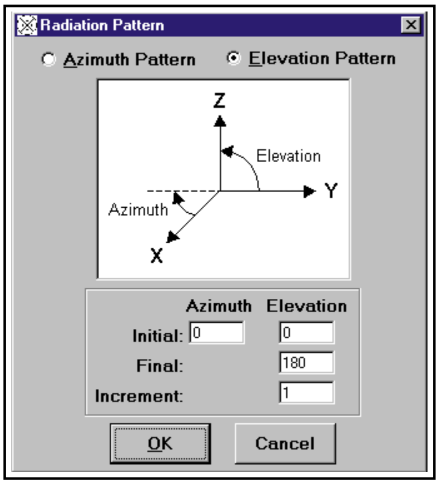

Figure 11—The *NEC-Win Plus* elevation pattern specification box.

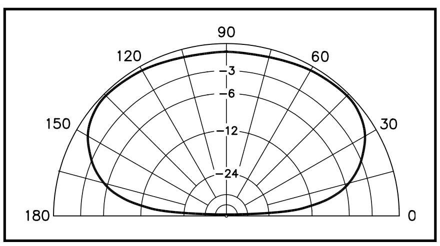

Figure 12—An (*EZNEC*) elevation pattern for a dipole at 40 feet above average ground at 7.15 MHz with an azimuth angle of 0 degrees.

We should notice two things about the model that may differ somewhat from reality. First, there is nothing in the model's backyard except the antenna. All of the power lines, trees, and other objects that can affect antenna performance are missing. Much of this "ground clutter" can be modeled, but it takes special techniques that go beyond the scope of the basics of modeling. Second, the ground is continuous to the horizon and homogenous to any depth beneath the antenna. In advanced modeling, we can add a second set of ground properties at a distance from the antenna, but we cannot capture the stratified nature of the subsurface ground that occurs in many places. For most purposes, neither of these limitations of the modeling program will invalidate the results of the modeling calculations.

What Output Pattern Do We Want?

If we have completely constructed our model and its environment, we have only one more step to go before we can hit the **RUN** button. We need to tell the program what kind of output pattern we want to see. The program will always calculate the source impedance, but most of us want to see a vivid graphic that tells us something about the gain and pattern shape of our antenna.

The entry is called the specification of a far field radiation pattern for our dipole. However, we may be initially at sea about what pattern to call and what specifications to enter for it. We know that the dipole radiates broadside to the wire and that this direction is an azimuth angle of zero (and 180) degrees. Let's begin, then, with an elevation pattern along the zero-180-degree line, usually specified as an azimuth angle of zero degrees. Most programs have a set of default values that you can use as starters. Figure 10 shows the *EZNEC* elevation data on the main screen, while Figure 11 shows the *NEC-Win Plus* elevation data selection box.

Now we are finally ready to run the model. We hit the right button and let the program do its calculations—very rapidly for this small model. After the run, *EZNEC* will bring up the pattern generated by the complex calculations, while in *NEC-Win Plus*, the design philosophy is to let the user call up any of the tables, graphs, or patterns desired. Figure 12 shows the *EZNEC* elevation pattern for our dipole.

Notice that the pattern provides us with several important pieces of information. First, we can see that low height (just above $^1/_4$ wavelength) sends much of the radiation at very high angles, too high for most skip paths. Looking at the available data gives us a gain of 5.87 dBi maximum at an angle of 49 degrees above the horizon. *NEC* calculates all gain figures as dBi values, that is as gain in decibels greater than a theoretical isotropic radiator that would send radiation equally in all possible directions. Since *NEC* does not have any built-in range test data or similar baselines, everything must be calculated against the isotropic radiator. If we are interested in using some other standard, we can always model the standard antenna and compare gain figures. We add and subtract gain in decibels, using the same reference standard. Notice also that the gain is given to two decimal places. For most operational purposes, a value of 5.9 dBi would be sufficient for any comparisons between antennas. Even so, the difference among 5.5, 5.8, and 6.0 dBi would not be detectable in amateur operation.

Figure 13 provides a *NEC-Win Plus* azimuth pattern taken at the elevation angle of maximum radiation. Note that there is a 1° difference in the elevation angles of maximum radiation—sometimes called the "take-off" angle—reported by the two programs. This difference is largely due to the complexity of the calculations involved as well as where and how a given program does its rounding from the long string of digits that computers use in their calculations. Also note that there is a 0.03-dB difference in reported gain, which is also insignificant. Of far greater importance is the pattern shape—a broad oval. Signals off the ends of the antenna will be weaker than those broadside to the antenna, but they may still be strong enough for contacts. The classic figure-**8** pattern is nowhere to be seen. The reason is the relative closeness of the antenna to the ground.

Before we leave the model, let's look at the source impedance data available as a table in most programs. The impedance listed is not the classic 72 Ω resistive that we associate with a resonant dipole. Instead, it is about $91 + j\,20\ \Omega$. The original cutting formula that we used to create our dipole model turns out to yield an antenna that is too long, as indicated by the inductive reactance at the feed point/source. As well, the resistive part of the impedance is considerably above the number used as the dipole standard. The numbers generated by *NEC* may be surprising. Nonetheless, they are accurate within the limits of the program, with its homogenous ground and clutterless field for the radiation.

Even though our main purpose in this episode was to get oriented to and started with antenna modeling, that does not mean that we can't discover some things about antennas—even using the simplest antenna possible. Even the most familiar antennas have new things to teach us about their behavior, and antenna modeling is a good way to learn them.

There remains much to be said about creating models out of wires and segments. The more complex the antenna structure, the more careful we must be. As well, we should look more closely at the information that the azimuth and elevation patterns can present to us, including some pitfalls to avoid. Next month we'll look more closely at the "ins" and "outs" of *NEC*.[7]

Notes

[1]Public domain *MININEC* is available in the following programs (with Web URLs listed):

NEC4WIN (*Windows*) from Orion: **http://www.cam.org/~mboukri**.

ELNEC (*DOS*) from W7EL: **http://www.eznec.com**.

Another version still used by numerous modelers is *AO* from K6STI. *AO* is a *DOS* program. For information e-mail **k6sti@n2.net**.

Expert *MININEC* is a proprietary program available at various levels from E.M. Scientific: **http://www.emsci.com/**.

[2]See the following references to using *MININEC* in ARRL publications:

John S. Belrose, "Modeling HF Antennas with *MININEC*—Guidelines and Tips from a Code User's Notebook," *The ARRL Antenna Compendium*, Vol. 3, pp 156-164.

L. B. Cebik, "A Beginner's Guide to Using Computer Antenna Modeling Programs," *The ARRL Antenna Compendium*, Vol. 3, pp 148-155.

Roy Lewallen, "*MININEC*: The Other Edge of the Sword," *QST* (February, 1991), 18-22.

The latter two items are republished in *Vertical Antenna Classics*.

[3]For a succinct history of method of moments programs for antenna analysis, see R. P. Haviland, "Programs for Antenna Analysis by the Method of Moments," *The ARRL Antenna Compendium*, Vol. 4, pp 69-73.

[4]There are at least three commercial implementations of *NEC*-2 readily available to amateurs at reasonable prices:

EZNEC 3.0 (*Windows*) from W7EL: **http://www.eznec.com** (reviewed in the September 2000 *QST* "Short Takes").

NEC-Win Plus (*Windows*) from Nittany Scientific: **http://www.nittany-scientific.com**.

Antenna Solver (*Windows*) from Grating Solver Development Co: **http://www.gsolver.com/**

[5]The actual equations used in developing antenna characteristics are available in the *NEC*-2 manuals. Although most users encounter only the final "Users" volume, the foundational volumes are available on-line at **http://www.qsl.net/wb6tpu/swindex.html** and at **http://members.home.net/NEC2**.

[6]In *MININEC*, the fundamental point of concern is not within the segment, but at segment junctions, called *pulses*. Hence, to center a source on a wire element, we would use an even number of segments and specify the centered junction as the source location.

[7]Those interested in pursuing each facet of basic *NEC* modeling more thoroughly may wish to consult *Basic Antenna Modeling: A Hands-On Tutorial*, available from Nittany Scientific (**http://www.nittany-scientific.com**). Although written to accompany *NEC-Win Plus*, with about 300 exercise files in .*NEC* format, the volume can be used with other implementations. A disk holding all of the exercise files in .EZ format for use with *EZNEC* is available from AntenneX (**http://www.antennex.com**).

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A Beginner's Guide to Modeling with *NEC*

Part 2: The Ins and Outs of Modeling

Last month we developed a basic understanding of what antenna modeling is, and became acquainted with some of the language of modeling. We also gained an orientation to the many parts of a good antenna model, including both the structure and its environment. This month we'll focus our attention on two fundamentals necessary to obtain reliable results from a *NEC* program. The first step is to grow comfortable with translating a physical array of wires or tubes into a set of dimensions that we can enter onto the coordinate system. The other basic element that we need to master is the selection and interpretation of the graphical outputs (the azimuth and elevation plots) from modeling programs. This installment cannot possibly say everything about both of these modeling fundamentals. However, we can hope to start you down a road toward working effectively on your own.

To save space throughout this series, we are limiting ourselves to modeling using the *NEC-2* calculating core, with illustrations from *EZNEC 3.0* and *NEC-Win Plus*. The figure captions will identify from which program the graphics have come.

Wires, Coordinates, and Conventions

One initial "mental block" to getting started in modeling is a certain discomfort with constructing antennas using the Cartesian coordinate system. Adopting a few conventions can dispel much of the uneasiness. By always (or nearly always) doing certain jobs in the same way, the system becomes more natural to use. There may be other equally good ways to do any job, but picking and sticking with one good way is the surest way to initial success.

Let's reacquaint ourselves with the coordinate system. In the horizontal plane, we can define any position—like the end of a wire that is part of an antenna element—by specifying a value for X and a value for Y. Z is the vertical dimension, corresponding to height, whether that is the height of the antenna structure itself or the height of the antenna above ground—or the sum of both in some cases.

When we set up an antenna model, we actually have many choices. We can set the model way over into high values of +X and +Y or into very negative values of each. Where the antenna is located in the coordinate system does not affect the accuracy of calculations. However, we want to strive for consistency, so let's set up the following conventions.

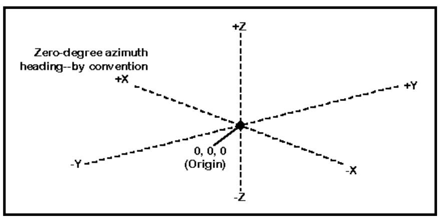

Figure 1—A "3-piece" dipole laid out on the coordinate system. The square indicates the location of the antenna source or feed point. The bold dots indicate a change from one component wire to the next in the overall element.

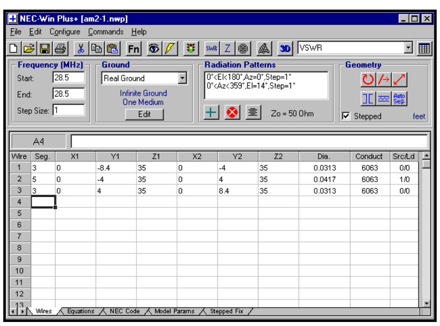

Figure 2—A *NEC-Win Plus* wire spreadsheet for the 3-piece dipole, showing the wire coordinates and other details of the model.

Convention 1: Wherever feasible, we'll split an element into equal parts on each side of a centerline. Therefore, an 8-foot element would have ends that are –4 and +4.

Convention 2: We'll use the Y-axis as the linear element axis. All linear elements will be on or parallel to the Y-axis. Our sample 8-foot element will therefore take values of Y=–4 and Y=+4 for its ends.

Convention 3: We'll use the X-axis for front-to-back dimensions. For single elements, we can use an X-value of zero.

Convention 4: The Z-axis will always indicate height.

Let's work our way through a few examples to see how the conventions work.

Example 1—A 3-piece dipole: Consider a 10-meter dipole (28.5 MHz) made up of two sizes of aluminum tubing ($^{1}/_{2}$ inch and $^{3}/_{8}$ inch diameters) placed 35 feet into the air. The center section will use the larger tubing. Even though we physically break the tubing in the middle to connect our feed line, we *do not* break the tubing in a model. Use a continuous piece and assign the source to its center. Let's make the centerpiece of half-inch tubing 8-feet long.

Each end of the dipole will consist of $^{3}/_{8}$-inch diameter pieces. We would place a bit of each tube inside the centerpiece in a real antenna. However, in a model, we are only concerned with the portion that shows. Let's make each visible end piece 4.4 feet long.

If we add up all the pieces, we have a total length of 16.8 feet for the entire element. It will consist of 3 "wires" or pieces. The next step is to place them into the wire spreadsheet. Although we might place them in any order and arrive at correct calculations, let's adopt one more convention.

Convention 5: We'll always work from the left end to the right end of any element. Left will normally mean a value more negative and right will mean a value more positive than whatever reference value we use. This convention will help us locate problems and read the modeling results in a consistent manner.

Now we are ready to determine the coordinates of the ends of each piece of wire. Set the units of measure for the program to feet.

1. Since there is only one element, all values of X will be zero.

2. Since the entire antenna is 35 feet in the air, all values of Z will be 35—assuming that we have selected "feet" as the unit of measure for the antenna.

The only thing left to do is to determine the Y-values. Figure 1 can help us in the task.

4. Since the entire antenna is 16.8 feet long, it will stretch 8.4 feet on either side of the centerline for the Y-axis. If we begin with the left end of the element (–Y2 in Figure 1), we assign the element tip a value of –8.4. The other end of this $^3/_8$ inch piece is 4.4 feet more positive, which gives us –4.0 (for –Y1 in Figure 1). This gives us all of the values we need for the first wire (W1 in Figure 1). End 1 is X=0, Y=-8.4, Z=35. End 2 is X=0, Y=–4.0, Z=35.

5. Wire 2 is the $^1/_2$-inch diameter center portion of the antenna. Since it connects to the second end of Wire 1, its End 1 coordinates are the same as Wire 1's End 2 coordinates. Since it is 8 feet long, then we add 8 to the –4 and arrive at a Y-value for End 2 of +4 (Y1 in Figure 1). Hence, Wire 2 coordinates are these: End 1—X=0, Y=–4.0, Z=35; End 2—X=0, Y=+4.0, Z=35.

6. Wire 3 is the far right tip of the element. Since it connects to the centerpiece, its End-1 coordinates are the same as the Wire 2 End-2 coordinates. The length of Wire 3 is 4.4 feet, which we add to the 4-foot position of the Wire 2 end. This gives us an End-2 Y-value of +8.4 for Wire 3's second end (Y2 in Figure 1). Hence, Wire 3 coordinates are these: End 1—X=0, Y=+4.0, Z=35; End 2—X=0, Y=+8.4, Z=35.

We have completely defined the element, despite its complex structure. Figure 2 shows the *NEC-Win Plus* wire entry spreadsheet for the element, where the X1, Y1, and Z1 columns represent End 1 values for each of the 3 wires. X2, Y2, and Z2 represent the end 2 values for each wire that composes our dipole element. We must add some other information to complete our model. Each line has an element diameter value. In *NEC-Win Plus*, this value is in the same units as the wire lengths, so we divide the diameters by 12 to get their values in feet. We chose aluminum for our material, and the "Conduct" (conductivity) column records 6063-type aluminum. (There are other types.) The "Src/Ld" column shows that we have a source on the center wire, and we'll assume that it has been correctly placed at the center of the wire.

Do not neglect the "Seg." column. We wish to have at least 10 segments per half-wavelength of element. A dipole is about a half-wavelength long, and the total number of segments is 11—within our specification. The center wire containing a source has an odd number of segments, meaning that the source segment can be precisely at the antenna's center. We may also note the frequency entry and the ground entry as fitting our original specification. We also note some radiation pattern requests that we'll explore a bit later. For now, we see a symmetrically specified dipole element composed of 3 wires.[1]

Example 2—A 3-element Yagi: Our second example will demonstrate the utility of adopting the convention by which we set elements symmetrically about a centerline. Consider a 3-element Yagi composed of $^1/_2$-inch diameter elements throughout. This specification means that we'll have only one wire per element, but also that we'll have 3 elements. The Yagi will be for 6 meters, 51 MHz, to be more exact. We'll place the antenna at a height of 240 inches (20 feet).

This model will be in inches. The element lengths are these: Reflector—114.36 inches; Driver—108.96 inches; Director:—102.44 inches. To make sure that the shorter elements are inset at their ends by the same amount on both ends—relative to longer elements—we'll build each element symmetrically around the same centerline. By convention, the centerline is the X-axis, with each element being set up parallel to the Y-axis. Each Y-value for the positive and negative values will be half the total length: Reflector—57.18 inches; Driver—54.48 inches; Director—51.22 inches.

The following spacing separates the elements from each other: Reflector-to-driver space—37.8 inches; Driver-to-Director space—40.14 inches. How shall we place the elements along the X-axis? There are numerous schemes. Some modelers like to start with the reflector at X=0 and place all other elements ahead of this position with +X values. Some modelers like to take the entire distance from the reflector to the director and place the model symmetrically on the X-axis. We'll adopt for our starting convention a third popular convention:

Convention 6: Place the driver for any multi-element array at X=0. Place the reflector at a negative value of X that equals the driver-to-reflector spacing. Place all directors at positive values of X equal to the spacing from the driver to that director.

To keep the elements readily identifiable, we should also adopt a convention for the order in which they appear on the wire table.

Convention 7: Order the wires beginning with the reflector(s), the driver(s) and the director(s) for each self-contained array.

With these new conventions in mind, we can develop the values for our wire spreadsheet. Set the units to inches. Use Figure 3 as an aid.

1. Start with the driver, but make it Wire 2. X2 in Figure 3 will be 0. The values for Y (–Y2 and +Y2 in Figure 3) will be the half-length of the driver element. The value of Z for this and all other wires in this model will be 240.

2. The reflector (Wire 1) will have values for Y (–Y1 and +Y1 in Figure 3) that are the half-length of the reflector. Since the reflector is behind the driver, the value of X (–X1 in Figure 3) will be –37.8.

3. The director (Wire 3) will have values for Y (–Y3 and +Y3 in Figure 3) that are the half-length of the director. Since the reflector is ahead of the driver, the value of X (+X3 in Figure 3) will be +40.14.

The resulting wire spreadsheet, in *EZNEC* form, appears in Figure 4. Be sure to set all of the frequency, source, material, and radiation pattern values appropriately. By making the Y-values for each element symmetrical about a centerline, we align the model as the antenna would be aligned on its boom. By using a positive value for the director on the X-axis, we assure ourselves of a pattern where the forward lobe points at zero degrees on a standard azimuth pattern. In

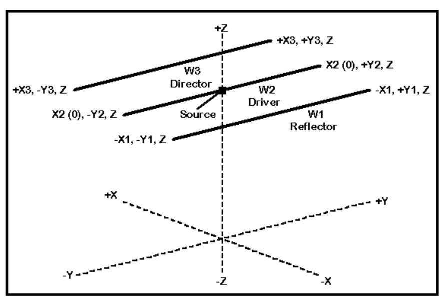

Figure 3—A 3-element Yagi laid out on the coordinate system.

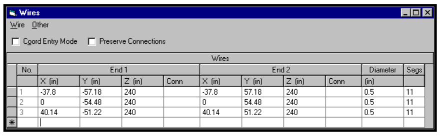

Figure 4—An *EZNEC* wire spreadsheet for the 3-element Yagi of example 2, showing the element end coordinates, wire diameter, and segmentation.

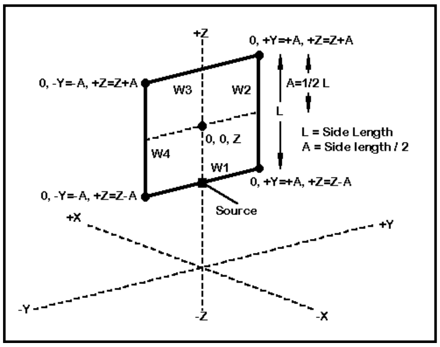

Figure 5—A single quad loop for 146 MHz laid out on the coordinate system.

the end, each convention that we adopt and use consistently contributes to being able easily to sort out the components and have reasonable expectations about the results.

Example 3—A single quad loop: So far, we have dealt with antennas that extend their structures only in the X and Y plane. Let's look at a quad loop in order to become comfortable dealing with antennas that extend into the Z dimension. We'll model a single quad loop for 146 MHz that is set up for broadside operation—where the main signal strength comes off each side of the plane of the loop. The loop will be about 87.04 inches in circumference, which makes it about 21.76 inches per side. The loop will use standard insulated spider construction (which means that we do not model the support arms). The center hub will be 20 feet or 240 inches off the ground.

First, the value of X for this model will be zero throughout. The loop wires will extend along the Y-axis and parallel to the Z-axis. However, the model opens up two questions about loop construction that we can answer with new conventions and with the aid of Figure 5.

Convention 8: Model a loop as a continuous series of wires such that End 2 of Wire 1 is also End 1 of Wire 2, etc.

Convention 9: Model the loop with Z initially equal to zero, and later add the "hub" height to each value of Z in the model.

As Figure 5 shows, the two conventions give us an orderly progression of development and a technique for specifying the dimensions. Since the length (L) of a side is 21.76 inches, the values of +Y and –Y will be half the side length—or A=10.88 inches. Initially, we'll also use the value of A for +Z and for –Z, that is, 10.88 inches.

1. Assign values for Y and for Z for each end of each wire (in order), using the half-length of the side, referring to Figure 5 for guidance. Wire 1, for instance will have the following values: End 1—X=0, Y=–10.88, Z=–10.88; End 2—X=0, Y=+10.88; Z=–10.88. Wire 2 will have these values: End 1—X=0, Y=+10.88, Z=–10.88; End 2—X=0, Y=+10.88; Z=+10.88. Wire 3 will have these values: End 1—X=0, Y=+10.88, Z=+10.88; End 2—X=0, Y=–10.88; Z=+10.88. Wire 4 will have these values: End 1—X=0, Y=–10.88, Z=+10.88; End 2—X=0, Y=–10.88; Z=–10.88.

2. Add the "hub" value of Z to the values developed to arrive at the final dimensions. The new values for Z alone will be as follows: Wire 1, End 1—Z=229.12, End 2—Z=229.12; Wire 2, End 1—Z=229.12, End 2—Z=250.88; Wire 3, End 1—Z=250.88, End 2—Z=250.88; Wire 4, End 1—Z=250.88, End 2—Z=229.12.

The values, plus the other model setup data, appears on the wire spreadsheet in *NEC*-Win form in Figure 6.[2]

By combining the conventions and techniques we have shown here, you should be able comfortably to model virtually any single antenna array, no matter how many elements or which way they point. However, the task requires an orderly procedure in each case. Very often, it is more efficient to do all of the preliminary work of setting the wire end coordinates on paper.[3]

Patterns, Patterns, and More Patterns

Once the model is satisfactory, our next inclination is to race through setting the other necessary parameters, run the model, and see what the pattern looks like. In this episode, I shall race with you, bypassing for the moment all of those less exciting but vital features. We'll land upon a potentially confusing set of graphical outputs. My aim will be to see if we cannot make a little initial good sense out of them.

Let's begin our adventure in free space. Among the ground options, we'll find a label that reads either "Free Space" or "No Ground." Setting the option here places the antenna in what amounts to outer space with nothing to reflect the radiation except possibly the elements themselves. In some programs, the radiation pattern itself is automatically set for

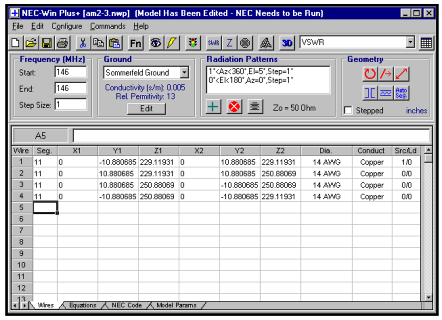

Figure 6—A *NEC-Win Plus* wire spreadsheet for the 2-meter quad loop, showing the wire coordinates and other details of the model.

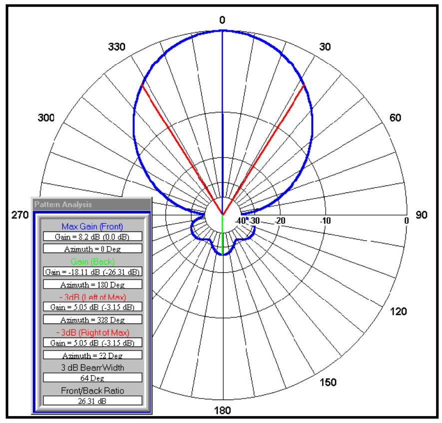

Figure 7—A *NEC-Win Plus* free-space azimuth pattern for the 3-element 6-meter Yagi.

full 360-degree patterns in both the azimuth and the elevation directions. However, other programs require the user to enter the start and stop degree numbers, along with increment between steps in the pattern tracing. The pattern itself is graphically developed outside the *NEC* core by simply connecting the dots that form the *NEC* data points. Hence, the smaller the increment, the smoother the pattern outline. One degree usually suffices for HF antennas at all reasonable heights, while 0.1 degree is sufficient for most VHF and UHF antennas.

The two most fundamental ways to get free-space patterns is to take azimuth and elevation patterns at zero-degrees, that is, along the X and along the Z axes. Figure 7 shows a *NEC-Win Plus* azimuth pattern, along with its analysis box. We may note the free-space gain as a rough measure of the antenna design quality, along with the front-to-back ratio, a measure of rearward QRM suppression. Equally notable is the -3 dB or half-power beamwidth (64°) of the antenna in the horizontal plane.

The elevation plot (Figure 8) of the antenna in free space comes from *EZNEC* and also includes the available analytic data. Note that the gain and front-to-back ratio are identical to those in the azimuth plot, despite the difference of programs. Both use *NEC*-2 calculating cores and hence, both will yield numbers that are coincident or very close to coincident. Most notable is the –3 dB beamwidth in the vertical plane, which is over 98° between half-power points.

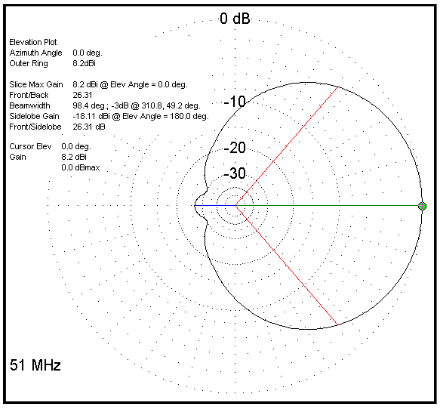

Figure 8—An *EZNEC* free-space elevation pattern for the 3-element 6-meter Yagi.

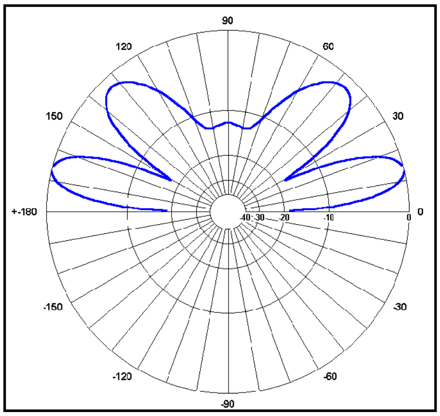

Figure 9—A *NEC-Win Plus* elevation pattern for the 10-meter dipole 1 wavelength above ground.

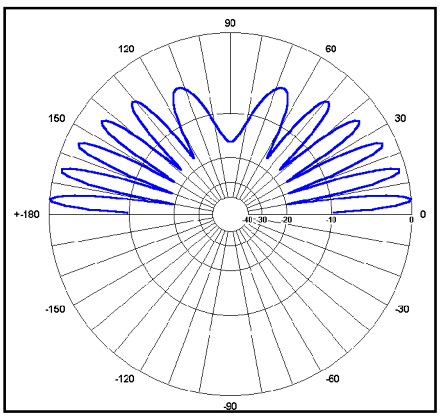

Figure 10—A *NEC-Win Plus* elevation pattern for the 2-meter quad loop 4.1 wavelengths above ground.

Our real antennas, of course, have a ground beneath them that plays a role in the reflection of signals. So let's move from free space back to our Sommerfeld-Norton ground. For all of the horizontal antennas that we'll look at in this episode, we will choose average ground with a conductivity of 0.005 S/m and a relative dielectric constant (permittivity) of 13. Changes in the ground constant values have only small effects on the performance of horizontal antennas, so using "average" ground will work nicely for most beginning analyses.

We'll begin with the 3-piece dipole that we modeled at 28.5 MHz. The antenna has a height of 35 feet, about 1 wavelength above ground. Let us take an elevation pattern, shown in Figure 9, a *NEC-Win Plus* graphic. Note that the pattern now breaks into lobes and nulls, that is, stronger and weaker directions of radiation as calculated for various elevation angles. Compare Figure 9 to Figure 10, an elevation pattern for the 2-meter quad loop that became our third case study of model construction. The quad loop elevation pattern has broken into many lobes and nulls, with the lowest one very near the horizon.

The key difference between the two antennas is not their shapes, but their heights. Height is not measured in feet or inches in this case. In fact, the quad loop is only at 30 feet hub height, whereas the dipole is 35 feet up. Instead, we measure height in terms of wavelength. The 10-meter dipole is 1 wavelength up, while the quad loop is about 4.1 wavelengths high. The higher the antenna in wavelengths, the more lobes and nulls to its elevation pattern.[4]

Let's return to the Yagi that we left in free space. Remember that the 6-meter antenna is 20 feet or 240 inches above the ground. Let's look at a 3-D pattern of the antenna above ground. Figure 11 provides the view in *EZNEC* form. Allowing for the blunting of the curves by virtue of the larger sampling increment, we still see an amazing pattern. It bears some resemblance to the dipole by virtue of having two main elevation lobes. The 2-lobe pattern results from the antenna height, which is close to 1 wavelength above ground. However, almost all of the energy is displaced along the X-axis forward of the antenna structure. In contrast, the dipole had equal amounts of energy in both directions broadside to the wire along the X-axis.

We can refine our view of the antenna pattern by calling for a 2-D elevation pattern. The *EZNEC* elevation pattern in Figure 12 smooths the lobe shapes by using a 1-degree increment between data points. As well, the rear lobes that had been obscured under a mass of 3-D close-spaced lines are now clear. An elevation pattern over ground provides other significant information, for example, the vertical beamwidth and the elevation angle of maximum radiation—the "take-off" angle. In reality, of course, terrain features may modify the actual take-off angle.

Although the elevation pattern for our Yagi has changed radically in the move from free space to a position over the ground, the azimuth pattern does not change shape appreciably for horizontal antennas. Compare Figure 7 with Figure 13, the azimuth pattern for the Yagi at a 13-degree elevation angle over average earth. The pattern shapes are virtually identical, even to the 64-degree –3 dB (half-power) beamwidth. What has changed is the forward gain of the antenna. It now records 13.35 dBi, compared to 8.2 dBi in free space: a 5.15 dB pick-up due to ground reflections. But remember that the forward lobe of the antenna in the free-space elevation pattern was smooth. Over ground, the added power in the main

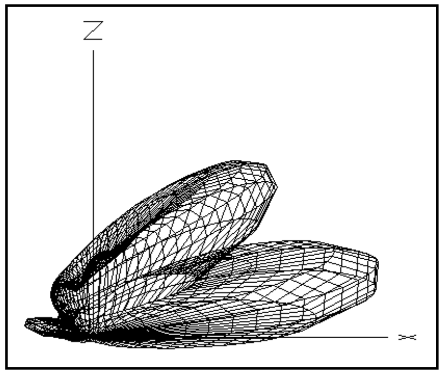

Figure 11—An *EZNEC* 3-D radiation pattern for the 3-element 6-meter Yagi 1 wavelength above ground.

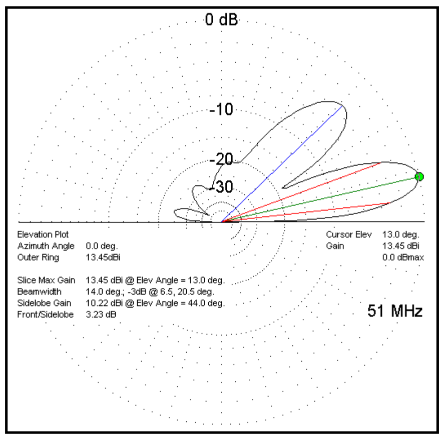

Figure 12—An *EZNEC* elevation pattern for the 3-element 6-meter Yagi 1 wavelength above ground.

lobes, of course, is offset by the reductions in power in the null areas.

NEC measures all pattern gain figures in dBi, which is decibels over an isotropic source. Since *NEC* has no built-in antenna range on which to use a real antenna standard for comparisons, it uses a mathematical standard. The isotropic radiator is defined as one radiating equally well in all directions (relative to a sphere that theoretically surrounds it). It is up to the individual modeler to make comparisons among antennas in order to figure out, for example, how much more gain the Yagi has than a dipole in the same setting.

By systematic modeling and comparisons, *NEC* yields useful information to us, information that might not arise by more haphazard methods and approaches. However, gain, front-to-back ratios, and beamwidths are not the only information that we can systematically develop with a modeling program. Now that we can model almost anything we wish, it is time to refine our modeling further. Next month, we'll explore some of the mysteries of sources, grounds, and frequency sweeps in an effort to clean up some relevant details.

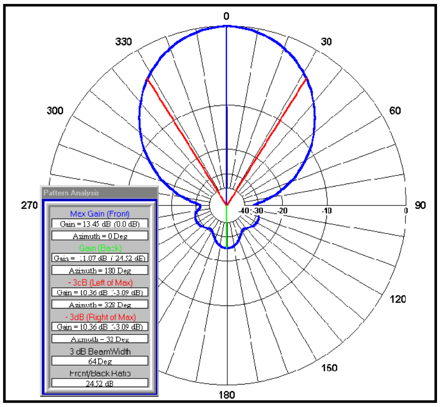

Figure 13—A *NEC-Win Plus* azimuth pattern for the 3-element 6-meter Yagi 1 wavelength above ground at a 13-degree elevation angle.

Notes

[1]Those who wish to experiment with their modeling software might wish to perform the following investigation. I noted that the model may be placed anywhere within the plane of the X and Y coordinate system (leaving Z as a constant) and that it would yield the same results. Here is a 3-step process to verify this note.

1. Change all values of X by the same amount (for example, changing all Xs to +36 or to –95).

2. Change all values of Y by adding the same amount (for example, adding +27 or –105).

3. Combine the changes of both X and Y. For each change, run the model and check the radiation pattern and source impedance.

[2]There are ways to simplify quad loop construction available to the user of either *EZNEC* or *NEC-Win Plus*. In *EZNEC*, there is a provision for changing the antenna height, a means of altering all of the values of Z simultaneously. The easiest way to change the dimensions of a quad loop is to determine the center or hub height in advance. Then construct the modeling using values of +A and –A (as defined in the text) to make up the loop. Finally, change the height by the value predetermined for the hub. The upper and lower wires will then be properly placed above and below this height. To alter the coordinates, reduce the height by the hub value, which places the loop center back at zero. Then enter the new values of –A and +A, and change the height back to its raised hub value again.

In *NEC-Win Plus*, there is a "model-by-equation" facility within which we can define the values of A and of the hub height (which we might call B). On the wire entry page, we then enter –A, +A, –A+B, and +A+B for the loop corner positions in the appropriate boxes on the spreadsheet. We can then change the dimensions (or the height) of the antenna simply by changing the value of the variables. Those interested in modeling by equation are invited to look at a four-part tutorial that appeared in the May through August editions of *AntenneX* (**www.antennex.com**) and which is available even to non-subscribers. Alternatively, the 4 parts are also at my site as columns 27 through 30 in the "Antenna Modeling" series (**www.cebik.com**).

[3]A form suitable for model planning (with front and back sheets) can be downloaded from the ARRL Web site in Adobe PDF format at **www.arrl.org/notes/qst/am2-f.pdf**.

[4]We can estimate the number and angle of the lobes for most horizontal antennas from the antenna height alone.

$$\theta = \arcsin \frac{A}{4h} \qquad \text{(Eq 1)}$$

where θ is the angle for a particular lobe, and h is the antenna height in wavelengths. An "arc sin" value means to use the inverse and then the sine button on your calculator. To find the angle of a lobe, use odd numbers for succeeding lobes, where 1 is the first lobe, 3 is the second lobe, etc. For nulls, use even numbers for A, where 2 is the first null, 4 is the second, etc. Of course, you reach the total number of lobes when the angle approaches or reaches 90 degrees.

Since the 10-meter dipole is 1 wavelength up, its first lobe is at about 14 degrees and its second is about 48 degrees up. For the 2-meter quad loop, the first lobe is about 3.5 degrees up, while the second is about 11 degrees. These estimates are more accurately calculated by the *NEC* core, so the numbers it yields would take precedent over estimates.

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By L. B. Cebik, W4RNL

A Beginner's Guide to Modeling With NEC

Part 3—Sources, grounds and sweeps

Once we progress beyond the construction of models and the interpretation of plot patterns, our next set of quandaries revolves around obtaining the best possible results from *NEC* modeling. This month we'll work with three clusters of ideas: the placement of sources, the selection of a ground—including making ground-plane radials—and using frequency sweeps productively. My selection of topics stems from the number of questions I receive from new modelers. These notes will not answer all of them, but perhaps they will promote some useful ways of thinking about sources, grounds, and sweeps in models. As always, we'll stick to *NEC-2*, using both *EZNEC* and *NEC-Win Plus* as our sample programs.

Sources: Where and Why?

Finding the source impedance of an antenna is vital. It gives us a good idea of whether to lengthen or shorten an element if we are aiming for resonance or for a specific reactance needed for a matching network. In nonresonant antennas, the source impedance, when combined with the transmission line we propose to use, can tell us something about the conditions our antenna tuners might see at their terminals.[1]

All of the examples in the preceding installments used a single source or feedpoint located at the center of the driven element. Hence, we needed only to use an odd number of segments on the wire containing the source and specify either the 50% mark or the number of the center segment as the source position. Life was easy, as shown by the "Source 1" designations in Figure 1.

However, not all antennas use a center feedpoint, as evidenced by the entire collection of antennas that we call "OCFs" or off-center-feedpoint antennas. Many of these antennas call for a specific distance either from the wire end or from the antenna center for the source position. As the upper portion of Figure 1 shows, if we use only the minimum number of segments per half wavelength for our wire, we do not stand a chance of placing the source close to the desired position.

The solution is simple: use many segments. It is not unreasonable or problematical to use 101 segments for a model of an OCF antenna that is a half-wavelength long. Suppose that a certain OCF design calls for a feedpoint position that is 14% of the distance from the center outward toward the end of the antenna. This is 86% of the distance from the end of the antenna to the center or 43% of the total distance from one end of the wire to the other. If we specify 101 total segments and place the source on segment 44, it will be 43.1% of the distance from the left end of the wire.

Having enough segments in a model to make fine movements of the source position can come in handy. Suppose that

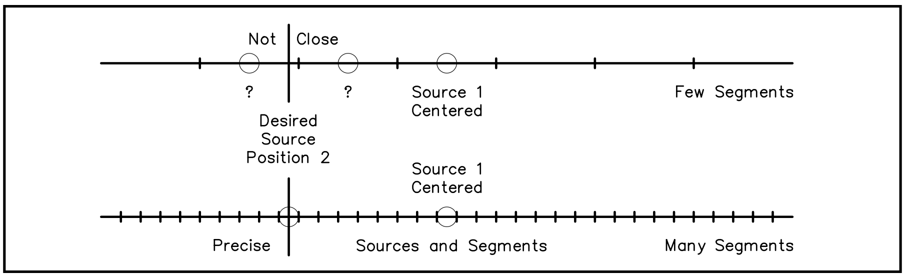

Figure 1—A comparison of low-segment density and high segment density with respect to precisely locating a desired source position.

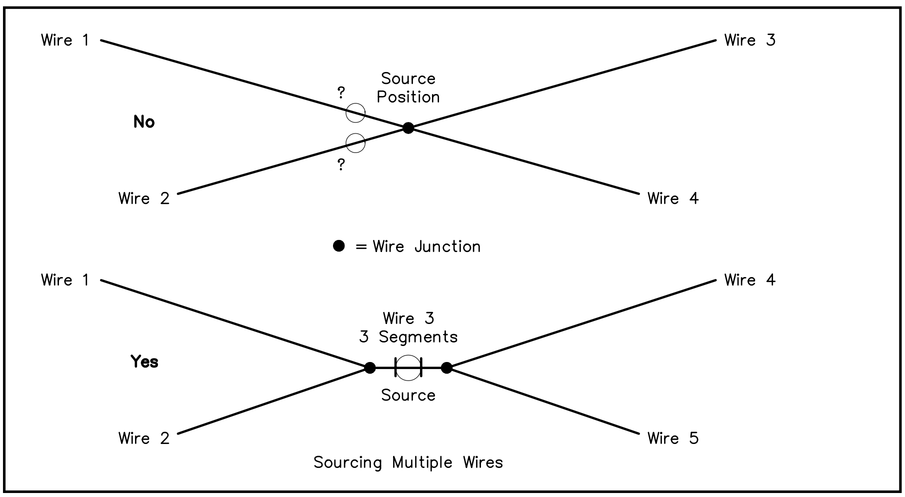

Figure 2—Incorrect and correct ways to model multiple elements with a common feedpoint, using a combined 20-meter and 15-meter dipole.

[1]Notes appear on page 48.

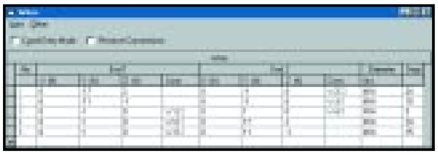

Figure 3—The *EZNEC* wires page for the correct model of the 20-meter and 15-meter combined dipole antenna.

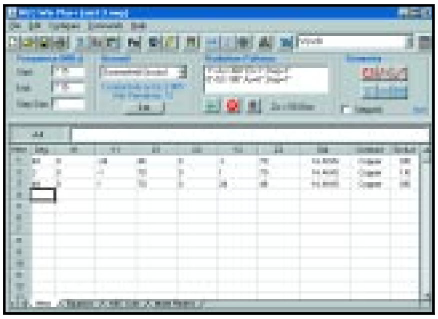

Figure 5—The *NEC-Win Plus* wires page for the 3-wire version of the inverted V.

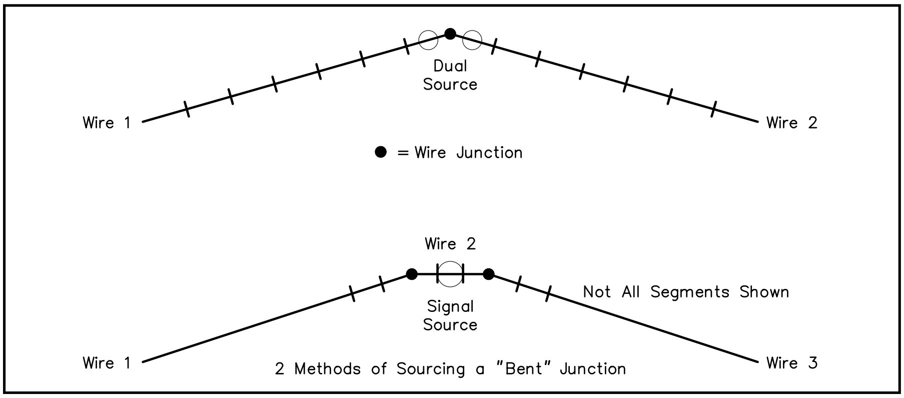

Figure 4—Two methods of modeling an inverted V (and similar elements) in order to obtain a correct source impedance value.

Table 1

Source Impedance Values for Crossing Dipoles Using an Over-Simplified Model and a Model With a Common Center Wire.

Source Placement:	14.175 MHz Impedance R +/– *j*X Ω	21.225 MHz Impedance R +/– *j*X Ω
Simple Crossed Wire Model		
On 20-meter wire	98.9 + *j*18.5	151.4 + *j*268.0
On 15-meter wire	16.8 – *j*346.1	35.9 – *j*102.7
Central Source Wire Model		
Centered on common wire	57.8 + *j*45.9	111.5 – *j*780.2

we are looking for the point along the wire that yields an impedance closest to 300 Ω. As we move out from the center point, we'll discover that the rate of change of source impedance per segment becomes ever greater. However, with enough segments, we can pinpoint quite closely the 300-Ω feedpoint impedance position.

Antennas very often are not quite so electrically simple as they seem to be from their physical appearance. One common type of antenna combines dipoles for two different band with a common feedpoint, for example 20 and 15 meters. The quick way of picturing this kind of antenna appears in the top sketch in Figure 2. We bring 4 wires together and join them at the center. Now we have the significant question: where do we place the source? We have essentially 2 choices: on the first segment adjacent to the junction on the 20-meter wire or on the corresponding position on the 15-meter wire. Table 1 gives us the source impedance values that we get for 14.175 MHz and for 21.225 MHz for each position for the model.

Which set of values is close to correct? We can't tell. In fact, neither set is accurate. Let's reform the model to match the bottom part of Figure 2. We'll bring the left ends of the 20-meter and the 15-meter elements to a common point that is shy of center. Then, we'll create a short, 3-segment wire that is centered. The right sides of each band's element moves from the junction point on the right of the center wire outward toward the ends. Figure 3 shows the model on the *EZNEC* Wires page.

The reason that the center wire (#3) has 3 segments is that we should always keep the current levels on either side of a source segment as equal as possible. The 3-segment source wire provides a simple solution to this need. Since the source wire is 2 feet long, each segment is about 8 inches long. The remainders of the element wires use lengths approximately equivalent to this value. With these precautions, we can now find the source impedances for the two frequencies on which the antenna operates. As Table 1 shows, the 20-meter wires are just a bit long, but the 15-meter wires are well short of resonant length. Try revising the end values for the 20-meter element to 16.0 and for the 15-meter element to 12.45 (both in feet, of course). Note how changes in the 20-meter wire lengths create large changes in the 15-meter source impedance, while changes in the 15-meter wires have smaller effects on the 20-meter source impedance.

Another common antenna, the inverted **V**, lets us demonstrate that sometimes we can use more than one sourcing technique to arrive at the same goal. Figure 4 shows two ways to model an inverted **V**—and by extension, any other antenna where single elements approach the feedpoint at an angle other than 180-degrees. The top version of the **V** shows the use of a dual source on the segments immediately adjacent to the junction. (Note that this example differs from the preceding one by using only a single element for one band.) Since the source impedance changes very slowly in the center area of a resonant $^{1}/_{2}$-wavelength antenna, the two sources together will closely approximate the source impedance at the exact center. For example, *NEC-Win Plus* reads each of the two values as 22.1 – *j*8.1 Ω. The actual source impedance is the sum of the two, adding the resistance and reactance separately: 44.2 – 16.2 Ω. (*EZNEC* has a "split" source option that automatically places the second source on the adjacent segment and which also does the addition for us: the result for the same model is a source impedance of 44.3 – *j*16.5 Ω.)

Alternatively, we can use the short 3-segment source wire technique so that we can place a single source. The bottom of Figure 4 shows the principle, which adds one wire to the model. Figure 5 gives us the NEC-Win Plus wires page, which also shows that once more, we have kept the segment length in the sloping wires about the same as in the center source wire. The impedance numbers yielded by this model are 44.2 + *j*3.6 Ω. The very slight difference in reactance is a result of our having added a tiny amount to the overall length of the wire by adding the source wire.

These sourcing techniques should let us handle with ease most of the antenna geometries that we might encounter.[2] So let our eyes drop to the ground for a while.

Grounds and Ground Planes

We have noted two of the types of ground permitted with *NEC* in past episodes: free-space (also referred to as "no ground") and the Sommerfeld-Norton high accuracy ground. Free-space, of course, eliminates the reflecting surface

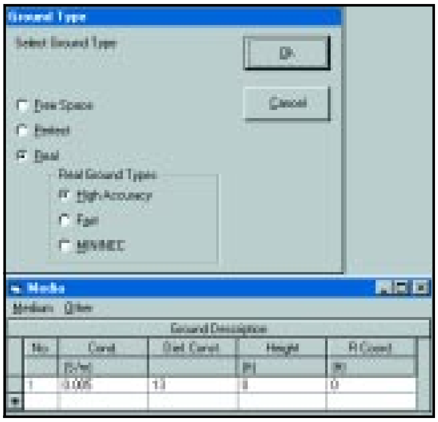

Figure 6—The *EZNEC Windows* boxes for selecting the ground type and for supplying the values for the conductivity and the dielectric constant.

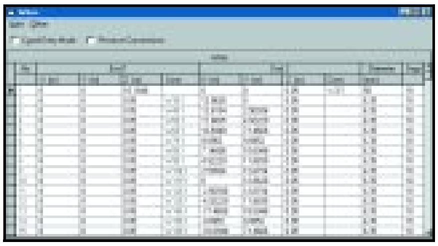

Figure 7—A partial *EZNEC* wires page for a 40-meter vertical monopole with a 32-element ground plane system.

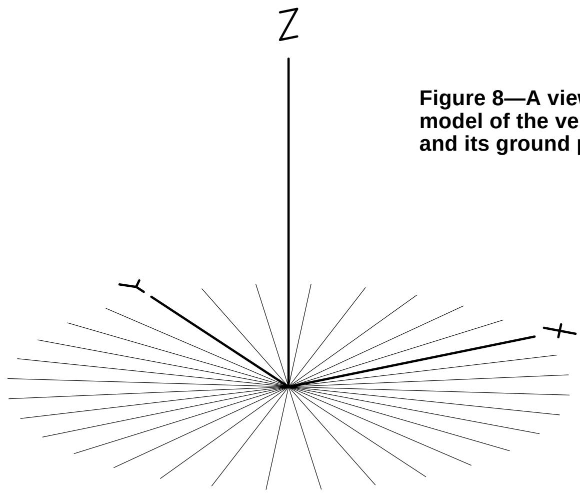

Figure 8—A view of the *EZNEC* model of the vertical monopole and its ground plane.

Table 2

Commonly Used Soil Quality Designations and their Corresponding Values of Conductivity and Permittivity

Type	*Conductivity (Siemens/meter)*	*Permittivity (dielectric constant)*
Very Poor	0.001	5
Poor	0.002	12
Average/Good	0.005	13
Very Good	0.0303	20
Salt Water	5.0	81

that we call ground so that antennas have a limitless sphere for their expanding radiation patterns.

Actually, *NEC* provides 3 types of ground, shown in Figure 6, the *EZNEC* boxes for both ground type and value. “Perfect” ground is sometimes useful for preliminary modeling of vertical antennas that touch the ground—akin to using free space for highly elevated antennas. The “real” ground possibilities include the fast or “reflection-coefficient” ground—which is inaccurate below about 0.1 wavelength antenna height—and the preferred Sommerfeld-Norton ground, which is accurate down to about 0.001 wavelength of antenna element height. (*EZNEC* provides the NEC-user with the *MININEC* ground system, but it has limited use for most modelers.) Modern fast computers let us zero in on the high accuracy ground for all of our work that places the antenna over earth.

Since all of our models so far have been horizontal, we have simply used the program default “average” ground values. However, as modeling becomes more serious or if we have a vertical antenna, it becomes increasingly important to select ground values that most closely approximate the conditions for the antenna we propose to build. Table 2 provides a short list of commonly used values, and a listing in *The ARRL Antenna Book* supplies many more.[3] However, looking up local values or testing one’s own ground is always more precise than a table of general values. For most hams, measuring conductivity is usually more feasible than measuring the soil dielectric constant.

The two numbers—conductivity in Siemens per meter and the relative dielectric constant (permittivity—no units)—together combine in engineering equations for the calculation of the effects of ground on antenna radiation, both in terms of reflections and of losses. However, *NEC* ground calculations presume a uniform soil beneath the antenna. At lower HF frequencies and below, the stratified nature of the soil beneath the antenna and its more distant area where the fields are reflected may play a role in advanced modeling. For the beginner, selecting one of the standard categories usually suffices for reasonable accuracy.

There is a second type of ground important to modelers, the radial ground plane we establish beneath our vertical antennas. Although we commonly place the radial wires either directly on the ground or slightly beneath the surface, *NEC* cannot model any wire on or under the ground. However, for a close approximation of ground plane action, we can construct a model of a radial system very close to the ground. The normal limit of close approach is about 0.001 wavelength, which amounts to under 2 inches at 40 meters. Some modelers have successfully experimented with ground planes as low as 0.0001 wavelength above the surface, although in every case, we must allow for the radius of the ground plane wire. The surface of the wire should not touch the ground.

Fortunately, both *EZNEC* and *NEC-Win Plus* include automated radial makers. We need only specify the center point, the number of radials, the number of segments per wire, and the wire diameter. (Some programs require that you set up the first radial and then the others become copies spaced the correct number of degrees apart.)

Figure 7 shows the first 14 radials (plus the vertical 40-meter antenna) of a 32-radial system. We could, of course, calculate the end coordinates of each radial with a little sine and cosine work from trigonometry, but the automated radial maker is much faster. In general, one should limit the number of junctions at a single point to about 30, since *NEC* can become less accurate as the angle between wires at a junction becomes too small. However, the rate of error increase is small and *NEC* appears to handle 32-radial systems with ease.

The radials in Figure 7 are dimensioned in meters (with the wire size in millimeters). The height of the radial sys-

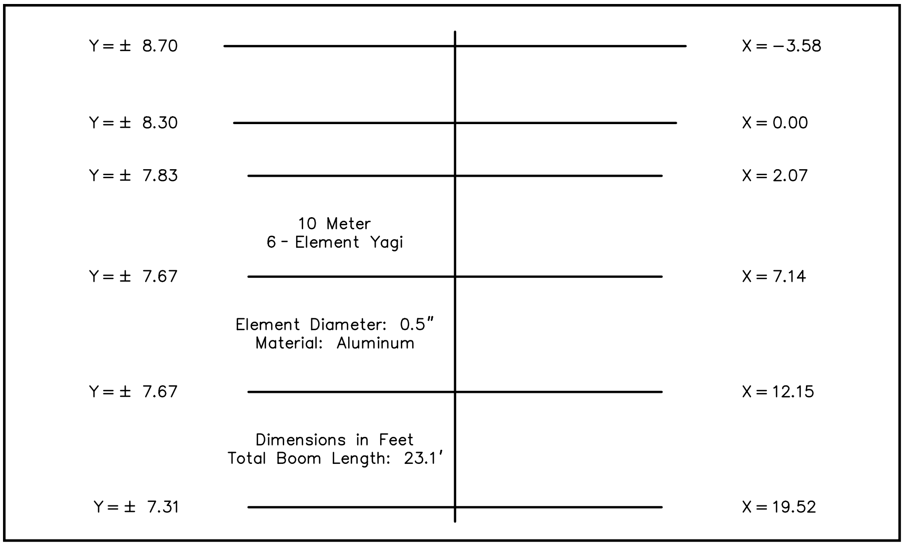

Figure 9—An outline sketch of a 6-element Yagi used in the frequency sweep exercise.

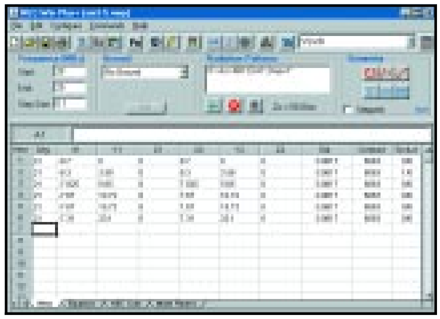

Figure 10—The *NEC-Win Plus* wires page showing the set-up of the 6-element Yagi model along with frequency sweep data.

Table 3

A Summary Table of Modeling Results from a 28 to 29 MHz Frequency Sweep of a 6-Element Yagi *NEC* Model

Frequency (MHz)	*Gain (dBi)*	*Front-to-Back Ratio(dB)*	*Source Impedance*	*50-Ω VSWR*
28.0	9.95	18.4	33 – *j* 6	1.54
28.1	9.98	19.9	35 – *j* 4	1.44
28.2	10.01	21.4	37 – *j* 2	1.36
28.3	10.04	22.9	39 – *j* 0	1.30
28.4	10.08	24.5	40 + *j* 2	1.25
28.5	10.11	25.8	42 + *j* 3	1.22
28.6	10.14	26.4	43 + *j* 5	1.19
28.7	10.16	26.1	45 + *j* 6	1.18
28.8	10.19	25.2	46 + *j* 6	1.17
28.9	10.21	23.9	48 + *j* 7	1.15
29.0	10.22	22.7	49 + *j* 6	1.13

tem is 0.05 m or 50 mm, which is just under 2 inches. I have used these dimensions as an alert: you will undoubtedly encounter models in both metric and in English units, so gaining some facility in translating between the two systems is very useful to every modeler.

Figure 8 is a view of the overall antenna model, showing the 1/4-wavelength vertical element along the Z-axis together with all 32 1/4-wavelength radials. Each wire has 10 segments, with the source segment being the lowest one on the antenna wire. The model's 330 total segments may seem large, but on modern PCs, the run time is quite fast. If your program permits the model size, you might wish to increase the number of segments per wire by a factor of 1.5 to 2. The resulting model would place the source a bit closer to the radial junction to improve the precision of the output.

We have chosen a complex radial system as our example, although much modeling will be done with simpler systems. Many upper HF models will use as few as 4 radials elevated far above ground. However, once you master the radial-maker in your program, as well as the limiting conditions that we have noted, then no radial system will be too complex to model.

Frequency Sweeps: Why and How?

One of the initial tendencies of most modelers is to model for perfection at a specific design frequency. For example, if we model a Yagi, we try to arrive at the maximum possible gain, the highest front-to-back ratio and resonance—all on one frequency. We then sometimes mistakenly think that our work is done.

However, amateur antennas only rarely are used at a single frequency. Instead, we normally use them across a band of frequencies, such as all of 20 meters or the first MHz of 10 meters. The modeler's work is not complete until the antenna is checked and analyzed at reasonably close spot frequencies across the band of use. Fortunately, *NEC* is designed for "frequency sweeping."

How we sweep and what a sweep might tell us can be illustrated with a single model, shown in outline form in Figure 9. The 6-element high performance Yagi looks more complex in the sketch than its models looks in Figure 10, a *NEC-Win Plus* main page. Here, we see all 6 elements, their diameter (in feet), their aluminum material, and the source located on the second or driven element. If we look to the top of the page, we see that the model will be run in free space, with only a simply azimuth pattern chosen. *NEC's* output tables will produce all data for each frequency swept, including the source impedance (and the program's calculation of the 50-Ω SWR), the currents on each element segment, and the radiation pattern values used in the output plot.

How we set up the sweep is shown in the upper left corner of Figure 10. We select a start and stop frequency, as well as an increment. In this case, we'll obtain all values for the range of 28 to 29 MHz at 0.1 MHz increments. (Interestingly, this system has resulted from user preference. Raw NEC actually specifies a start frequency, the number of steps to be swept, and the increment of increase for each step. Commercial implementations make the transition from user-input to NEC core invisible.)

If we run the sweep, then we can obtain a truly overwhelming volume of data. Most users reduce the volume to a set of select values. Most commonly gleaned are the gain, the 180° front-to-back ratio, the source impedance, and the SWR relative to a user-preset standard. Occasionally, we might add the –3 dB beamwidth to the collection, and sometimes the currents along the element may be important. However, in the beginning, the data in Table 3 will satisfy most requirements.

Note that in the table, I have recorded values in different levels of precision, some with more operational significance than others. For example, no one can tell the difference on the air between 9.95 and 9.98 dBi free-space gain. However, in making up tables from *NEC* output data, it is often useful to use the level of numerical precision that shows most clearly

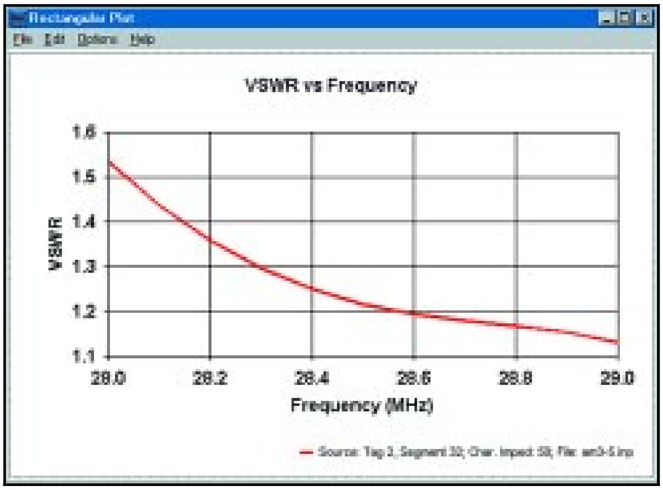

Figure 11—A *NEC-Win Plus* 50-Ω SWR plot from 28 to 29 MHz for the 6-element Yagi.

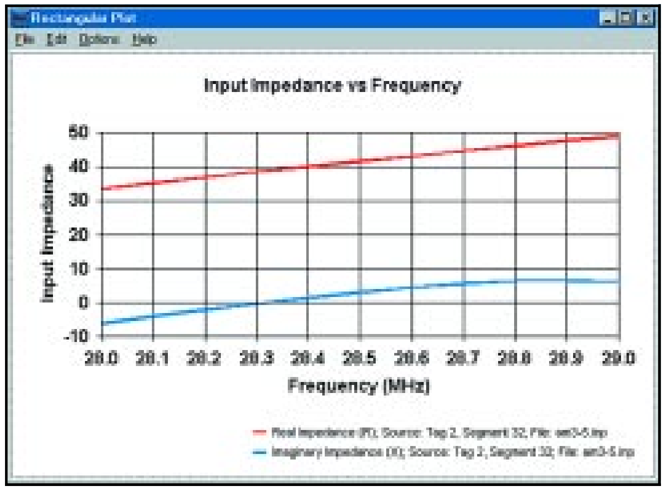

Figure 12—A *NEC-Win Plus* graph of the source resistance and reactance values from 28 to 29 MHz for the 6-element Yagi.

the trends in the figures. For the source impedance data, whole numbers are sufficient. For the front-to-back date, a single decimal place works well, while some of the gain trend might be lost if we used fewer than 2 decimal places. Use the level of precision that coincides with the task at hand. *NEC* will always supply more precision than we can ever use, and our performance requirements may be looser than those we may want to impose on the data for study purposes.

From the table, we can detect certain trends. For example, the peak front-to-back ratio occurs above the mid-band point of 28.5 MHz. (Very often, for the highest front-to-back ratio at the band edges, the peak value for a Yagi should be a little below the band center.) At the same time, the gain increases all across the band, but that is natural to Yagis having one or more directors.

Graphing some of the trends is useful, and some programs have built-in graphing facilities. Figure 11 shows the *NEC-Win Plus* 50-Ω SWR graph, which gives us the same data as Table 3. We begin to see that the peak front-to-back ratio at 28.6 MHz coincides with the fact that the minimum SWR occurs at the upper end of the design range for the model. The *NEC-Win Plus* graph of the source resistance and reactance adds further confirmation. The source resistance only approaches 50 Ω at the high end of the range, although reactance should not be a problem, since it peaks at 7 Ω and then descends again.

The picture we get from the frequency sweep is that our design work is not finished. For optimal operation of the antenna from 28 to 29 MHz, we would like to increase the element lengths just a bit to better center the maxima and peaks in the sweep table. Perhaps moving the peaks downward by about 0.2 MHz might give us a minimum of 10 dBi gain, a minimum front-to-back ratio of 20 dB across the band, and a peak 50-Ω SWR value of about 1.35:1.

The more you get into the habit of frequency sweeping your antenna models, the more insight you will gain into various designs. Trends in performance can be as important as peak performance data in telling us how antennas of various types do their work. Some sweeps may cover wide frequency ranges at greater intervals—for example, when checking the performance of a log periodic dipole array (LPDA) from 14 MHz through 30 MHz. Other sweeps may use very small intervals over restricted frequency ranges—for example, determining at what frequency (or frequencies) the 50-Ω SWR passes the 2:1 point for a 40-meter antenna and deriving from that an operating bandwidth.

In this part of our series, we have covered considerable ground: source placement, grounds and ground planes, and frequency sweeps. Part 4, will cover even more ground, as it corrals a number of topics: loads, transmission lines, model tests, and limitations of *NEC*. However, by the time the last installment appears, you may have already obtained a modeling program, read the manual, practiced a lot, and be way of ahead of me.

Notes

[1]The new *ARRL Antenna Book*, just released in its 19th edition, has an excellent program for using the source impedance along with most kinds of feed lines to show the impedance at the antenna tuner end of the line, whatever length of line we specify. Written by Dean Straw, N6BV, *TLW* also provides a wealth of other data for the antenna system builder.

[2]In our look at sources in this episode, we won't focus on whether we are using a voltage or a current source. However, we'll work though an exercise in the last episode of the series that will show at least one situation in which choosing one type of source over the other makes our work easier.

[3]See Chapter 3 of the 19th Edition of *The ARRL Antenna Book* for a good treatment of the effects of the earth on antennas, and especially pages 3-6 for a picture of ground values applicable to various parts of the US.

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By L. B. Cebik, W4RNL

A Beginner's Guide to Modeling With *NEC*

Part 4: Loads, transmission lines, tests and limitations

In this fourth and final installment of our series designed to get you started in modeling with *NEC*, we'll look at two disparate areas of modeling. The first arena involves a pair of auxiliary facilities built into *NEC*: the ability to model reactive (capacitive and/or inductive) loads and the ability to model transmission lines—both within limits. The second area is composed of model testing and some of the limits within which successful modeling occurs. Some words of caution will be a good way to conclude our preliminary survey. As we have done in the first three parts, we'll focus on *NEC*-2 and two commercial implementations: *EZNEC* 3.0 and *NEC-Win Plus*.

Currents and Current Sources

In the very first episode of this series, we noted that using a voltage source is the most normal procedure for simple models with a single feedpoint. We can leave the source values at a magnitude of 1.0 and a phase of 0.0 degrees (the default values) for most models, since the critical output data in which the beginning modeler is interested does not depend on the source values. Gain, front-to-back ratio and the source impedance will come out the same for a single-feed antenna no matter what source values we use.

Sometimes it is convenient to use a current source. Should you wish to model phased arrays, you'll need to use current sources to establish the relative magnitudes and phases of currents for the feedpoint of each driven element. Our beginning project, however, will be much simpler: we want to look at the current levels along a simple dipole. We can do this by using a voltage source, but the typically low current values tend to be hard to interpret without some further arithmetic. If we only had a way to set the source current at a value of 1.0, then all of the other values along the dipole would be relative to 1 for easier comprehension.

Commercial versions of *NEC*-2 provide a current source capability. The network used to transform the natural voltage source of *NEC* into a current source at the antenna feedpoint is invisible to the user. However, by selecting a current source and using the default value of 1.0 for the magnitude, we can perform our survey with ease.[1] Our one caution is to note that while the *NEC* core and *NEC-Win Plus* use peak values of voltage and current, *EZNEC* translates these values into their corresponding RMS values. For our work here, the difference will not have significance, but for translating voltage, currents and impedances into power levels and back again, peak values must be transformed into RMS values.

Now let's build a simple free-space (no ground) model, a 20-meter (14.175 MHz) dipole using 1-inch diameter aluminum, 21 segments, and a modeling length along

[1]Notes appear on page 35.

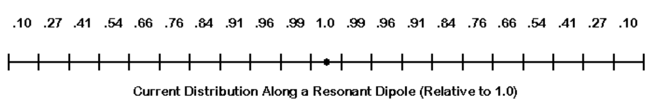

Figure 1—The relative current distribution along a resonant dipole, using a source current value of 1.0 as a reference.

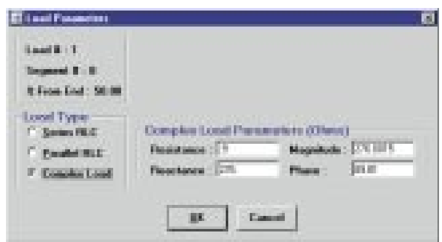

Figure 2—The *NEC-Win Plus* basic entry screen for a load consisting of a resistance and a reactance in series (called a "complex load").

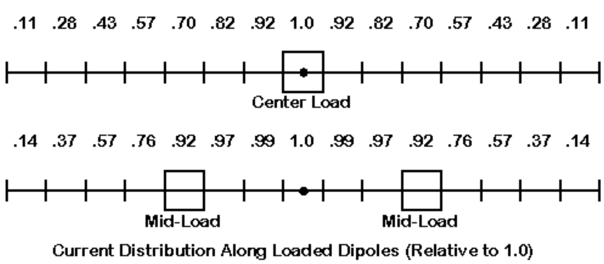

Figure 3—A comparison of current distributions along equal-length short dipoles using a center-loading inductor and 2 mid-element-loading inductors, referenced to a source current value of 1.0.

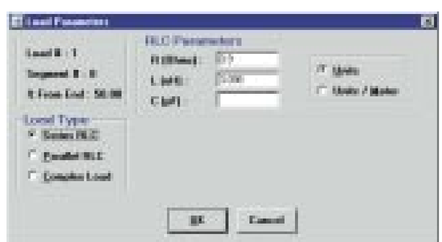

Figure 4—The *NEC-Win Plus* basic entry screen for loads consisting of a resistance and an inductance in series. A series capacitor, not used in this example, could be added to the mixed load. Note that parallel combinations of resistance, inductance and capacitance are also possible.

the Y-axis of +/–198.75 inches. We should find a source impedance at the design frequency of about 72 Ω with only a fraction of an ohm of reactance.

Our interest lies in Figure 1, a summary of the current magnitude on each segment of the model. *NEC* provides these values, and commercial implementations make them available as one of the tabular outputs. Figure 1 will be a standard for the next phase of our work, but for the moment, we can note two key items. First, the progression of values is almost, but not quite, a sinusoidal curve. Second, the lowest value is not zero because the calculation is for roughly the center of the outermost segment, not the very end.

Loads

Next, let's shorten the dipole to +/–144 inches, or 24 feet overall. Reduce the number of segments to 15 so that each segment will be about the same length as in the original longer dipole. The shortened antenna, of course, will not be resonant. In fact, it will report a source impedance of about 27 – *j*275 Ω. If we want to resonate the antenna, we shall have to compensate for the high capacitive reactance with loading coils somewhere in the antenna structure.

NEC lets us model reactive loads. The loads can have a resistive as well as a reactive component, as shown by the *NEC-Win Plus* load screen in Figure 2. Adding a series resistance to the reactance lets us account for the Q of the loading coil. Note the reactance value: 276 Ω, just enough to compensate for the capacitive reactance. The resistance value (0.9 Ω) reflects a coil Q of 300. The upper left corner of the figure shows that the load has been placed at the center of the antenna, on the same segment as the source. Loads are always in series with a source on the same segment.

All loads that we introduce are mathematical models, not physical models. The difference is this: a physical model, such as the antenna wire, contributes to the radiation pattern. The mathematical loads do not. So any variations (normally insignificant) in radiation patterns that result from using large or small coils will not show up in the output of *NEC*.

If we run our model with its load, we'll find a source impedance of about 31 Ω and a fractional value for reactance. Remember that the inductive reactance of the load cancelled out the capacitive reactance at the source by simple addition. In series circuits, we add resistances and add reactances. The added resistance of the coil shows up in the resistive part of the source impedance.

All loads that we introduce are mathematical models, not physical models. The difference is this: a physical model, such as the antenna wire, contributes to the radiation pattern. The mathematical loads do not.

We need not always use a center loading coil. Instead, we can place coils in the middle of each antenna leg away from the feedpoint. If we remove the center loading coil, we can replace it with a coil 30% from the left end (segment 5) and another matching coil 70% from the right end (segment 11). Experimentally, we can adjust the reactance of the two coils until the antenna is once more resonant. For the 24-foot 20-meter model, values of *j* 212 Ω (reactance) will do the job, and for a Q of 300, we can assign the resistance box a value of 0.7 Ω. Running our new mid-element loaded dipole will yield

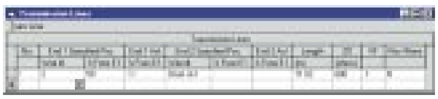

Figure 5—The *EZNEC* screen for introducing a mathematical transmission line into a model.

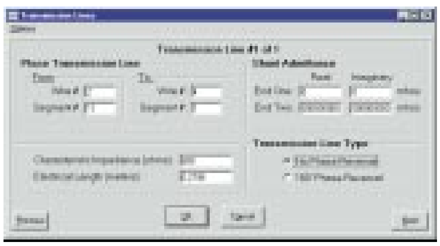

Figure 6—The *NEC-Win Plus* screen for introducing a mathematical transmission line into a model.

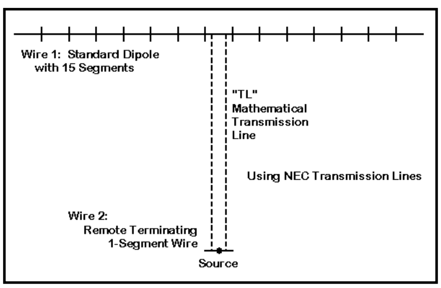

Figure 7—A standard use of a transmission line between the antenna wire and a short, 1-segment terminating wire that becomes the location of the antenna system source.

a resonant impedance of about 45 Ω. The impedance value is higher than with center-loading, but lower than the impedance of a self-resonant dipole.

Before we leave the loaded dipoles, let's look at the current tables (since we used a current source for our runs). Refer also to Figure 1 for comparison. The current level on the antenna wire past the loads suddenly decreases relative to the current distribution on an unloaded dipole. Hence, we would expect either loaded dipole to show somewhat less gain than the unloaded standard.

There are some cautions to observe for loads. First, the mathematical load assumes equal currents on both ends of a coil. As Figure 3 shows, this condition only exists for the center loading coil, but not for the mid-element coils. Hence, the calculations you make for mid-element loading coils will be slightly less precise relative to building the coil. Second, using the coil's reactance is good only for a single frequency. If you wish to perform a frequency sweep of the antenna, re-enter the coil values, an inductance and a resistance in the series RLC option for entry, as shown in Figure 4, a *NEC-Win Plus* load box for the center loading coil. Standard handbook equations for transforming reactance to inductance (or capacitance) apply here.[2] Some implementations of *NEC* call for µH and pF, while others may call for basic units. With inductive, capacitive, and resistive units, loads will show the correct reactance at each checkpoint of a frequency sweep, and the resulting source impedance values (and SWR values, if needed) will be much closer to the reality of the antenna's performance.

Transmission Lines

A second mathematical convenience offered by *NEC* is the use of transmission lines in a model. Like loads, these lines do not enter into the calculation of radiation patterns. If the pattern influence of a transmission line is significant to a model, the modeler must physically model the line, which is possible for parallel lines, but not generally feasible for coaxial cables.

Figure 5 shows the *EZNEC* transmission line entry screen, while Figure 6 shows the *NEC-Win Plus* equivalent. Both show the same line: a shorted stub of 600-Ω line having a length of 11.02 inches or 0.2799 meters. *EZNEC* provides an invisible structure for open and shorted stubs, while *NEC-Win* shows the actual construction. Every transmission line must run from one wire to another. In *NEC-Win Plus* or raw *NEC*, we create a new short (1 segment) thin wire that is

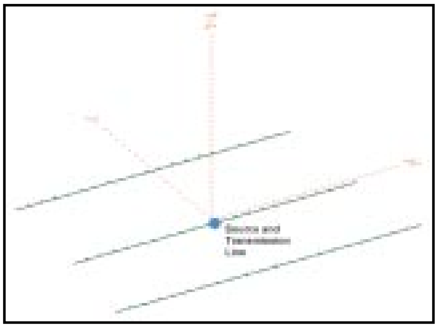

Figure 8—An *EZNEC* view of the 3-element Yagi with a beta-match shorted transmission-line stub (hairpin) at the driven element terminals.

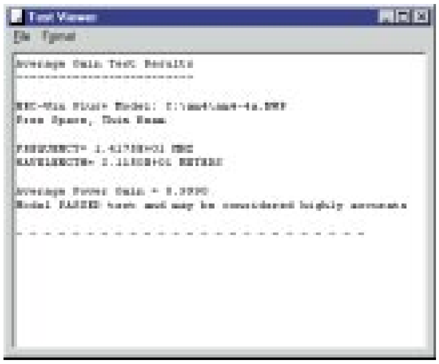

Figure 10—The *NEC-Win Plus* report on the results of the average gain test for the 3-element Yagi used for the beta-match illustration.

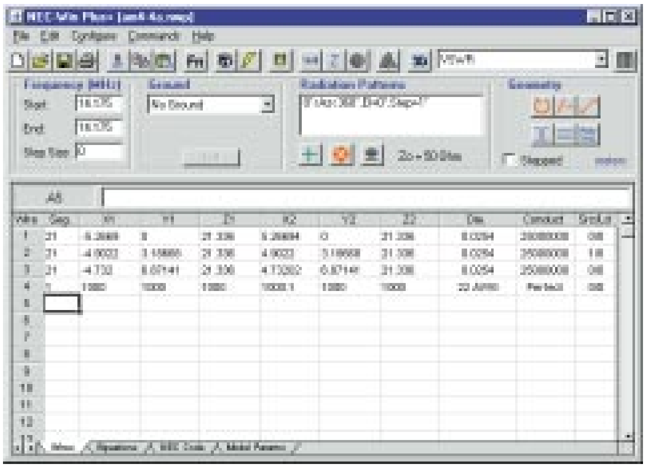

Figure 9—The *NEC-Win Plus* wires page for the 3-element Yagi and beta-match stub, showing the remote terminating wire for the transmission-line stub.

far away from the antenna. Its position is not critical, since the line length entered into the proper box on the transmission line screen controls the calculation. A shorted stub requires a high shunt admittance. The long numerical entry for 1^{10} (1 to the tenth power) is used to assure a true short circuit at the far end. Note in passing that we can reverse the line between the two terminating wires, essentially giving it a half twist—a useful feature for modeling phased arrays.

The transmission line entry boxes illustrate the critical elements of a *NEC* transmission line. Figure 7 shows the layout of such a standard sort of model using a transmission line used with a dipole. The dipole wire is one end of the line, while a new short 1-segment line terminates the transmission line. For this kind of application, we move the source from its usual position at the center of the dipole and place it on the new wire. We might wish to see what impedance we might obtain at the end of the line using various line lengths. We need only change the line length, perhaps in quarter-wavelength increments, to explore the effects of line length on the system source impedance. Note that some programs have a velocity factor entry box, which lets you enter the physical line length. Other programs do not have a velocity factor box, so you must precalculate the electrical length of the line and use that figure.[3]

There are cautions to observe in the use of *NEC* transmission lines. First, they do not account for line losses. For short line runs, the source impedance error will likely not be significant, but the error will grow with very long transmission line runs. Second, transmission lines are in parallel with sources (in contrast to loads, which are in series with sources). Third, transmission lines are accurate only where the antenna element current on each side of the line is equal. Hence, they are most accurate at element centers and other low impedance points along an antenna and become quite inaccurate at low current, high voltage positions.

Transmission line runs to a remote source are only one use of this *NEC* facility. Stubs are also useful for modeling some kinds of matching networks for antennas. For example, consider the 20-meter 3-element Yagi in free space, as shown in Figure 8. Before adjustment with a matching network, it has a source impedance of about $24 - j25\ \Omega$. The resistance and capacitive reactance are exactly suited to the use of a beta match. We can implement the match with a small coil across the feedpoint or with a shorted transmission line stub (often called a "hairpin"). In fact, the stub that we used to illustrate the basic transmission-line setup in Figure 5 and Figure 6 is exactly what we need to introduce an inductive reactance of about 50 Ω across the antenna terminals. Because transmission lines are mathematical and use remote terminating wires for stubs, Figure 8 does not show the stub, but indicates its presence with a dot. (If the view tried to show the terminating wire for the stub, the antenna structure itself would shrink almost to invisibility in the graphic.)

Figure 9 shows the *NEC-Win Plus* wires page that goes with Figure 6, the corresponding transmission line screen. Wire 4 is the remote 1-segment thin wire that terminates the shorted stub. The units of measure are meters, which coincides with the stub length in Figure 6. If we run the model, we should get a source impedance at 14.175 MHz of about $51 - j3\ \Omega$. You may wish to run a frequency sweep of the antenna across the entire 20-meter band to check the 50-Ω VSWR at the band edges.

Besides their use as standard transmission lines and as stubs in matching networks, transmission lines have other uses in advanced modeling. For example, the phase-line needed in a log periodic dipole array (LPDA) runs from one element to the next with a half twist between each element. Such structures are extremely difficult to model physically, but the transmission line facility in *NEC* not only simplifies the process, but as well increases the accuracy of the array analysis. Used with care and with their mathematical (non-physical) nature always in mind, transmission lines in *NEC* can be a valuable design tool for many types of antennas.

Testing Models

I have stressed that both loads and transmission lines must be used with care and within their limitations if we are to achieve accurate model results that coincide closely with the physical antennas the models represent. This same caution applies to the physical structure of models. There are two general tests that we can apply in order to increase our confidence in a given model.

The first analysis is called the convergence test. In Part 1 of the series, we noted the minimum number of segments to be used on open-ended linear elements. However, as the antenna geometry becomes more complex, we may need more than the minimum number of segments to assure an accurate model. Moreover, segment length should ideally be about the same throughout a model. Whether we have enough segments of the right lengths is subject to a simple test.

Start by running the original model and recording the gain and source impedance. Then increase the number of segments for each wire by about 50%. Again, record the gain and source impedance. You may wish to give the test a third trial with another 50% increase in the number of segments per wire and record the results.

The level of segmentation at which the output figures for the model do not change significantly is the minimum level of segmentation for the model. The models are said to converge at this segmentation level. In some cases, minimum segmentation is satisfactory. In others, especially for antennas having a closed geometry (like angular loops), the required segmentation level may be higher. A few antennas, such as those with angular elements of different lengths extending from the feed point, may not converge until very high levels of segmentation. And some models will not converge at all because they exceed the limitations of the *NEC* core or have other construction errors. There is no absolute standard of what counts as the borderline between converged and non-converged models. However, if two successive levels of segmentation produce results that indicate differences in antenna performance or structure that go beyond normal tune-up adjustments, the models are likely not sufficiently converged.

A second test is called the average gain test. If we place a horizontal antenna model in free space or a vertical antenna over perfect ground, we can then perform a 3-dimensional radiation pattern test, using equally spaced checkpoints. To perform the test, we omit wire losses and resistive loads. The reason for these moves is that the average gain of a lossless antenna, taking into account a fair sampling of all possible directions of radiation, is 1. Resistive losses would interfere with this result.

For the 3-element Yagi that we used to illustrate the beta matching stub, we receive the *NEC-Win Plus* report shown in Figure 10. Equal in quality to the 0.999 average gain value would have been 1.001, since the test is run with a large but not exhaustive sample of directions for the radiation pattern checkpoints. Again, there is no absolute standard for what counts as "highly accurate." The level may depend on whether we are preparing to home brew an antenna or whether we are deriving some detailed performance trends. For most uses, values of 0.95 to 1.05 for the average gain test indicate a very usable model for virtually any purpose.

However, both the convergence and average gain tests are necessary conditions of model adequacy. They are not sufficient conditions. There are at least a few types of models that can pass both tests and still yield inaccurate results. However, passing both tests should increase our confidence that we have a good model.

NEC Limitations

A bad model (one which fails either or both tests) does not necessarily mean that the modeler is at fault. *NEC* has limitations. We saw some of those limitations in Part 1, when we noted certain guidelines for the minimum segment length to diameter ratio, segments per half wavelength of wire, etc. There are others, a few of which are illustrated in Figure 11. For example, letting two wires touch at mid-segment points (in contrast to junctions) will trigger the *NEC* core to reject the model. Most of the *NEC* core rejection messages occur due to simple mistakes in creating or revising the geometry of an antenna model. The solution is to find and correct the error. By using the paper planning techniques shown in Part 2, we minimize the chances of receiving a core rejection notice.

More subtle are *NEC* limitations that the core does not signal with a rejection message. For example, *NEC* will normally yield inaccurate results when two wires of different diameters meet at an angular junction. The difficulty grows more pronounced as we add more segments to each wire. Consider a folded **X**-beam composed of 1-inch aluminum elements in the facing **V** sections with thin wire tails pointing toward each other in each side of the structure. This antenna will not converge at any level of segmentation in *NEC*.[4]

Likewise, *NEC* can grow inaccurate when two wires of different diameters are brought close together. Wires of the same diameter should have their segment junctions well aligned when in proximity for highest accuracy, for example, with a folded dipole. However, even if the segment junctions are aligned, wires of different diameters and lengths will show errors of both gain and source impedance as they approach too closely. The degree of error depends on many factors, including the wire diameter, the spacing, the frequency, and the relative element lengths. The average gain test will normally catch this overstep of the limitations inherent in *NEC*.[5]

The *NEC* core also has a limitation in handling tapered-diameter elements, that

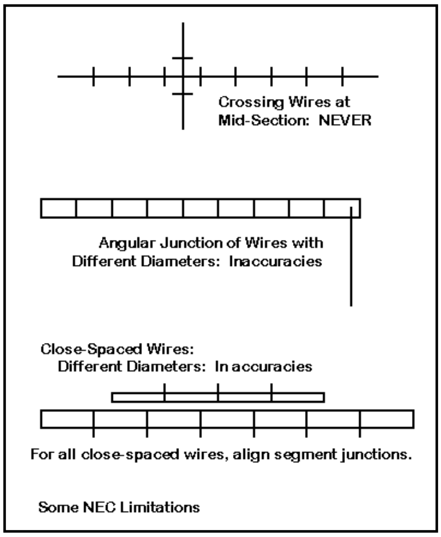

Figure 11—Some *NEC* limitations, including the prohibition against wires crossing at mid-segment locations, and accuracy difficulties with angular junctions of wire having different diameters and close-spaced wires of different lengths or diameters.

Most of the NEC core rejection messages occur due to simple mistakes in creating or revising the geometry of an antenna model. The solution is to find and correct the error.

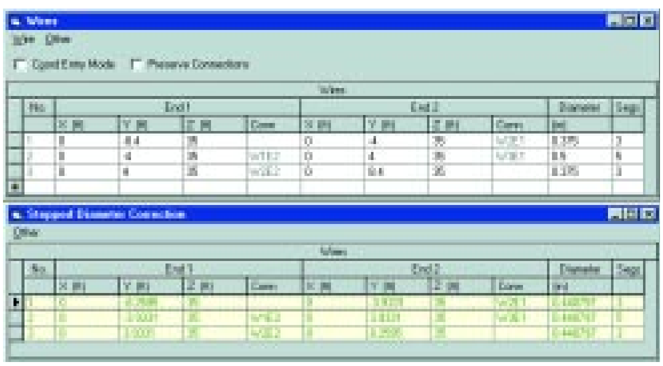

Figure 12—A sample, from *EZNEC*, of the original tapered-diameter element and its uniform-diameter Leeson substitute.

is, elements composed of ever-smaller diameters of tubing as we move outward from the element center. However, commercial implementations of *NEC*, including both *EZNEC* and *NEC-Win Plus*, offer the modeler a system of carefully calculated substitute elements having a uniform diameter. The corrective elements are based on the work of Dave Leeson, W6QHS (now W6NL).[6] Using a complex set of equations, the program precalculates substitute elements. However, the equations only work within about 15% of the design frequency and on symmetrical open-ended linear elements with no mid-element loads or transmission lines. Despite these limitations, the correction factor has been a boon to designers of directional arrays for the upper HF and lower VHF region.

Figure 12 provides a small sample of the Leeson corrections in action, using *EZNEC* as the source. The upper part of the figure shows the 3-wire dipole used as an example in Part 2 of this series. The lower portion of the figure shows the substitute elements that replace the tapered diameter model in *NEC* calculations. Note that the uniform-diameter element is not simply the average of the two diameters in the tapered-diameter version. As well, the uniform-diameter version is shorter than the physical dimensions being modeled. Elements that taper toward thinner diameters as we move away from the center feedpoint require longer physical element lengths for resonance than do uniform-diameter elements. Finally, note that the length dimension affects not only the outer ends of the element, but the length of the inner element piece as well.

The Leeson corrections have made the design of Yagis and similar directional arrays routine. Of course, the corrections must be used within the limitations that we noted above. The upshot is that there are arrays which are difficult (if not impossible) to model within *NEC*. Nonetheless, despite the limitations, *NEC* is capable of accurately modeling an almost endless variety of antennas for frequencies ranging from below the AM broadcast band into the upper UHF region.

Conclusion

We have explored *NEC*-2 modeling with the eyes of a beginning modeler, starting from the basic language of the modeling enterprise and ending with some fairly advanced cautionary notes about the limits of *NEC*-2. We have not exhausted all of the possibilities for combining the features of the *NEC* core and its commercial interfaces to improve the precision of our analyses or to ease the work involved in creating models. For example, we have not mentioned trap antennas, which can be modeled with good results. We have not delved into modeling by equation, which can simplify the construction and revision of models and so speed up the design process. And we have not touched upon the modeling or complex structures, such as typical tower sections, or the use of substitute models.[7]

Elements that taper toward thinner diameters as we move away from the center feedpoint require longer physical element lengths for resonance than do uniform-diameter elements.

What we have attempted to do in this 4-part series is to acquaint you sufficiently with the fundamentals of *NEC* modeling so that you can embark on your own exploration of the antennas in which you have the most interest. Hopefully, there is enough information in these notes to make your initial efforts successful and make the next steps confident ones on your own.

Think of *NEC* as a precision tool. Even as I write, various improvements to the modeling process—some general, some for specific applications—continue to develop. However, even though *NEC*-2 is nearly two decades old, it remains far more precise than older calculation methods. It is superior by far to those rules of thumb by which we measure dipoles and quads, and it is a distinct advance in antenna pattern and gain analysis compared to aperture-area calculations that were popular in the middle of the 20th century. In short, *NEC* is a good tool for the student of antennas to master as we move into the 21st century.

However, like every precision tool, *NEC* requires care, practice, patience, and focus to master well. What we learn about antennas along the way will be the reward for our efforts.

Notes

[1]Users of raw *NEC* can achieve a source current of 1.0 in the following way. For a resonant antenna, use the voltage source at its default values to obtain the source impedance. Then use the source impedance as a revised voltage magnitude and phase-values, and rerun the model. The source current should be 1.0, since current equals the voltage divided by the impedance. Likewise, one can explore the actual current for a given power level by using the initial run source impedance and the desired power level. Select a voltage equal to the square root of the power times the impedance. See the main text for cautions concerning *NEC*'s use of peak voltage and current.

[2]As a reminder, here are the transformation equations for inductance and capacitance and their respective reactance values:

$$X_L = 2\pi fL \quad L = \frac{X_L}{2\pi F} \qquad \text{(Eq 1)}$$

where X_L is the inductive reactance in Ohms, L is the inductance in Henries, and f is the frequency in Hz.

$$X = \frac{1}{2\pi fC} \quad C = \frac{1}{2\pi fX_C}\ 2 \qquad \text{(Eq 2)}$$

where X_c is the capacitive reactance in Ohms, C is the capacitance in Farads, and f is the frequency in Hz. In addition, when using either the series or parallel RLC option, place a zero in the box for a missing value, for example, the capacitance box of Figure 4. *NEC* interprets the zero as a missing value and not as 0 pF capacitance.

[3]For reference,

$$L_P = VF \bullet L_e \quad L_e = \frac{L_p}{VF} \qquad \text{(Eq 3)}$$

where L_p is the physical length of the line, L_e is the electrical length of the line (in the same units), and VF is the velocity factor, ordinarily 1.0 or less.

[4]Interestingly, *MININEC* has no difficulty in modeling the angular junctions of dissimilar wires, although length tapering may be needed at the acute angle corners. *NEC*-4 improves on the performance of *NEC*-2 for such structures, but remains shy of perfection.

[5]Once more, *MININEC* has no problem with close spaced wires of different diameters and lengths. Hence, it yields quite accurate results for folded dipoles that use wires of different diameters. For further details of *NEC* limitations, especially as they appear in *NEC*-4, see L. B. Cebik, "*NEC*-4.1: Limitations of Importance to Hams," *QEX* (May/June, 1998, pp 3-16). The limitations of *NEC*-4 also apply to *NEC*-2.

[6]David B. Leeson, W6QHS, *Physical Design of Yagi Antennas* (Newington: ARRL, 1992), Chapter 8. Once more, *MININEC* does not have difficulties in dealing with tapered-diameter elements and is used as a comparative standard by Leeson. (However, *MININEC* 3.13—the public domain version—does have numerous limitations of its own, such as a very slow-running core, limitations on the total number of available segments, no transmission line facility, a relatively poor system for calculating ground effects, source impedance calculated only over perfect ground, etc. These limitations have made *NEC*-2 the more preferred modeling core among radio amateurs, although *MININEC* still has important uses. *NEC*-4 requires a license and advanced software, both of which have placed this improved *NEC* core beyond the economic reach of most hams.)

[7]Those whose interests in antenna modeling grow deeper are invited to look at the series of *AntenneX* columns that I do monthly, all of which are at my Web site (**www.cebik.com**) under the "Antenna Modeling" heading, or to the text *Basic Antenna Modeling: A Hands-On Tutorial*, available from Nittany Scientific, Inc (**www.nittany-scientific.com**). The original *NEC*-2 manuals remain the most authoritative references for understanding the operation of the core. The on-line or paper manuals accompanying commercial implementations of *NEC*-2 are also authoritative for the respective software packages.

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