TABLE OF CONTENTS

Chapter 8 —
CD-ROM Content

Supplemental Articles

- "How to Start Modeling Antennas Using *EZNEC*" by Greg Ordy, W8WWV

Chapter 8

Antenna Modeling

8.1 OVERVIEW: ANTENNA ANALYSIS BY COMPUTER

As pointed out in **The Effects of Ground** chapter, irregular local terrain can have a profound effect on the launch of HF signals into the ionosphere. A *system approach* as described in the **HF Antenna System Design** chapter is needed to create a scientifically planned station. Antenna modeling programs do not generally take into account the effects of irregular terrain and by "irregular" we mean any sort of ground that is not flat. Most modeling programs based on *NEC-2* or *MININEC* do model reflections, but they do not model diffractions.

On the other hand, while a ray-tracing program like *HFTA* (HF Terrain Assessment by Dean Straw, N6BV — described in the **HF Antenna System Design** chapter) does take into account diffraction, it doesn't explicitly factor in the mutual impedance between an antenna and the ground. Instead, *HFTA* makes the basic assumption that the antenna is mounted sufficiently high above ground so that the mutual impedance between an antenna and the ground is minimal.

In this chapter we'll look at modeling the antennas themselves on the PC. We'll evaluate some typical antennas over flat ground and also in free space. Once characterized — or even optimized for certain characteristics — these antennas can then be analyzed over real terrain using *HFTA* and the other tools discussed in the **HF Antenna System Design** chapter.

Previous editions of this book have included *EZNEC-ARRL*, a version of *EZNEC* antenna modeling software that worked with a special set of model files. Effective with this edition, the demo version of *EZNEC 6.0* will run all *EZNEC-ARRL* models, subject to the limitations spelled out in the demo version documentation. The demo version of *EZNEC 6.0* is free and can be downloaded from **www.eznec.com**. Previous versions of *EZNEC-ARRL* will continue to operate properly with *EZNEC-ARRL* files as before. Model files including those referenced in this chapter are provided as supplementary content on the CD-ROM that comes with the *ARRL Antenna Book.*

8.1.1 A SHORT HISTORY OF ANTENNA MODELING

With the proliferation of personal computers since the early 1980s, amateurs and professionals alike have made significant strides in computerized antenna system analysis. It is now possible for the amateur with a relatively inexpensive computer to evaluate even complicated antenna systems. Amateurs can obtain a keener grasp of the operation of antenna systems — a subject that has been a great mystery to many in the past. We might add that modern computing tools allow hams to debunk overblown claims made about certain antennas.

The most commonly encountered programs for antenna analysis are those derived from a program developed at US government laboratories called *NEC*, short for "Numerical Electromagnetics Code." *NEC* uses a so-called *Method of Moments (MoM)* algorithm. (The name derives from a numerical method of dealing with accumulated errors in fields generated by current distributed along an antenna.) If you want to delve into details about the Method of Moments, see the excellent chapter in *Antennas*, 2nd edition, by John Kraus, W8JK. See also the article "Programs for Antenna Analysis by the Method of Moments," by Bob Haviland, W4MB, in *The ARRL Antenna Compendium*, Vol 4.

The mathematics behind the MoM algorithm are pretty formidable, but the basic principle is simple. An antenna is broken down into a number of straight-line wire segments, and the field resulting from the RF current in each segment is evaluated by itself and also with respect to other mutually coupled segments. Finally, the field from each contributing segment is vector-summed to yield the total field, which can be computed for any elevation or azimuth angle desired. The effects of flat-earth ground reflections, including the effect of ground conductivity and dielectric constant, may be evaluated as well.

In the early 1980s, *MININEC* was written in *BASIC* for use on personal computers. Because of limitations in memory and speed typical of personal computers of the time, several simplifying assumptions were necessary in *MININEC*, limiting potential accuracy. Perhaps the most significant limitation was that perfect ground was assumed to be directly under the antenna, even though the radiation pattern in the far field did take into account real ground parameters. This meant that antennas modeled closer to ground than approximately 0.2 λ

Commercial Implementations of *MININEC*, *NEC-2*, and *NEC-4* Programs

Ever since the source code for *NEC-2* and *MININEC* came into in the public domain, enterprising programmers have been upgrading, extending and improving these programs. There are a number of "freeware" versions available and also a variety of commercial implementations.

This sidebar deals only with the most popular programs that many hams use. You should keep in mind that whatever program you choose will require an investment in learning time, if not in dollars. Your time is valuable, of course, and so is the ability to swap modeling files you create with other modelers. Studying model files, particularly when you are just starting out, is a great way to learn how the "experts" do their modeling. For example, there are archives of *EZNEC* model files available on the Internet, since this popular modeling program has been around for a number of years.

The following table summarizes the main features and the pricing as of early 2015 for some popular commercial antenna modeling programs. The programs that use the *NEC-4* core require separate licenses from Lawrence Livermore National Laboratories.

Commercial Implementations of *MININEC* and *NEC-2* programs

Name	*EZNEC 6.0 (6.0+ version)*	*EZNEC-Pro/2 v.6.0 (Pro4 v.6.0)*	*NEC-Win Plus*	*NEC-Win Pro*	*GNEC*	*Antenna Model*
Manufacturer	Roy Lewallen	Roy Lewallen	Nittany Scientific	Nittany Scientific	Nittany Scientific	Teri Software
Core	*NEC-2*	*NEC-2 (NEC-4)*	*NEC-2*	*NEC-2*	*NEC-2/NEC-4*	*MININEC*
Operating System	*Windows 32/64 bit*	*Windows 32/64 bit*	*Windows 32 bit*	*Windows 32 bit*	*Windows 32 bit*	*Windows 32 bit*
Number Segments	500 (2000, + ver.)	20,000	10,000	10,000	80,000	Limited by memory
***NEC*-Card Inputs**	No	Yes	Yes	Yes	Yes	No
Other Input	ASCII (NEC, + ver.)	ASCII,NEC	CAD *.DXF	CAD *.DXF	CAD *.DXF	No
Wires by Equation	No	No	Yes	Yes	Yes	Yes
Source Setting	By %	By %	By %	By %	By %	By %
Source Type	Current/ Voltage/Split	Current/ Voltage/Split	Current/ Voltage/Split	All types	All types	Current/Voltage
R + j X Loads	Yes	Yes	Yes	Yes	Yes	Yes
RLC Loads	Series, Parallel, Trap	Series, Parallel, Trap	Series, Parallel	Series, Parallel	Series, Parallel	Series, Parallel
True Trap Loads	Yes	Yes	No	No	No	No
Laplace Loads	Yes	Yes	Yes	Yes	Yes	No
Transmission Lines	Yes	Yes	Yes	Yes	Yes	No
Conductivity Table	Yes*	Yes*	Yes	Yes	Yes	Yes
Average Gain Test	Yes	Yes	Yes	Yes	Yes	Yes
Transmission Lines	Yes	Yes	Yes	Yes	Yes	No
View Geometry	Excellent	Excellent	Good	Good	Good	Very Good
Geometry Checking**	Yes	Yes	Yes	Yes	Yes	Yes
Easy Height Change	Yes	Yes	No	No	No	No
Polar Plots	ARRL, linear-dB	ARRL, linear-dB	ARRL, linear-dB	ARRL, linear-dB	ARRL, linear-dB	ARRL, linear-dB
	Az/El, Circ. (+ ver.)	Az/El, Circ.	Az/El Patterns	Az/El Patterns	Az/El Patterns	Az/El Patterns
Rectangular Plots	SWR	SWR	SWR, Zin	SWR, Zin, Az/El, Currents	SWR, Zin, Az/El, Currents	Gain, SWR, F/B, F/R, Rin, Xin
Operating Speed	Fast	Fast	Very Fast	Very Fast	Very Fast	Slow
Smith Chart	Yes (Freq sweep, + ver.)	Yes Freq sweep	No	Yes Freq sweep	Yes	Yes
Near/Far Field Tables	Both	Both	Far	Both	Both	Both
Ground Wave Analysis	No	Yes	No	Yes	Yes	No
Pricing	$99 Web; $109 CD-ROM, $149 (+ ver.)	$525 ($675) (must have *NEC-4* license)	$150	$425	$795	$90

*Wire conductivity is the same for all wires.
**Excellent, Very Good, Good ratings from previous edition

sometimes gave erroneous impedances and inflated gains, especially for horizontal polarization. Despite some limitations, *MININEC* represented a remarkable leap forward in analytical capability. See Roy Lewallen's (W7EL) "*MININEC* — the Other Edge of the Sword" in Feb 1991 *QST* for an excellent treatment on pitfalls when using *MININEC*.

Because source code was made available when *MININEC* was released to the public, a number of programmers produced some very capable commercial versions for the amateur market, many incorporating exciting graphics showing antenna patterns in 2D or 3D. These programs also simplify the creation of models for popular antenna types, and several come with libraries of sample antennas.

By the end of the 1980s, the speed and capabilities of personal computers had advanced to the point where PC versions of *NEC* became practical, and several versions are now available to amateurs. The most recent public-domain version is *NEC-2* and this is the computational core that we'll use as an example throughout this chapter.

Like *MININEC*, *NEC-2* is a general-purpose modeling package and it can be difficult to use and relatively slow in operation for certain specialized antenna forms. Thus, custom commercial software has been created for more user-friendly and speedier analysis of specific antenna varieties, mainly Yagi arrays described in the chapter on **HF Yagi and Quad Antennas**. Also see the sidebar, "Commercial Implementations of *MININEC* and *NEC-2* Programs."

The following material on antenna modeling is by necessity a summary since entire books have been written on this subject. Serious modelers may want to consider purchasing the modeling tutorials "Basic Antenna Modeling: A Hands on Tutorial" and "Intermediate Antenna Modeling: A Hands on Tutorial" by L. B. Cebik, W4RNL (SK) from **www.antennex.com**. The books contain a great deal of information, tips and techniques concerning antenna modeling by computer. The ARRL has also published a step-by-step introduction to *EZNEC* in the book *Antenna Modeling for Beginners* by Ward Silver, NØAX. We also strongly recommend that you read the HELP files available with the demo version of *EZNEC*. It contains a wealth of practical information on the finer points of antenna modeling.

8.1.2 COMPARING *NEC-2* TO *NEC-4*

The following section was contributed by Greg Ordy, W8WWV, for the 23rd edition. Another article by Greg, "How to Start Modeling Antennas Using EZNEC," is included on the CD-ROM accompanying this book.

Two popular antenna modeling programs are *EZNEC* and *4nec2*. They are GUI (graphical user interface) shells or wrappers that use an *NEC* modeling engine to perform the antenna simulation. (See the Reference section of this chapter for website URLs for these and other programs referenced in this sidebar.)

NEC versions 2 and 4 are the engines available to both modeling programs. I know of no antenna model where *NEC-2* would be preferred to *NEC-4*. *NEC-2* survives because it is free software in the public domain and *NEC-4* is licensed software that costs at least several hundred dollars. Programs such as *EZNEC* and *4nec2* have augmented *NEC-2* with extensions that address the most serious of the *NEC-2* deficiencies in many models.

For a wide range of models, the choice between the *NEC-2* and *NEC-4* engines makes little difference. There are models, however, where the choice of engine becomes very important if the highest accuracy is desired.

This section highlights the differences between *NEC-2* and *NEC-4*. Most of the information comes from the references included at the end of this chapter.

History

The acronym "NEC" (pronounced *neck*) stands for Numerical Electromagnetics Code. It is not related to the other popular use of "NEC," which is used to refer to the National Electrical Code.

- *NEC-1* was developed at the Lawrence Livermore National Lab (LLNL) in 1977. *NEC-1* built upon versions 1 and 2 of the *Antenna Modeling Program* (*AMP*). They date back to 1974.
- *NEC-2* was released in 1980, with its user manual dated January, 1981.
- *NEC-3* was released in 1983. It addressed one of the two major problems with *NEC-2*. It accepts buried wires and wires that penetrate a lossy media (such as ground).
- *NEC-4* was released in 1992. It extends and improves *NEC-3*. In particular, it corrects the problem that *NEC-2* and *NEC-3* have with stepped-radius wires and junctions of tightly coupled wires.

NEC-2 is the most recent version that was released in source form without restriction into the public domain. It has been used as part of many commercial and freeware software packages. It's safe to say that more models have been run using *NEC-2* than any other modeling engine.

NEC-4 supersedes *NEC-3*. *NEC-4* remains licensed software. To use *NEC-4* legally it is necessary to obtain a license from the Lawrence Livermore National Laboratory (LLNL). The one-time license fee is a function of the intended use of the software (personal/commercial/foreign). The cost ranges from $300 to $1500 (as of early 2015). The license is non-transferable.

It is worth mentioning the *MININEC* modeling engine. *MININEC* was developed as a personal computer antenna modeling engine in 1982. It is written in the *BASIC* programming language as opposed to *FORTRAN*. Despite the name, it is not a cut down version of *NEC*. While it has its own set of issues and concerns, in some areas it is considered to be superior to *NEC-2* and potentially even *NEC-4*. In particular, *MININEC* models stepped-radius wires accurately. *MININEC* has its place in the world of antenna modeling. It is available in packages such as *MMANA-GAL*.

In recent years, the specific version of *NEC-4* that has been in common use is version 4.1. In 2011, version 4.2 was released, and is included along with version 4.1 as part of the licensed package from LLNL. Version 4.2 adds a new ground option. In some cases, it can be more accurate than the 4.1 version. Using it, however, does slow down running the model. Look for *NEC* version 4.2 to be adopted by modeling packages in the future. Rudy Severns, N6LF, has completed some experiments testing the accuracy of the *NEC-4.2* engine. His analysis and conclusions are in the process of being published.

The modeling engine software dates back to the time before the explosive expansion of the power and capacity of the personal computer (PC). To provide the highest performance at the time, programmers included options such as using single-precision (32-bit) floating point computations as opposed to double-precision (64-bit) computations. After almost 30 years of PC evolution, there are very few cases where using the single-precision modeling engine makes sense. There are cases, however, where the added precision of the double-precision engine improves accuracy.

NEC-4 is more "idiot proof" than *NEC-2*. It has fewer idiosyncrasies and modeling guidelines to follow. To use *NEC-2* effectively, you have to be smarter about how to use it, and even when to use it.

It has always been possible to directly use the *NEC* engines and skip the wrapper or shell programs. Be aware, however, that the original interface to *NEC* is a deck of punch cards on the input and a long plain-text output file intended for a line printer.

Average Gain Test

Regardless of the engine in use, it's always a good idea to use the Average Gain Test to evaluate and increase the confidence in a model. When a model is inappropriate due to guideline violations or using an engine incorrectly, the Average Gain Test can highlight the problem.

A lossless antenna in a lossless environment radiates all incoming power in some direction. To perform the average gain test all loss is removed from the model. When run, all of the power supplied to the antenna should be captured in the pattern. If not, then the lossless antenna is acting like an amplifier or attenuator, and since it is neither, something is wrong with the results.

Details on running the Average Gain Test can be found in the program documentation. Often times the model can be adjusted to pass the test. If that is not possible, then the numeric results of the test can be used to correct the reported gain. If your model results are way out of line with common sense expectations, then it is a good time to run the Average Gain Test.

Differences Between *NEC-2* and *NEC-4*

Stepped Wire Diameters

Perhaps the biggest failing with *NEC-2* is its handling of stepped-diameter wire connections. If this sounds esoteric, please remember that telescoping aluminum tubing is used to construct many of our antennas — including the Yagi and ground-mounted vertical. When an aluminum tube slides into the next size tube, a stepped diameter situation is created. This problem was finally addressed in *NEC-4*, and *MININEC* does a good job of handling it appropriately too. If not for the ability to compensate or correct for this problem, I think it's fair to say that *NEC-2* would have been abandoned — certainly for this class of antenna.

The correction approach used was developed by Dr David Leeson, W6NL (ex-W6QHS). It is detailed in Chapter 8 of his book *Physical Design of Yagi Antennas*. Although more than 20 years old, it is still a valuable reference for anyone who is serious about the mechanical or electrical aspects of a Yagi.

The stepped-diameter correction algorithm converts a set of coaxial and stepped wires into a single wire with a uniform diameter. The before and after elements are considered to be equivalent. The shell programs such as *EZNEC* and *4nec2* identify correction opportunities and apply the algorithm automatically. The corrected model is sent to the engine. Although this tight integration makes it painless to use the correction algorithm, there are a set of conditions that have to be true in order for the correction to be used. Needless to say, if you believe that the correction is being used, but it isn't, the results will contain more error than expected.

The *EZNEC* Help documentation contains a complete list of the constraints on the use of the stepped diameter correction algorithm. The program also indicates when the correction is in use, but in the heat of modeling the antenna it's possible to lose track of the status information.

Over-simplified, the correction can only be applied to a set of two or more wires that are all collinear with more than one diameter. In addition, if there the model includes a Source or Load or Transmission Line, they must be connected in the middle of the element. These constraints allow for many antenna designs, but not all.

Situations that would disable the correction include:

1. Phasing lines running down and connecting to a set of elements.

2. Loading coils or traps not located at the center of an element.

3. Wires located near the feed point used in matching networks such as the gamma or hairpin (beta) match.

4. Non-collinear wires, such as squares or rectangles in antennas such as quads or the Moxon Rectangle.

5. Wires groups that are not within 15% of the half-wave resonant length (or quarter-wave resonant length for wire groups with one end grounded).

If a particular model cannot use stepped diameter correction where needed, and the highest accuracy is desired, then moving to *NEC-4* (or possibly *MININEC*) is the solution.

While on the topic of modeling Yagis, two more correction or compensation situations warrant mention. They are compensating for the metal boom and the metal element clamps. The metal present in the boom and clamps changes the electrical length of the element.

Boom compensation for the typical HF Yagi is on the order of 1/8 inch per half-element. This might be smaller than the construction accuracy and is often ignored. On VHF and UHF antennas, however, where the ratio between element length and boom diameter is much lower, boom compensation is an important consideration.

The element clamping scheme also creates a need for compensation, even at HF. There are a number of clamp styles and sizes in use. Chapter 9 of Leeson's book tackles the problem of clamp compensation. The approach converts the dimensions of a set of clamp styles into a wire length and diameter that can be located at the center of the element in the model. This is a clever way to incorporate the effect of the clamp by turning it into something that can be modeled — a fat and short wire located at the middle of the element.

The *AutoEZ* program from Dan Maguire, AC6LA, is a very powerful antenna modeling tool that uses *EZNEC* as its engine. *AutoEZ* incorporates the Leeson clamp models. By selecting a clamp style and then entering the dimensions, *AutoEZ* will compute the equivalent wire and add it to the model.

When you come across a model for a Yagi, especially an existing commercial product, and if you find a relatively short and fat wire at the center of an element it's safe to assume that it is a proxy for the element to boom mounting clamp. This is most certainly true if the wire is not part of the mechanical specification. It's intended to represent the effect of the actual metal clamp in the model.

The errors introduced by not using stepped diameter correction (*NEC-2* only) or boom compensation, or clamp compensation, all shift the model performance in the same direction. If they are not used the model results will be shifted downward in frequency. The natural response to this result is to scale the design up in frequency, usually by shortening the elements. Now, the model results line up with the target frequency. Unfortunately, if you build the antenna using those dimensions and then measure characteristics such as SWR, you will find that the antenna performance characteristics have been shifted above the target frequency. This leads to the sad realization that your elements are too short.

In several monoband HF Yagi projects the author has been involved with over the past few years, the impact on the actual antenna is on the order of 1/2 inch per each element end on 15 meters, a little bit more on 20 meters and a little bit less on 10 meters. This is for antennas modeled using *NEC-4*, but without clamp or boom compensation added to the model. The size and shape of the clamps will influence the amount of compensation needed.

If the short and fat wire representing the clamp contains a *NEC* Source, representing the feed point, then even with *NEC-4* there can be additional error in the results depending upon the segment length to diameter ratio. One approach is to use the average gain as a correction factor, or, use the stepped diameter correction algorithm even with the *NEC-4* engine.

Wires Below Ground

Since before the classic paper "Ground Systems as a Factor in Antenna Efficiency" was published by Brown, Lewis and Epstein in 1937 (see the Bibliography for the chapter **Effects of Ground**), the topic of ground wires and radials for ground mounted vertical antennas has been discussed. If you wish to explore what modeling predicts about wires very near to the surface of the ground or buried below the surface, you must use *NEC-4*.

Rudy Severns, N6LF, has written extensively on the topic of radial systems, using both *NEC-4* models and field measurements. His work is an excellent place to start any investigation of this topic, including the material in this book's chapter, **Effects of Ground**.

If it's not possible to model ground radial systems with *NEC-2* then that should surely imply that vertical antennas with ground radials can only be modeled with *NEC-4*. Fortunately, that is not the case. *NEC-2* has been modified to include a ground type that was first used with the *MININEC* engine. This is called the *MININEC*-type ground. In this case, the approach is to directly connect the vertical to *MININEC* ground, and then add a resistive Load at the base with a value chosen to simulate the expected ground resistance for the presumed radial system. Many sources such as the *ARRL Antenna Book* and ON4UN's *Low-Band DXing* explore the topic of ground resistance for radial fields.

The use of the *MININEC*-type ground turns out to be a good solution because the truth is that in most cases precise modeling of radial fields is work. The *MININEC* solution works well for investigating vertical antennas and arrays of vertical antennas.

If you are investigating buried wires with *NEC-4*, but sure to use the real/high accuracy ground model. There is a general admonition against using the *MININEC* ground with any horizontal wire less than 0.2 wavelength above ground. Elevated radials can be modeled with either *NEC-2* or *NEC-4*.

Other Differences

Here are two other differences between *NEC-2* and *NEC-4* that should be kept in mind while modeling. Quoting from the *EZNEC* Help documentation, "*NEC* has some difficulty in accurately modeling multiple wires joining at a very acute angle, such as with a 'fan' antenna, the difficulty being greater with *NEC-2* than with *NEC-4*."

Similarly, quoting from the *NEC-4.2* User's Manual, "The size of the segments determines the resolution in solving for the current on the model, since the current is computed at the center of each segment. Earlier versions of *NEC* suffered a loss of precision or complete failure of the solution when very short segments were used, but this problem has been corrected in *NEC-4*. The extremely short segments can be used with *NEC-4*, subject to limitations related to the wire radius as discussed below."

Geometry and Segmentation Checks

NEC models are built out of wires. Wires are divided into segments. The number of segments on a wire is specified by the modeler. The number of segments on a wire is an important factor in determining the accuracy of the results as well as the time it takes to run the model.

Segments are like the story of Goldilocks and the Three Bears — you do not want to use too few or too many segments. There are many trade-offs in determining the best number of segments to use.

1. Reducing the number of segments speeds up the *NEC*

engine. Past some point, accuracy suffers because the model becomes too coarse.

2. Increasing the number of segments slows down the *NEC* engine. The maximum number of allowed segments may be limited by the modeling package. At some point, too many segments can reduce the accuracy of the results. This is especially true with *NEC-2*. Blindly using more segments is not a solution.

3. There are situations where it's desirable to align segments between closely-spaced wires.

Fortunately the programs that drive the *NEC* engines include a number of checks that follow the *NEC* segmentation guidelines. You should observe their warnings related to the segment count. It is also possible to have the program automatically segment the wires in a model.

If there is any concern about the number of segments being used, you should perform segment convergence testing. The idea is to run a model, note the results (SWR, impedance, gain, F/B, and so on), change the number of segments, and run it again. As you move from too few toward too many segments, the results should converge. Once they do, there is little point in increasing the number of segments. If you notice that the results are very sensitive to segmentation, then it may signal a model that challenges the *NEC* engines, and might have less trustworthy results. *4nec2* has a convergence test option that automates much of the process. Getting segmentation correct is more important with *NEC-2* than *NEC-4*.

In addition to the material here, an additional tutorial on antenna modeling using *EZNEC* has been contributed by Greg Ordy, W8WWV and is included on the CD-ROM distributed with this book. It features alternate perspectives on topics in this chapter and covers additional material in depth. The tutorial was originally presented in support of a presentation at Contest University in 2011.

8.2 THE BASICS OF ANTENNA MODELING

This chapter will discuss the following antenna-modeling topics for *NEC-2*-based modeling software, using *EZNEC* as an example:

- Program outputs
- Wire geometry
- Segmentation, warnings and limitations
- Source (feed point) placement
- Environment, including ground types and frequency
- Loads and transmission lines
- Testing the adequacy of a model

While *EZNEC* is very popular among amateurs, two other programs also based on *NEC-2* are available and widely used. *4nec2* is a free application by Arie Voors that offers a graphical interface for design and a 3-D color radiation pattern display many find useful. For Apple Macintosh users, Kok Chen, W7AY, has published *cocoaNEC 2.0*. Both can use the *NEC-4* engine, assuming licensing permission has been obtained. See the Reference section of this chapter for more modeling software and links to the websites for these and other programs. Actively supported programs such as *4nec2* also offer tutorials via the website and user groups may also be available online to help with questions and share model files.

8.2.1 PROGRAM OUTPUTS

Instruction manuals for software programs traditionally start out describing in detail the input data needed by the program. They then demonstrate the output data the program can generate. We feel it is instructive, however, to turn things around and start out with a brief overview of the output from a typical antenna-modeling program.

We'll look at the output from public-domain *NEC-2*. Next, we'll look at the output information available from commercial adaptations of *NEC-2*, using *EZNEC* as an example. (From now on in this chapter we'll refer merely to *EZNEC* rather than *EZNEC 6.0*, the official name, or the *EZNEC* demo version. Both programs function identically.) After this brief overview of the output data, we'll look in detail at the input data needed to make a modeling program work. In the following discussions it will be very instructive if you to bring up *EZNEC* on your computer and open the specific modeling files used in each example.

Native *NEC-2*

Native *NEC-2* was written in the Fortran language, which stands for *Formula Translation*. The original program used Hollerith punch-cards to enter the program and input data. The output of the program was raw numeric data printed on many sheets of paper. Commercial software that uses the *NEC-2* computational core algorithms shields provides much easier methods of entering antenna design information and generates graphic output that is much easier to understand. Numerical tables are provided where they are useful, such as for source impedance and SWR at a single frequency, or the characteristics of a load or a transmission line. *EZNEC* produces the following types of graphs:

- Polar (linear-dB or ARRL-style) graphs of the far-field elevation and azimuth responses.
- 3-D wire-frame graph of the total far-field response.
- Graph of the SWR across a frequency band.
- Graphical display of the RF currents on various conductors in a model.
- Rotatable, zoom-able 3-D views of the wires used to make a model.
- Output to programs capable of generating Smith charts and performing other analysis

Figure 8.1 shows the computed far-field 2-D elevation and azimuth patterns for a 135-foot long horizontal dipole, mounted in a flattop configuration 50 feet above flat ground.

These figures were generated using *EZNEC* at 3.75 MHz. Figure 8.1C shows a 3-D wire-frame picture of the far-field response, but this time at 14.2 MHz.

Figure 8.2 shows the computed SWR curve over the frequency range 3.0 to 4.0 MHz for this dipole, fed with lossless 50-Ω transmission line. *EZNEC* generated this plot using the "SWR" button. Figures 8.1 and 8.2 are typical of the kind of graphical outputs that commercial implementations of the *NEC-2* computing core can produce — a vast improvement over tables of numbers from a mainframe computer's line printer! Now, let's get into the details of what kind of input data is required to run a typical method-of-moments antenna-modeling program.

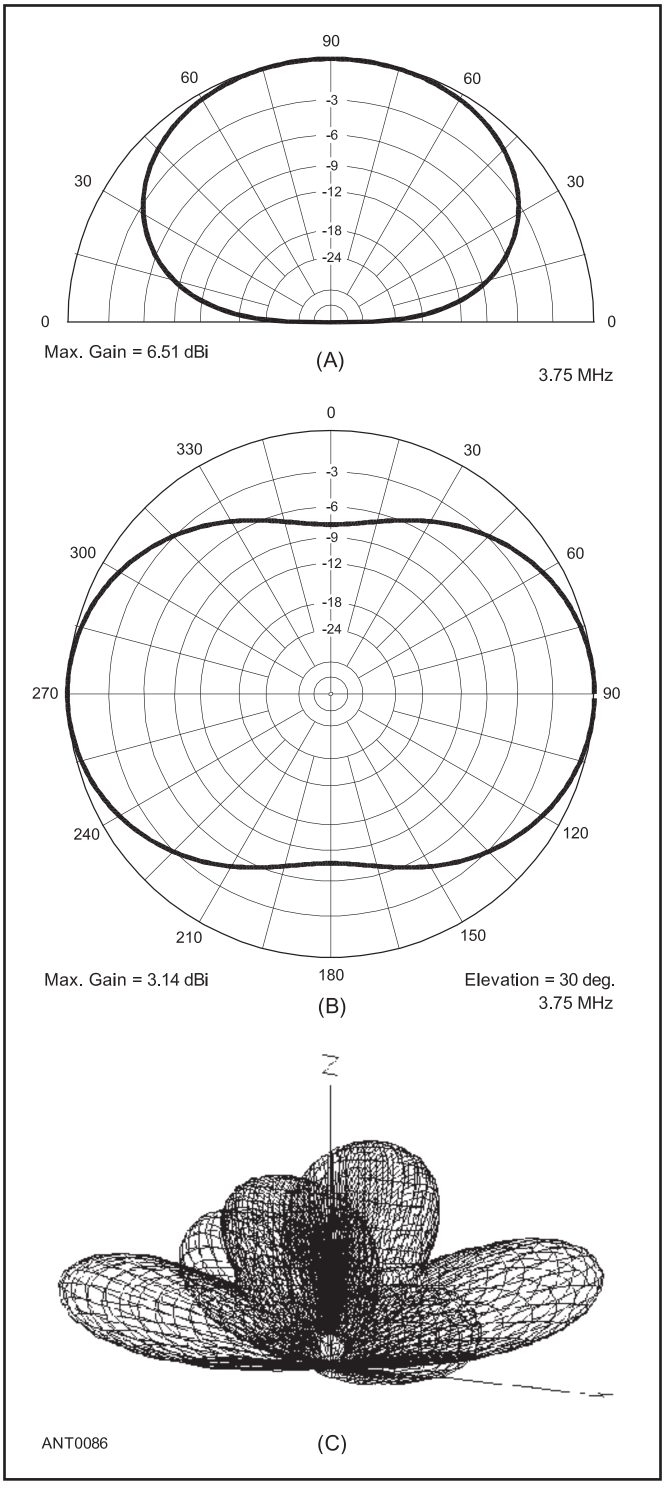


Figure 8.1 — At A, far-field elevation-plane pattern for a 135- foot-long horizontal dipole, 50 feet above flat ground, at 3.5 MHz. At B, the far-field azimuth-plane pattern at an elevation angle of 30°.

8.2.2 PROGRAM INPUTS: WIRE GEOMETRY

Coordinates in an X, Y and Z World

The most difficult part of using a *NEC*-type of modeling program is setting up the antenna's geometry — you must condition yourself to think in three-dimensional, Cartesian coordinates. Each end point of a wire is represented by three numbers: an x, y and z coordinate. These coordinates represent the distance from the origin (x-axis), the width of an antenna (y-axis), and the height (z-axis).

An example should help sort things out. **Figure 8.3** shows a simple model of a 135-foot center-fed dipole, made of #14 copper wire placed 50 feet above flat ground. The common term for this antenna is "flattop dipole." For convenience, the ground is located at the origin of the coordinate system, at (0, 0, 0) feet, directly under the center of the dipole. **Figure 8.4** shows the *EZNEC* spreadsheet-like input data for this antenna. (Use model file: **Ch8-Flattop Dipole.EZ**.) *EZNEC* allows you to specify the type of conductor material from its main window, using the WIRE LOSS button to open a new window. We will click on the COPPER button for this dipole.

Above the origin, at a height of 50 feet on the z-axis, is the dipole's *feed point*, called a *source* in *NEC* terminology. The width of the dipole goes toward the left (that is, in the "negative-y" direction) one-half the overall length of 135 feet, or –67.5 feet. Toward the right, our dipole's other end is at +67.5 feet. The x-axis dimension of our dipole is zero, meaning that the dipole wire is parallel to and directly

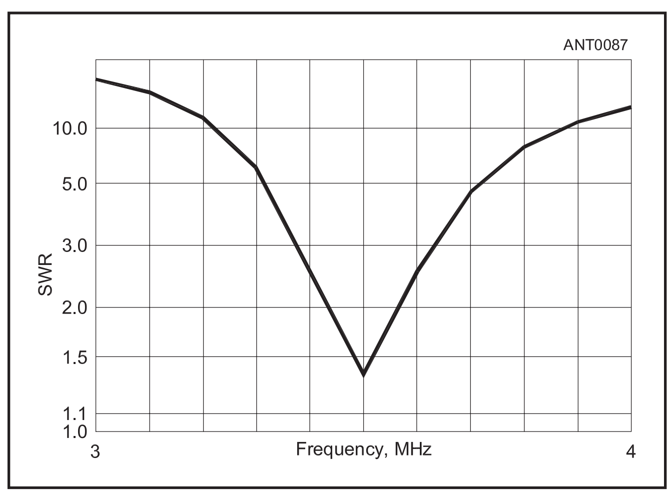


Figure 8.2 — SWR curve for 135-foot flattop dipole over the frequency range 3.0 to 4.0 MHz for a 50-Ω feed line. This antenna is an example and is not optimized for the amateur band.

above the x-axis. The dipole's ends are thus represented by two points, whose coordinates are (0, –67.5, 50) and (0, 67.5, 50) feet. The use of parentheses with a sequential listing of (x, y, z) coordinates is a common practice among antenna modelers to describe a wire end point.

Figure 8.3B includes some other useful information about this antenna beyond the wire geometry. Figure 8.3B overlays the wire geometry, the current distribution along the wire and the far-field azimuth response, in this case at an elevation angle of 30°.

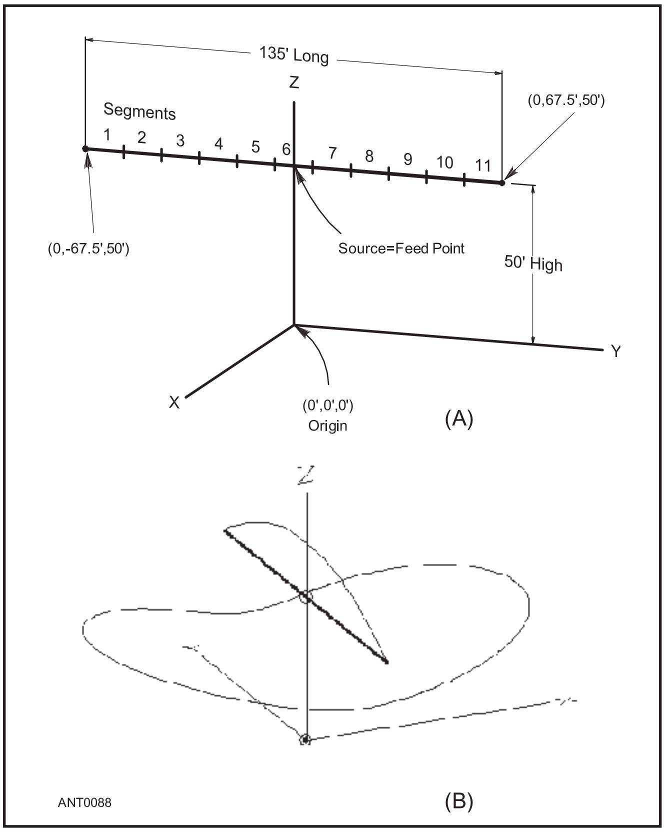
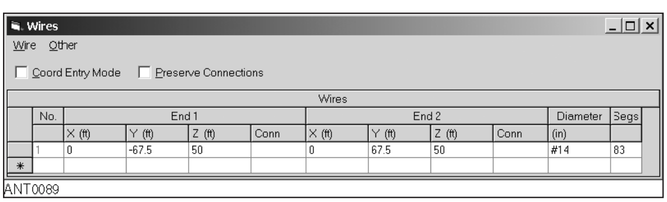


Figure 8.3 — At A, simple model for a 135-foot long horizontal dipole, 50 feet above the ground. The dipole is over the y-axis. The wire has been segmented into 11 segments, with the center of segment number 6 as the feed point. The left-hand end of the antenna is –67.5 feet from the center feed point and that the right-hand end is at 67.5 feet from the center. At B, *EZNEC* "View Antenna" screen, showing geometry of wire and the x, y and z axes. Overlaid on the wire geometry drawing are the current distribution along the wire and the far-field azimuthal response at an elevation angle of 30°.



No.	End 1				End 2				Diameter	Segs
	X (ft)	Y (ft)	Z (ft)	Conn	X (ft)	Y (ft)	Z (ft)	Conn	(in)	
1	0	-67.5	50		0	67.5	50		#14	83

Figure 8.4 — *EZNEC* "View Wires" data entry screen for simple flattop dipole in Figure 8.3. The numbers shown are in feet, except for the wire diameter, which *EZNEC* allows you to specify as an AWG gauge, in this case #14. Note that 83 segments have been specified for this antenna for analysis over the range from 3.5 to 29.7 MHz.

Although not shown specifically in Figure 8.3, the thickness of the antenna is the diameter of the wire, #14 AWG. Note that native *NEC* programs specify the *radius* of the wire, rather than the diameter, but programs like *EZNEC* use the more intuitive diameter of a wire rather than the radius. *EZNEC* (and other commercial programs) also allows the user to specify the wire as an AWG gauge, such as #14 or #22, for example.

We've represented our simple dipole in Figure 8.3 using a single, straight wire. In fact, all antenna models created for method-of-moments programs are made of combinations of straight wires. This includes even complex antennas, such as helical antennas or round loops. (The mathematical basis for modeling complex antennas is that they can be simulated using straight-wire polygons. A circular loop, for example, can be modeled using an octagon.)

Segmentation and Specifying a Source Segment

We've specified the physical geometry of this simple one-wire dipole. Now several more modeling details surface — you must specify the number of *segments* into which the dipole is divided for the method-of-moments analysis and you must somehow feed the antenna. The *NEC-2* guideline for setting the number of segments is to use at least 10 segments per half-wavelength. This is a general rule of thumb, however, and in many models more dense segmentation is mandatory for good accuracy.

In Figure 8.3, we've specified that the dipole be divided into 11 segments for operation on the 80 meter band. This follows the rule of thumb above, since the 135-foot dipole is about one half-wavelength long at 3.5 MHz.

Setting the Source Segment

The use of 11 segments, an odd rather than an even number such as 10, places the dipole's feed point (a feed point is referred to as a *source* in *NEC*-speak, a word choice that can befuddle beginners) right at the antenna's center, at the center of segment number six. In concert with the "EZ" in its name, *EZNEC* makes choosing the source segment easy by allowing the user to specify a percentage along the wire, in this case 50% centers the source in the middle of the segment.

At this point you may very well be wondering why no center insulator is shown in the middle of our center-fed dipole. After all, a real dipole would have a center insulator. However, method-of-moments programs assume that a source generator is placed across an infinitely small gap in the antenna wire. While this is convenient from a mathematical point of view, the unstated use of such an infinitely small gap often confuses newcomers to the world of antenna modeling. We'll get into more details, caveats and limitations in source placement later in this chapter. For now, just trust that the model we've just described with 11 segments, fed at segment 6, will work well over the entire amateur band from 3.5 to 4.0 MHz.

Now, let's consider what would happen if we want to use our 135-foot long dipole on all HF amateur bands from 3.5 to 29.7 MHz, rather than just from 3.5 to 4.0 MHz. Instead of feeding such an antenna with coax cable, we would feed it with open-wire line and use an antenna tuner in the shack to create a 50-Ω load for the transmitter. To comply with the segmentation rule above, the number of segments used in the model should vary with frequency — or at least be segmented at or above the minimum recommended level at the highest frequency used. This is because a half-wavelength at 29.7 MHz is 16.6 feet, while a half-wavelength at 3.5 MHz is 140.6 feet. So the number of segments for proper operation on 29.7 MHz should be 10 × 135/16.6 = 81. We'll be a little more conservative than the minimum requirement and specify 83 segments. Figure 8.4 shows the *EZNEC* input spreadsheet for this model. (Use model file: **Ch8-Multiband Dipole.EZ**.)

The penalty for using more segments in a program like *NEC* is that the program slows down roughly as the square of the segments — double the number of segments and the speed drops by a factor of four (two squared). Using too few segments will result in inaccuracies, particularly in computing the feed point impedance. We'll delve into the area of segmentation density in more detail later when we discuss testing the adequacy of a model.

Segment Length-to-Wire-Diameter Ratio

Even if you're willing to live with the slowdown in computing speed for situations involving a large number of wire segments, you should make sure the ratio between the segment length and the diameter of any wire is greater than 1:1. This is to say that the length of each segment should be longer than the diameter of the wire to avoid internal limitations in the *NEC* program.

For the #14 wire specified in this simple 135-foot long dipole, it's pretty unlikely that you'll bump up against this limitation for any reasonable level of segmentation. After all, #14 wire has a diameter of 0.064 inch and 135 feet is 1620 inches. To stay above a segment length of 0.064 inch, the maximum number of segments is 1620/0.064 = 25,312. This is a very large number of segments and it would take a very long time to compute, assuming that your program can handle that many segments.

Staying above a 1:1 ratio in segment length to wire diameter can be more challenging at VHF/UHF frequencies, however. This is particularly true for fairly large "wires" made of aluminum tubing. Incidentally, this is another point where newcomers to antenna modeling can be led astray by the terminology. In a *NEC*-type program, all conductors in a model are considered to be wires, even if they consist of hollow aluminum or copper tubes. The skin effect keeps the RF current in any conductor confined to the outer surface of that conductor, and thus it doesn't matter whether the conductor is hollow or solid, or even a number of wire strands twisted together.

Let's look at a half-wave dipole at 420 MHz. This would be about 14.1 inches long. If you use ¼-inch diameter tubing for this dipole, the maximum segment length meeting the 1:1 diameter-to-length ratio requirement is also ¼ inch long. The maximum number of segments then would be 14.1/0.25 = 56.4, rounded down to 56. From this discussion you should now understand why method-of-moments programs are known for using a "thin-wire approximation." Really fat conductors can get you into trouble, particularly at VHF/UHF.

Some Caveats and Limitations Concerning Geometry

Example: Inverted-V Dipole

Now, let's get a little more complicated and specify another 135-foot-long dipole, but this time configured as an inverted V. As shown in **Figure 8.5**, you must now specify two wires. The two wires join at the top, at (0, 0, 50) feet. (Again, the program doesn't use a center insulator in the model.)

If you are using a native version of *NEC*, you may have to go back to your high-school trigonometry book to figure out how to specify the end points of our "droopy" dipole, with its 120° included angle. Figure 8.5 shows the details, along with the trigonometric equations needed. *EZNEC* is indeed more "easy" here since it allows you to tilt the ends of each wire downward an appropriate number of degrees (in this case –30° at each end of the dipole) to automatically create an inverted-V configuration. **Figure 8.6A** shows the *EZNEC* spreadsheet describing this inverted-V dipole with a 120° included angle between the two wires.

See the *EZNEC* HELP section under "Wire Coordinate Shortcuts" for specific instructions on how to use the "elevation rotate end" shortcut "RE-30" to create the sloping wires easily by rotating the end of the wire down 30°. Now the specification of the source becomes a bit more complicated. The easiest way is to specify two sources, one on each end segment at the junction of the two wires. *EZNEC* does this automatically if you specify a so-called *split-source* feed. Figure 8.6B shows the two sources as two open circles at the top ends of the two wires making up the inverted-V dipole.

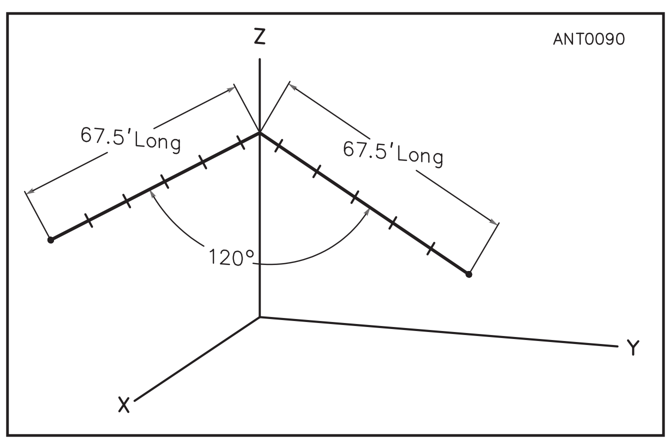
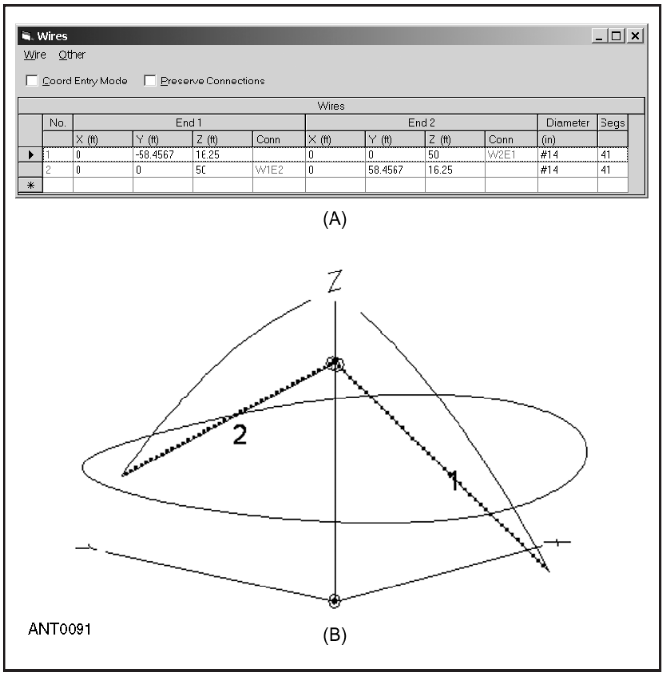


Figure 8.5 — Model for an inverted-V dipole with an included angle between the two legs of 120° apex at 50' high. Sine and cosine functions are used to describe the heights of the end points for the sloping arms of the antenna.



Wires										
No.	End 1				End 2				Diameter	Segs
	X (ft)	Y (ft)	Z (ft)	Conn	X (ft)	Y (ft)	Z (ft)	Conn	(in)	
1	0	-58.4567	16.25		0	0	50	W2E1	#14	41
2	0	0	50	W1E2	0	58.4567	16.25		#14	41

Figure 8.6 — At A, *EZNEC* "View Wires" data entry screen for inverted-V dipole in Figure 8.5. Now the ends of the inverted-V dipole are 16.25 feet above ground, instead of 50 feet for the flattop dipole. At B, *EZNEC* "View Antenna" screen, with overlay of geometry, current distribution and azimuth plot.

What *EZNEC* is doing is creating two sources, one in each of the segments immediately on either side of the junction of the two wires. *EZNEC* sums up the two source impedances to provide a single result.

Navigating in the View Antenna Window

At this point it's worthwhile to explore some of the ways you can look at the antenna you've designed using the *EZNEC* VIEW ANT button on the main window. Bring up the file **Ch8-Inverted V Dipole.EZ** in *EZNEC*, and click on the VIEW ANT button. You will see a small inverted-V dipole raised over the (0, 0, 0) origin on the ground directly under the feed point of the inverted-V dipole. First, "rotate" the dipole by holding down the left-mouse button and moving the mouse. You can orient the picture any way you wish.

Let's take a closer look at the junction of the two wires at the feed point. Click the CENTER ANT IMAGE checkbox toward the bottom of the window to anchor the center of the image at the center of the window, then move the *Zoom* slider upward to zoom in on the image. At some point the junction of the two slanted wires will move up beyond the edge of the window, so you will need to click on the left-hand side of the Z MOVE IMAGE slider to bring the junction back into view. You should be able to see a zoomed view of the junction along with the two open circles that represent the location of the split sources in the middle of the segments adjacent to the wire junction.

Place the mouse cursor over one of the slanted wires and double click the left-mouse button. *EZNEC* will now identify that wire and show its length, as well as the length of each segment on that wire. Pretty slick, isn't it?

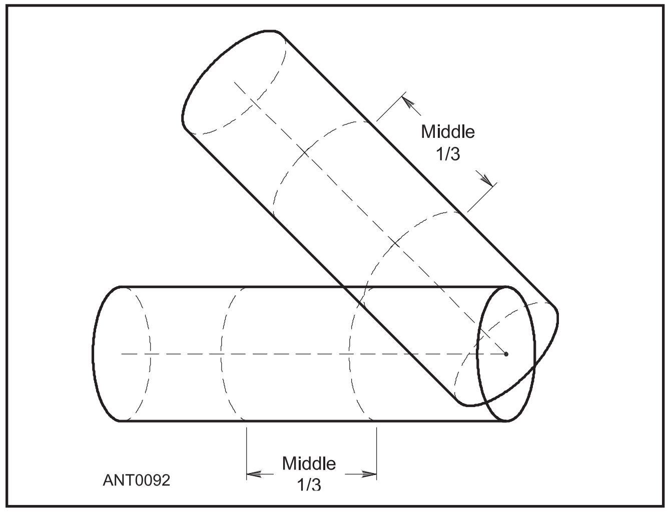


Figure 8.7 — A junction of two short, fat wire segments at an acute angle. This results in inter-penetration of the two wire volumes beyond the middle-⅓ recommended limit.

Short, Fat Wires and the Acute-Angle Junction

Another possible complication can arise for wires with short, fat segments, particularly ones that have only a small included angle between them. These wire segments can end up inter-penetrating within each other's volumes, leading to problems in a model. Once you think of each wire segment as a thick cylinder, you can appreciate the difficulty in connecting two wires together at their ends. The two wires always inter-penetrate each other's volume to some extent. **Figure 8.7** depicts this problem graphically for two short, fat wires joined at their ends at an acute angle. A rule of thumb is to avoid creating junctions where more than ⅓ of the wire volumes inter-penetrate. You can achieve this by using longer segment lengths or thinner wire diameters.

Some Other Practical Antenna Geometries

A Vertical Half-Wave Dipole

If you turn the 135-foot-long horizontal dipole in Figure 8.1 on its end you will create a vertical half-wave dipole that is above the origin of the x, y and z axes. See **Figure 8.8**, where the bottom end of the dipole is placed 8 feet off the ground to keep it away from humans and animals at (0, 0, 8) feet. The top end is thus at 8 + 135 = 143 feet off the ground at (0, 0, 143). Figure 8.8 also shows the current distribution and the elevation pattern for this antenna. (Use *EZNEC* model file: **Ch8-Vertical Dipole.EZ**.)

A Ground-Plane Antenna

The ground-plane model is more complicated than previous ones because a total of five wires are now needed: one for

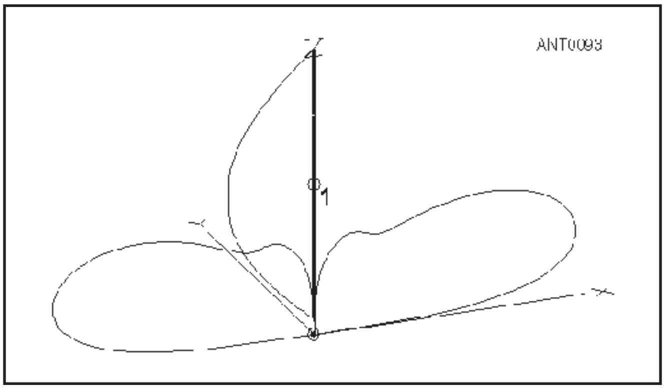


Figure 8.8 — A vertical half-wave dipole, created by turning the dipole in Figure 8.3 on its end, with a minimum height at the lower end of 8 feet to keep the antenna away from people and animals. The current distribution and the elevation pattern for this antenna are also shown overlaid on the wire geometry.

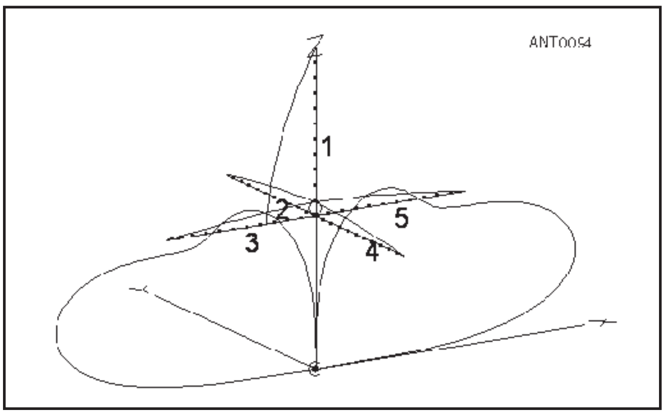


Figure 8.9 — A vertical ground-plane antenna. The radials and the bottom of the vertical radiator are located 15 feet off the ground in this model. The current distribution along each wire and the far-field elevation-plane pattern are overlaid on the antenna geometry.

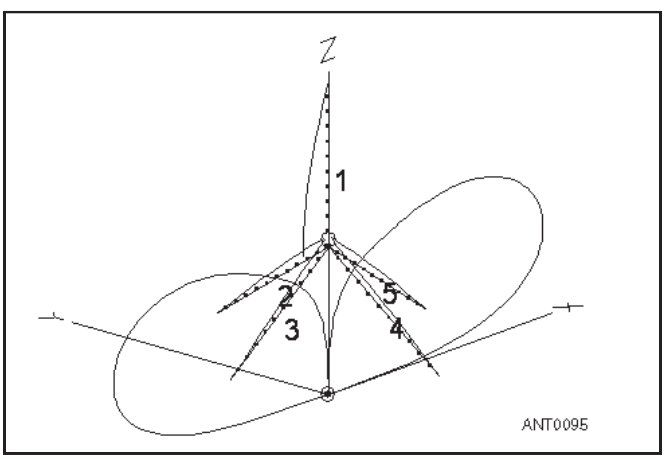


Figure 8.10 — *EZNEC* "View Antenna" screen for the ground-plane antenna with its four radials tilted downward by 40° to improve the SWR at the feed point.

Table 8.1

520-40W.YW, using #14 AWG wire from 520-40H.YW
14.000 14.174 14.350 MHz

5 elements	inches
Spacing	.064
0.000	210.923
72.000	200.941
72.000	199.600
139.000	197.502
191.000	190.536

the vertical radiator and four for the radials. **Figure 8.9** shows the *EZNEC* view for a 20 meter ground plane mounted 15 feet off the ground (perhaps on a garage roof), with the overlay of both the current distribution and the elevation-plane plot. (Use *EZNEC* model file: **Ch8-GP.EZ**.) Note that the source has been placed at the bottom segment of the vertical radiator. Once again, the program needs no bottom insulator since all five wires are connected together at a common point. *EZNEC* reports that this antenna has a resonant feed-point impedance of about 22 Ω, which would show an SWR of 2.3:1 for a 50-Ω coax feed line if no matching system is used, such as a gamma or hairpin match.

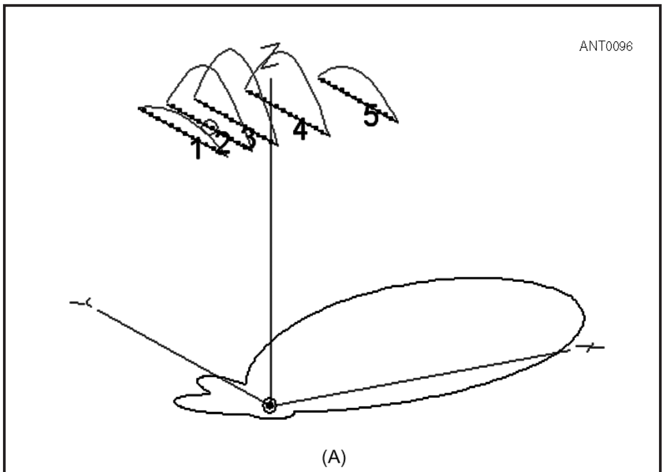
Figure 8.10 shows the same antenna, except that the radials have now been tilted downward by 35° to raise the feed point impedance to present an almost perfect 50-Ω match (SWR = 1.08:1). In addition, the length of the radiator in this model was shortened by 6 inches to re-resonate the antenna. (Use *EZNEC* model file: **Ch8-Modified GP.EZ**.) The trick of tilting the radials downward for a ground-plane antenna is an old one, and the modeling programs validates what hams have been doing for years.

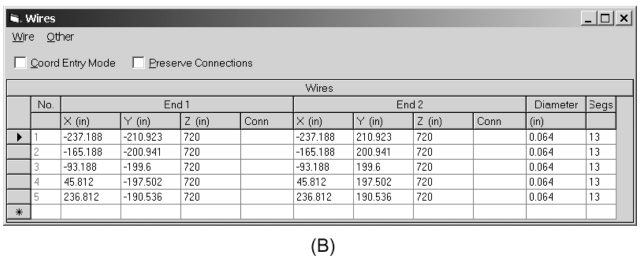
A 5-Element Horizontal Yagi

This is a little more challenging modeling exercise. Let's use a 5-element design on a 40-foot boom, but rather than using telescoping aluminum tubing for the elements, we'll use #14 wire. The *SCALE* program (available for download from **www.arrl.org/antenna-book**) converted the aluminum-tubing 520-40.YW to a design using #14 copper wire. **Table 8.1** shows the element lineup for this antenna. (Later in this chapter we'll see what happens when telescoping aluminum tubing is used in a real-world Yagi design.)

Some explanations of what Table 8.1 means are in order. First, only one half of each element is shown. The *YW* program (*Yagi for Windows*), included on the CD-ROM, computes the other half of the Yagi automatically, essentially mirroring the other half on the opposite side of the boom. Having to enter the dimensions for only half of a real-world Yagi element that uses telescoping aluminum tubing is much easier this way.

Second, the placement of the elements along the boom starts at 0.0 inches for the reflector. The distance between adjacent elements defined in this particular file is the spacing between the element itself and the element just before it. For example, the spacing between the driven element and





No.	End 1 X (in)	End 1 Y (in)	End 1 Z (in)	End 1 Conn	End 2 X (in)	End 2 Y (in)	End 2 Z (in)	End 2 Conn	Diameter (in)	Segs
1	-237.188	-210.923	720		-237.188	210.923	720		0.064	13
2	-165.188	-200.941	720		-165.188	200.941	720		0.064	13
3	-93.188	-199.6	720		-93.188	199.6	720		0.064	13
4	45.812	-197.502	720		45.812	197.502	720		0.064	13
5	236.812	-190.536	720		236.812	190.536	720		0.064	13

(B)

Figure 8.11 — At A, geometry for 5-element Yagi on a 40-foot boom, mounted 720 inches (60 feet) above flat ground, with an overlay of current and the azimuth pattern. At B, *EZNEC* "View Wires" screen for this antenna. This design uses #14 wire for simplicity.

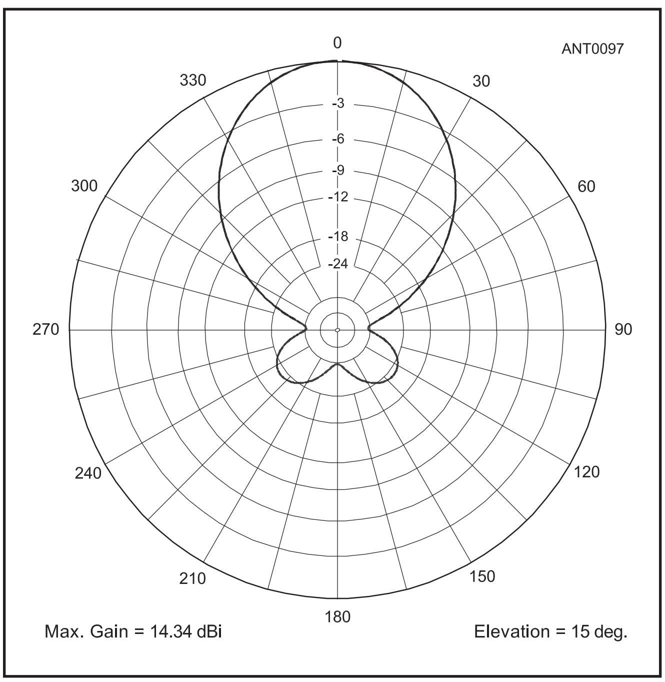


Figure 8.12 — *EZNEC* azimuth-plane pattern at an elevation angle of 15° for #14 AWG wire Yagi described in Figure 8.11.

the reflector is 72 inches and the spacing between the first director and the driven element is also 72 inches. The spacing between the second director and the first director is 139 inches.

Figure 8.11A shows the wire geometry for this Yagi array when it is mounted 720 inches (60 feet) above flat ground and Figure 8.11B shows the *EZNEC* Wires spreadsheet that describes the coordinates. (Use *EZNEC* model file: **Ch8-520-40W.EZ**.) You can see that the x-axis coordinates for the elements have been automatically moved by the *SCALE* program so that the center of the boom is located directly above the origin. This makes it easier to evaluate the effects of stacking different monoband Yagis on a rotating mast in a typical "Christmas Tree" arrangement, such as 20, 15 and 10 meter monobanders on a single rotating mast sticking out of the top of the tower.

Figure 8.12 shows the computed azimuth pattern for this Yagi at 14.175 MHz, at an elevation angle of 15°, the angle at which the peak of the forward lobe occurs for this height above flat ground. The antenna exhibits excellent gain at 13.1 dBi, as well as a clean pattern behind the main lobe. The worst-case front-to-rear ratio at any point from 90° to 270° in azimuth is better than 23 dB. *EZNEC* says the feed point impedance is 25 – *j* 23 Ω, just the right impedance suited for a simple hairpin or gamma match.

A Monoband 2-Element Quad

Unlike a Yagi, with its elements existing only in the x-y plane, a quad type of beam is a three-dimensional antenna. A quad loop has height in the z-axis, as well as width and length in the x-y plane. Each individual loop for a monoband quad consists of four wires, joined together at the corners. **Figure 8.13** shows the coordinates for a 2-element 15-meter quad, consisting of a reflector and a driven element on a 10-foot boom.

You can see that the axis of symmetry, the x-axis, runs

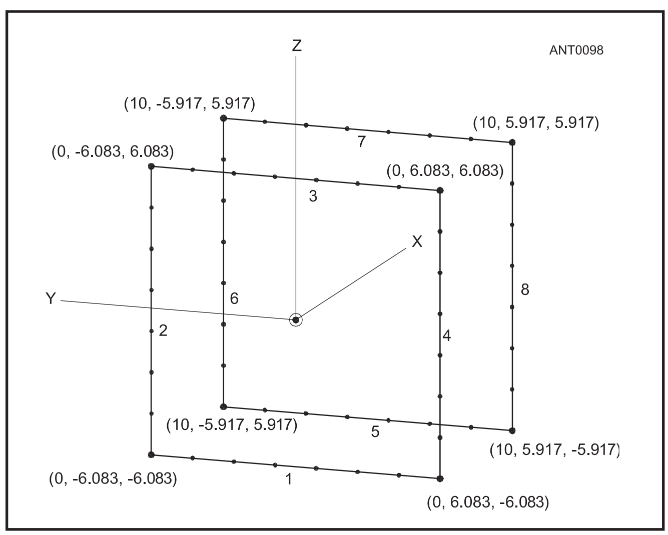
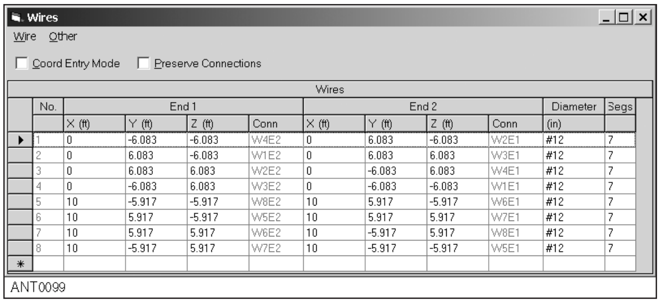


Figure 8.13 — Wire geometry for a 2-element quad, with a reflector and driven element. The x-axis is the axis of symmetry for this free-space model.



Wires

Wire Other

Coord Entry Mode   Preserve Connections

No.	End 1				End 2				Diameter	Segs
	X (ft)	Y (ft)	Z (ft)	Conn	X (ft)	Y (ft)	Z (ft)	Conn	(in)	
1	0	-6.083	-6.083	W4E2	0	6.083	-6.083	W2E1	#12	7
2	0	6.083	-6.083	W1E2	0	6.083	6.083	W3E1	#12	7
3	0	6.083	6.083	W2E2	0	-6.083	6.083	W4E1	#12	7
4	0	-6.083	6.083	W3E2	0	-6.083	-6.083	W1E1	#12	7
5	10	-5.917	-5.917	W8E2	10	5.917	-5.917	W6E1	#12	7
6	10	5.917	-5.917	W5E2	10	5.917	5.917	W7E1	#12	7
7	10	5.917	5.917	W6E2	10	-5.917	5.917	W8E1	#12	7
8	10	-5.917	5.917	W7E2	10	-5.917	-5.917	W5E1	#12	7

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Figure 8.14 — *EZNEC* "View Wires" screen showing the coordinates used for the quad in Figure 8.13. Note how the x-axis describes the position of an element on the 10-foot boom and also is the axis of symmetry for each element. The values for the z-axis and y-axis vary above and below the axis of symmetry.

down the center of this model, meaning that the origin of this particular x, y and z-coordinate scheme is in the center of the reflector. The (0, 0, 0) origin is placed this way for convenience in assigning corner coordinates for each element. For actual placement of the antenna at a particular height above real ground, the heights of all z-axis coordinates are changed accordingly. *EZNEC* has a convenient built-in function to change the height of all wires at a single stroke.

Figure 8.14 shows the input *EZNEC* spreadsheet for this quad in free space, clearly showing the symmetrical nature of the corner coordinates. (Use *EZNEC* model file: **Ch8-Quad.EZ**.) This is a good place to emphasize that you should enter the wire coordinates in a logical sequence. The most obvious example in this particular model is that you should group all the wires associated with a particular element together — for example, the four wires associated with the reflector should be in one place. In Figure 8.14 you can see that all four wires with an x-coordinate of zero represent the reflector.

It's best to follow a convention in entering wires in a loop structure in a logical fashion. The easiest way is to connect the end point of one wire to the starting point of the next wire. For example, in Figure 8.13 you can see that the left-hand end of Wire 1 is connected to the bottom of Wire 2, and that the top of Wire 2 connects to the left-hand end of Wire 3. In turn, Wire 3 connects to the top of Wire 4, whose bottom end connects to the right-hand end of Wire 1. The pattern is known as "going around the horn" meaning that the connections proceed smoothly in one direction, in this case in a clockwise direction.

You can see that the entry for the wires making up the elements in the 5-element Yagi in Figure 8.11B also proceeded in an orderly fashion by starting with the reflector, then the driven element, then director 1, then director 2 and finally director 3. This doesn't mean that you couldn't mix things up, say by specifying the driven element first, followed by director 3, and then the reflector, or whatever. But it's a pretty good bet that doing so in this quasi-random fashion will result in some confusion later on when you revisit a model, or when you let another person use or review your model.

8.2.3 THE MODELING ENVIRONMENT

The Ground

Above, when considering the 135-foot dipole mounted 50 feet above flat earth, we briefly mentioned the most important environmental item in an antenna model — the ground beneath it. Let's examine some of the options available in the *NEC-2* environment in *EZNEC*:

- Free space
- Perfect ground
- *MININEC* type ground
- "Fast" type ground
- Sommerfeld-Norton ground.

The free space environment option is pretty self-explanatory — the antenna model is placed in free space away from the influence of any type of ground. This option is useful when you wish to optimize certain characteristics of a particular antenna design. For example, you might wish to optimize the front-to-rear ratio of a Yagi over an entire amateur band and this might entail many calculation runs. The free-space option will run the fastest because there is no ground interaction to compute.

Perfect ground is useful as a reference case, especially for vertically polarized antennas over real ground. Antenna evaluations over perfect ground are shown in most classical antenna textbooks, so it is useful to compare models for simple antennas over perfect ground to those textbook cases.

MININEC type ground is useful when modeling vertical wires, or horizontal wires that are higher than 0.2 λ above ground. A *MININEC* type ground will compute faster than either a "Fast" ground or a Sommerfeld-Norton type of ground because it assumes that the ground under the antenna is perfect, while still taking into account the far-field reflections for ground using user-specified values of ground conductivity and dielectric constant. The fact that the ground under the antenna is treated as perfect allows the *NEC-2* user of a *MININEC* type ground to specify wires that touch (but don't go below) the ground surface, something that only users of the advanced *NEC-4* program can do with the more accurate Sommerfeld-Norton type of ground described below. (*NEC-4* is presently not in the public domain. Software based on *NEC-4*, such as *EZNEC-PRO*, requires an additional license from the copyright holder — the US government. See the section Comparing *NEC-2* to *NEC-4* at the beginning of this chapter.) The ability to model grounded wires is useful with vertical antennas. The modeler must be wary of the feed-point source impedances reported for either horizontally or vertically polarized wires because of the perfect-ground assumption inherent in a *MININEC*-type ground.

The "Fast" type of ground is a hybrid type of ground that makes certain simplifying assumptions to speed up calculations, provided that horizontal wires are higher than about 0.1 λ above ground. With today's high-speed computers, the simplifications are no longer required and the Sommerfeld-Norton model is preferred.

The Sommerfeld-Norton ground (referred to in *EZNEC* as "High Accuracy" ground) is preferable to the other ground models because it has essentially no practical limitations for wire height. It has the disadvantage that it runs about four times slower than a *MININEC* type of ground but today's fast computers make that almost a non-issue. Again, *NEC-2*-based programs cannot model wires that penetrate into the ground (although there are workarounds described below).

As mentioned above, for any type of ground other than perfect ground or free space the user must specify the conductivity and dielectric constant of the soil. (See the section "Ground Parameters for Antenna Analysis" in the chapter **The Effects of Ground**.) *EZNEC* allows selection of several user-friendly categories, where σ is conductivity in siemens/meter and ε is dielectric constant:

- Extremely poor: cities, high buildings (σ = 0.001, ε = 3)
- Very Poor: cities, industrial (σ = 0.001, ε = 5)
- Sandy, dry (σ = 0.002, ε = 10)
- Poor: rocky, mountainous (σ = 0.002, ε = 13)
- Average: pastoral, heavy clay (σ = 0.005, ε = 13)
- Pastoral: medium hills and forestation (σ = 0.006, ε = 13)
- Flat, marshy, densely wooded (σ = 0.0075, ε = 12)
- Pastoral, rich soil, US Midwest (σ = 0.010, ε = 14)
- Very Good: pastoral, rich, central US (σ = 0.0303, ε = 20)
- Fresh water (σ = 0.001, ε = 80)
- Saltwater (σ = 5, ε = 80)

Let's use *EZNEC*'s ability to overlay one or more plots together on one graph to compare the response of the vertical ground plane antenna in Figure 8.9 for two different types of ground: Saltwater and Poor. Open the **Ch8-GP.EZ** file in *EZNEC*. Click the GROUND DESCRIP button and then right-click anywhere in the Media window that opens up. Choose first the "Poor: rocky, mountainous" option button, click OK and then FF PLOT. When the elevation plot appears, click the File menu at the top of the main window, and then SAVE AS. Choose an appropriate name for the trace, perhaps "Poor Gnd. PF."

Go back and select saltwater using GROUND DESCRIP and follow the same procedure to compute the far-field plot for saltwater ground. Now, add the Poor Gnd.PF trace, by clicking menu selection FILE, ADD TRACE. **Figure 8.15** shows this comparison, which greatly favors the saltwater environment, particularly at low elevation angles. At 5° the ground plane mounted over saltwater has about a 10 dB advantage compared to its landlocked cousin.

You might be wondering what happens if we move the ground-plane antenna down closer to the ground. The lower limit to how closely radials may approach lossy ground is 0.001 λ or twice the diameter of the radial wire. A distance of 0.001 λ is about 6 inches at 1.8 MHz and 0.4 inch at 30 MHz. While *NEC-2*-based programs cannot model wires that penetrate the ground, radial systems just above the ground with more than about eight radial wires can provide a work-around to simulate a direct-ground connection.

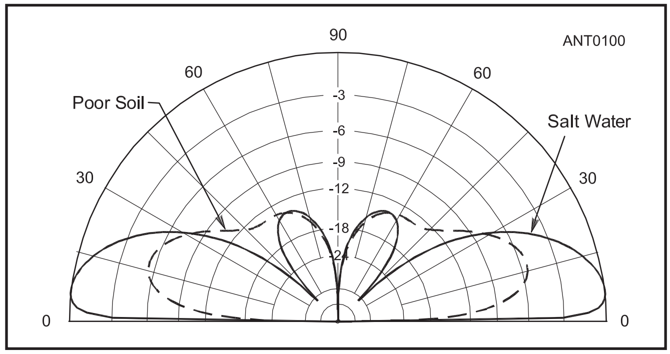


Figure 8.15 — A comparison of the elevation response for the vertical ground plane in Figure 8.9 over saltwater and over "poor: rocky, mountainous" soil. Saltwater works wonders for verticals, providing excellent low-angle signals.

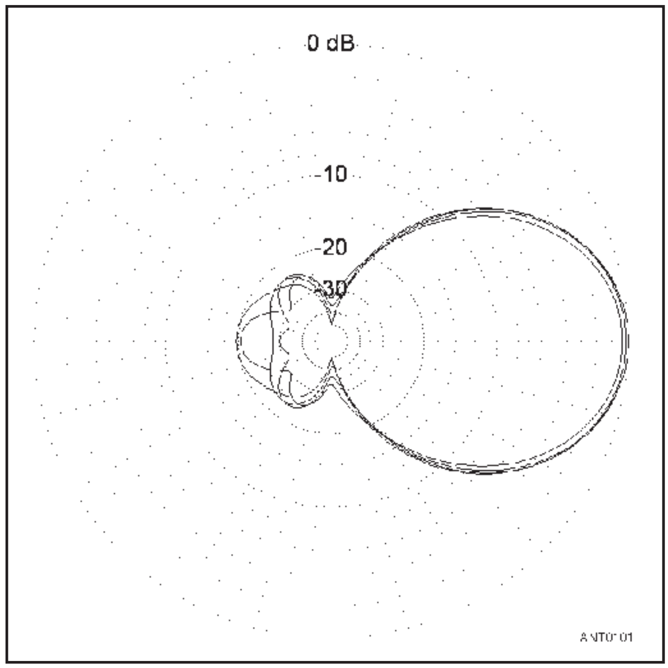


Figure 8.16 — Frequency sweep of 5-element Yagi described in Figure 8.11, showing how the azimuth pattern changes with frequency.

Modeling Environment: Frequency

It's always a good idea to evaluate an antenna over a range of frequencies, rather than simply at a single spot frequency. Trends that become quite apparent on a frequency sweep are often lost when looking simply at a single frequency. Native *NEC-2* has built-in frequency sweep capabilities but once again the commercial programs make the process easier to use and understand. You saw in the SWR curve of Figure 8.2 the result of one such frequency sweep using *EZNEC*. **Figure 8.16** shows a frequency sweep of the azimuth response for the 5-element Yagi in Figure 8.11 across the 20 meter band, using steps of 117 kHz so there are four evaluation frequencies. At 14.0 MHz this Yagi's gain is down a small amount compared to the gain at 14.351 MHz but the rearward pattern is noticeably degraded, dropping to a front-to-back ratio of just under 20 dB.

EZNEC can save frequency sweeps of elevation (or azimuth) patterns to a series of output plot files. In essence, the program automates the process described above for saving a plot to disk and then overlaying it on another plot. *EZNEC* can save the following parameters to a text file for later analysis (or perhaps importation into a spreadsheet) chosen by the user:

- Source data
- Load data
- Pattern data
- Current data
- *MicroSmith* numeric data
- Pattern analysis summary.

Frequency Scaling

EZNEC has a very useful feature that allows you to create new models scaled to a new frequency. You invoke the algorithm used to scale a model from one frequency to another by checking the RESCALE box after you've clicked the FREQUENCY button. *EZNEC* will scale all model dimensions (wire length, height and diameter) except for one specific situation — if you originally specified wire size by AWG gauge, the wire diameter will stay the same at the new frequency. For example, #14 copper wire for a half-wave 80-meter dipole will stay #14 copper wire when the antenna is scaled to become a 20-meter half-wave dipole. If, however, you specified diameter as a floating point numeric value originally (such as 0.064 inch), the diameter will be scaled by the ratio of new to old frequency, along with wire length and height.

Start up *EZNEC* and open up the file **Ch8-520-40W.EZ** for the 5-element 20-meter Yagi on a 40-foot boom. Click the FREQUENCY box and then check the RESCALE check box. Now, type in the frequency of 28.4 MHz and click OK. You have quickly and easily created a new 5-element 10-meter Yagi, that is mounted 29.9949 feet high, the exact ratio of 28.4 MHz to 14.1739 MHz, the original design frequency on 20 meters. Click the FF PLOT button to plot the azimuth pattern for this new Yagi. You will see that it closely duplicates the performance of its 20 meter sibling. Click SRC DAT to see that the source impedance is 25.38 – *j* 22.19 Ω, again very close to the source data for the 20-meter version.

8.2.4 REVISITING SOURCE SPECIFICATION

Sensitivity to Source Placement

Earlier, we briefly described how to specify a source on a particular segment using *EZNEC*. The sources for the relatively simple dipole, Yagi and quad models investigated so far have been in the center of an easy-to-visualize wire. The placement for the source on the vertical ground plane was at the bottom of the vertical radiator, an eminently logical place. In the other cases we specified the position of the source at 50% of the distance along a wire, given that the wire being fed had an odd number of segments. Please note that in each case so far, the feed point (source) has been placed at a relatively low-impedance point, where the current changes relatively slowly from segment to segment.

Now we're going to examine some subtler source-placement problems. *NEC-2* is well-known as being very sensitive to source placement. Significant errors can result from a haphazard choice of the source segment and the segments surrounding it.

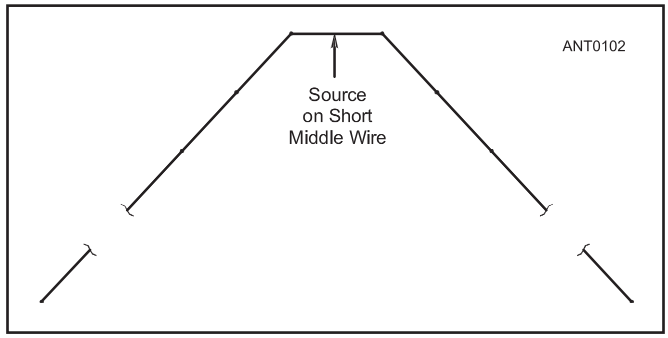


Figure 8.17 — Model of inverted-V dipole using a short center wire on which the source is placed.

Table 8.2
135-Foot Inverted-V Dipole at 3.75 MHz

Case	*Segments*	*Source Impedance (Ω)*	*Max. Gain (dBi)*
1	82	72.64 + *j* 128.2	4.82
2	246	73.19 + *j* 128.9	4.82
3	67	73.06 + *j* 129.1	4.85
4	401	76.21 + *j* 135.2	4.67

Let's return to the inverted-V dipole in Figure 8.5. The first time we evaluated this antenna (**Ch8-Inverted V Dipole.EZ**) we specified a split source in *EZNEC*. This function uses two sources, one on each of the segments immediately adjacent to the junction of the two downward slanting wires.

Another common method to create a source at the junction of two wires that meet at an angle is to separate these two slanted wires by a short distance and bridge that gap with a short straight wire which is fed at its center. **Figure 8.17** shows a close-up of this scheme in which the length of the segments surrounding the short middle wire are purposely made equal to the length of the middle wire bridging the gap between them. The segmentation for the short middle wire is set to one. **Table 8.2** lists the source impedance and the maximum gain the *EZNEC* computes for four different models:

1. **Ch8-Inverted V Dipole.EZ** (the original model)
2. **Ch8-Inverted V Dipole Triple Segmentation.EZ**
3. **Ch8-Modified Inverted V Dipole.EZ** (as shown in Figure 8.17, for the middle wire set to be 2 feet long)
4. **Ch8-Mod Inverted V Poor Segmentation.EZ** (where the number of segments on the two slanted wires have been increased to 200)

Case 2 shows the effect of tripling the number of segments in Case 1. This is a check on the segmentation, to see that the results are stable at a lower level compared to a higher level of segmentation (which theoretically is better although slower in computation). We purposely set up

Table 8.3
135-Foot Inverted-V Dipole at 7.5 MHz

Case	*Segments*	*Source Impedance (Ω)*	*Max. Gain (dBi)*
1	82	2297 – *j* 2668	5.67
2	246	1822 – *j* 2553	5.66
3	67	1960 – *j* 2583	5.66
4	401	2031 – *j* 2688	5.48

Case 4 so that the lengths of the segments on either side of the single-segment middle wire are significantly different (0.33 feet) compared to the 2-foot length of the middle wire.

The feed point and gain figures for the first three models are close to each other. But you can see that the figures for the fourth model are beginning to diverge from the first three, with about a 5% overall change in the reactance and resistance compared to the average values, and about a 3% change in the maximum gain. This illustrates that it is best to keep the segments surrounding the source equal or at least close to equal in length. We'll soon examine a figure of merit called the *Average Gain* test, but it bears mentioning here that the average gain test is very close for the first three models and begins to diverge for the fourth model.

Things get more interesting if the source is placed at a high-impedance point on an antenna — for example, in the center of a full-wave dipole — the value computed for the source impedance will be high and the results will be quite sensitive to the segment lengths. We'll repeat the computations for the same inverted-V models, but this time at twice the operating frequency, at 7.5 MHz.

Table 8.3 summarizes the results. The source impedance is high, as expected. Note that the resistance term varies quite a bit for all four models with a range of about 23% around the average value. Interestingly, the poorly segmented model's resistance falls in between the other three. The reactive terms are closer for all four models but still cover a range of 4% around the average value. Maximum gain shows the same tendency to be somewhat lower in the fourth model compared to the first three and thus looks as potentially untrustworthy at 7.5 MHz as it does at 3.75 MHz.

This is, of course, a small sampling of segmentation schemes and caution dictates that you shouldn't take these results as being representative of all possibilities. Nevertheless, the lesson to be learned here is that the feed-point (source) impedance can vary significantly at a point where the current is changing rapidly, as it does at a high impedance point on the antenna. Another general conclusion that can be drawn from Tables 8.2 and 8.3 is that more segments, particularly if they surround the source segment improperly, is not necessarily better.

Voltage and Current Sources

Before we leave the topic of sources, you should be aware that programs like *EZNEC* and others have the ability to simulate both voltage sources and current sources. Although native *NEC-2* has several source types, voltage sources are the most commonly used by amateurs. Native *NEC-2* doesn't have a current source but a current source is nothing more than a voltage source delivering current through a high impedance. Basic network theory says that every Thevenin voltage source has a Norton current source equivalent.

Various commercial implementations of *NEC-2* approach the creation of a current source in slightly different fashions. Some use a high value of inductive reactance as a series impedance, while others use a high value of series resistance. Why would we want to use a current source instead of a voltage source in a model? The general-purpose answer is that models containing a single source at a single feed point can use a voltage source with no problems. Models that employ multiple sources, usually with different amplitudes and different phase shifts, do best with current sources.

For example, *driven arrays* feed RF currents at different amplitudes and phase shifts into two or more elements. The impedances seen at each element may be very different — some impedances might even have negative values of resistance, indicating that power is flowing out of that element into the feed system due to mutual coupling to other elements. Having the ability to specify the amplitude and phase of the current rather than a feed voltage at a feed point in a program like *EZNEC* is a valuable tool.

Next, we examine one more important aspect of building a model — setting up loads. After that, we'll look into two tests for the potential accuracy of a model. These tests can help identify source placement, as well as other problems.

8.2.5 LOADS

Many ham antennas, in particular electrically short ones, employ some sort of *loading* to resonate the system. Sometimes loading takes the form of *capacitance hats*, but these can and should be modeled as wires connected to the top of a vertical radiator. A capacitance hat is not the type of loading we'll explore in this section.

Here, the term *loads* refers to discrete inductances, capacitances and resistances that are placed at some point (or points) in an antenna system to achieve certain effects. One fairly common form of a load is a *loading coil* used to resonate an electrically short antenna. Another form of load often seen in ham antennas is a *trap*. *EZNEC* has a special built-in function to evaluate parallel-resonant traps, even at different frequencies beyond their main parallel resonance.

Just for reference a more subtle type of load is a *distributed* material load. We encountered just such a load in our first model antenna, the 135-foot long flattop dipole — although we didn't identify it specifically as a load at that time. Instead, it was identified as a "wire loss" associated with copper.

The *NEC-2* core program has the capability of simulating a number of built-in loads, including distributed material and discrete loads. *EZNEC* implements the following discrete loads:

- Series R ± *j* X loads.
- Series R-L-C loads, specified in Ω of resistance, μH of

inductance and pF of capacitance.

- Parallel R-L-C loads, specified in Ω of resistance, µH of inductance and pF of capacitance.
- Trap loads, specified in Ω of resistance in series with µH of inductance, shunted by pF of capacitance, at a specific frequency.
- Laplace loads, specified as mathematical Laplace coefficients (sometimes used in older modeling programs and left in *EZNEC* for backward compatibility).

It is important to recognize that the discrete loads in an antenna modeling program *do not radiate* and they have zero size which is why *NEC-2* discrete loads are described as being *mathematical loads*. The fact that *NEC-2* loads do not radiate means that the popular mobile antennas that use helical loading coils wound over a length of fiberglass whip cannot be modeled accurately with *NEC-2* because such coils do radiate.

Let's say that we want to put an air-wound loading coil with an unloaded Q of 400 at the center of a 40-foot long, 50-foot high, flattop dipole so that it is resonant at 7.1 MHz. The schematic of this antenna is shown in **Figure 8.18**. Examine the modeling file **Ch8-Loaded Dipole.EZ** to see how a discrete series-RL load is used to resonate this short dipole at 7.1 MHz, with a feed-point (source) impedance of 25.3 Ω. This requires a series resistance of 1.854 Ω and an inductive reactance of +741.5 Ω. Note that we again used a single wire to model this antenna, and that we placed the load at a point 50% along the length of the wire.

Specifying this value of reactance represents a 16.62 µH coil with an unloaded Q of 741.5/1.854 = 400 which is just what we wanted. Let's assume for now that we use a perfect transformer to transform the 25.3-Ω source impedance to 50 Ω. If we now attempt to run a frequency sweep over the whole 40 meter band from 7.0 to 7.3 MHz, the load reactance and resistance will not change, since we specified fixed values for reactance and resistance. Hence, the source impedance will be correct only at the frequency where the reactance and resistance are specified since the reactance of an actual coil changes with frequency.

Let's use a different type of load, a 16.62 µH coil with a series 1.854-Ω resistance at 7.1 MHz. We'll let *EZNEC* take care of the details of computing both the reactance and the changing series resistance at various frequencies. The degree that both reactance and series loss resistance of the coil change with frequency may be viewed using the LOAD DAT button from the main *EZNEC* window. By specifying inductance or capacitance, the model's reactance will change with frequency as expected.

Figure 8.19 shows the computed SWR curve for a 25.3-Ω ALT SWR Z0 reference resistance. The 2:1 SWR bandwidth is about 120 kHz. As could be expected, the antenna has a rather narrow bandwidth because it is electrically short.

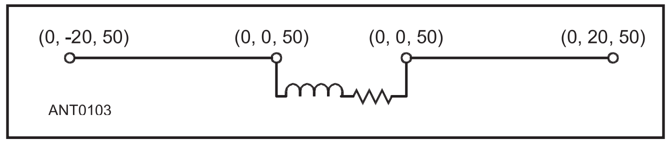


Figure 8.18 — Schematic diagram of a 40-foot long flattop dipole with a loading coil placed at the center. This coil has an unloaded Q of 400 at 7.1 MHz.

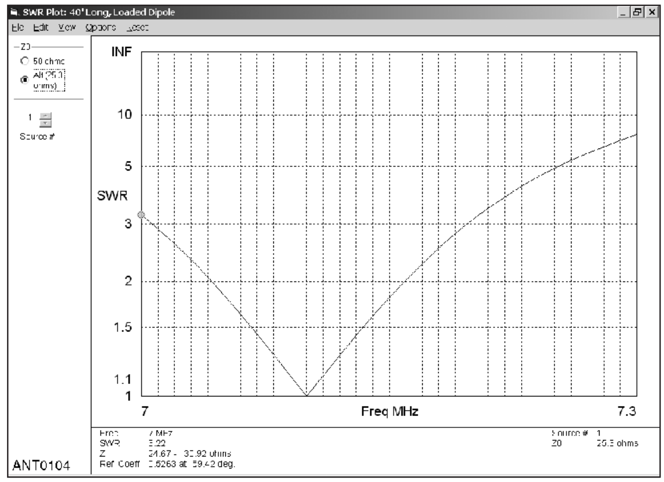


Figure 8.19 — SWR graph of the loaded 40-foot long flattop dipole shown in Figure 8.18.

8.2.6 ACCURACY TESTS

There are two tests that can help identify accuracy problems in a model:

- The Convergence test.
- The Average Gain test.

Convergence Test

The idea behind the Convergence test is simple: If you increase the segmentation in a particular model and the results change more than you'd like, increase the segmentation until the computations converge to a consistent answer. This process has the potential for being subjective but simple antenna models do converge quickly. In this section, we'll review several more of the antennas discussed previously to see how they converge.

Let's go back to the simple dipole in Figure 8.3. The original segmentation was 11 segments, but we'll start with a very low value of segmentation of three, well below the minimum recommended level. **Table 8.4** shows how the source impedance and gain change with increase in segmentation at 3.75 MHz. For this simple antenna, the gain levels off at 6.50 dBi when segmentation has reached 11 segments. Going to ten times the minimum-recommended level (to 111 segments) results in an increase of only 0.01 dBi in the gain.

Arguably, the impedance has also stabilized by the time we reach a segmentation level of 11 segments, although purists may opt for 23 segments. The tradeoff is a slowdown in computational speed.

Let's see how the 5-element Yagi model converges with changes in segmentation level. **Table 8.5** shows how the source impedance, gain, 180° front-to-back ratio and worst-case front-to-rear ratio change with segmentation density. By the time the segmentation has reached 11 segments per wire,

Table 8.4
135-Foot Flattop Dipole at 3.75 MHz

Segments	Source Impedance (Ω)	Max. Gain (dBi)
3	85.9 + *j* 128.0	6.34
5	86.3 + *j* 128.3	6.45
7	86.8 + *j* 128.8	6.48
11	87.9 + *j* 129.5	6.50
23	88.5 + *j* 130.3	6.51
45	89.0 + *j* 130.8	6.51
101	89.4 + *j* 131.1	6.51

Table 8.5
5-element Wire Yagi at 14.1739 MHz

Segments	Source Impedance (Ω)	Max. Gain (dBi)	180° F/B (dB)	F/R (dB)
3	28.5 – *j* 30.6	12.79	23.2	22.4
5	26.3 – *j* 25.6	13.02	30.5	23.1
7	25.6 – *j* 24.0	13.07	34.8	23.1
11	25.1 – *j* 22.9	13.09	39.9	23.1
25	24.9 – *j* 22.0	13.10	43.7	23.1
99	24.7 – *j* 21.5	13.10	44.2	23.1

the impedance and gain have stabilized quite nicely, as has the F/R. The 180° F/B is still increasing with segmentation level until about 25 segments, but a relatively small shift in frequency will change the maximum F/B level greatly. For example, with 11 segments per wire, shifting the frequency to 14.1 MHz — a shift of only 0.5% — will change the maximum 180° F/B from almost 50 dB down to 27 dB. For this reason the F/R is considered a more reliable indicator of the adequacy of the segmentation level than is F/B.

Average Gain Test

The theory behind the Average Gain test is a little more involved. Basically, if you remove all intentional losses in a model and if you place the antenna either in free space or over perfect ground, then all the power fed to the antenna should be radiated by it. Internally, the program runs a full 3-D analysis, adding up the radiated power in all directions and dividing that sum by the total power fed to the antenna. Ideally, the ratio of input power to radiated power should be unity. Since *NEC-2* is very sensitive to source placement, as mentioned before, the Average Gain test is a good indicator if something is wrong with the specification of the source.

Various commercial versions of *NEC-2* handle the Average Gain test in different ways. *EZNEC* requires the operator to turn off all distributed losses in wires or set to zero any discrete resistive losses in loads. Next set the ground environment to free space (or perfect ground) and request a 3-D pattern plot. *EZNEC* will then report the average gain, which will be 1.000 if the model has no problems. Average gain can be lower or higher than 1.000 but if it falls within the range 0.95 to 1.05 it is usually considered adequate.

As L. B. Cebik, W4RNL has stated: "Like the convergence test, the average gain test is a necessary but not a sufficient condition of model reliability." Pass both tests, however, and you can be pretty well sure that your model represents reality. Pass only one test, and you have reason to worry about how well your model represents reality.

Once again, open the model file **Ch8-Mod Inverted V Poor Segmentation.EZ** and set WIRE LOSS to zero, GROUND TYPE to FREE SPACE and PLOT TYPE to 3-DIMENSIONAL. Click on the FF PLOT button. *EZNEC* will report that the Average Gain is 0.955 = –0.2 dB. This is very close to the lower limit of 0.95 considered valid for excellent accuracy. This is a direct result of forcing the segment lengths adjacent to the source segment to be considerably shorter than the source segment's length. The gain reported using this test would be approximately –0.2 dB from what it should be — just what Table 8.3 alludes to also.

Now, let's revisit the basic model **Ch8-Inverted V Dipole.EZ** and look at Case 2 in Table 8.3. Case 2 amounts to a Convergence test for the basic inverted-V model. Since the impedance and gain changes were small comparing the basic model to the one using three times the number of segments, the model passed the Convergence test. The Average Gain test for the basic model yields a value of 0.991, well within the limits for good accuracy. This model has thus passed both tests and can be considered accurate.

Running the Average Gain test for the 5-element Yagi (using 11 segments per wire and whose convergence we examined in Table 8.5) yields a value of 0.996, again well within the bounds indicating a good model. The simple flattop dipole with 11 segments at 3.75 MHz yields an Average Gain result of 0.997, again indicating a very accurate model.

8.2.7 OTHER POSSIBLE MODEL LIMITATIONS

Programs based on the *NEC-2* core computational code have several well-documented limitations that you should know about. Some limitations have been removed in the restricted-access *NEC-4* core (which is not generally available to users), but other limitations still exist, even in *NEC-4*.

Closely Spaced Wires

If wires are spaced too close to each other, the *NEC-2* core can run into problems. If the segments are not carefully aligned, there also can be problems with accuracy. The worst-case situation is where two wires are so close together that their volumes actually merge into each other as we discussed earlier for wire junctions. This can happen where wires are thick, parallel to each other and close together. You should keep parallel wires separated by at least several wire diameters.

For example, #14 AWG wire is 0.064 inch in diameter. The rule then is to keep parallel #14 wires separated by more than 2 × 0.064 = 0.128 inch. And you should run the Convergence test to assure yourself that the solution is indeed converging when you have closely spaced wires, especially if the two wires have different diameters. To model antennas containing closely spaced wires, very often you will need many more segments than usual and you must also carefully ensure that the segments align with each other.

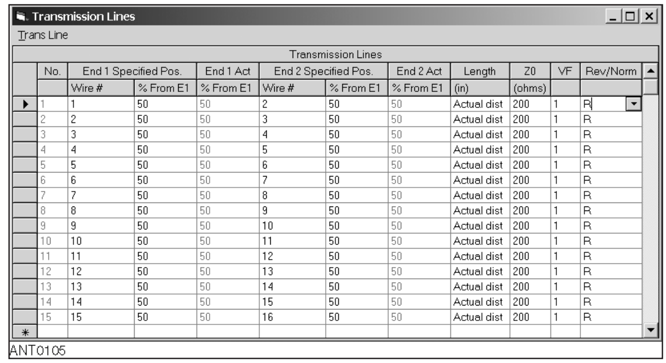
Things can get a little more tricky when wires cross over or under each other, simply because such crossings are sometimes difficult to visualize. Again, the rule is to keep crossing wires separated by more than two diameters from each other and if you intend to join two wires together, make sure you do so at the ends of the two wires, using identical end coordinates. When any of these rules are violated, the Convergence and Average Gain tests will usually warn you of potential inaccuracies.

Parallel-Wire Transmission Lines and LPDAs

A common example of problems with closely spaced wires is when someone attempts to model a parallel-wire transmission line. *NEC-2*-based programs usually do not work as well in such situations as do *MININEC*-based programs. The problems are compounded if the diameters are different for the two wires simulating a parallel-wire transmission line. In *NEC-2* programs, it is usually better to use the built-in "perfect transmission line" function than to try to model closely spaced parallel wires as a transmission line.

For example, a Log Periodic Dipole Array (LPDA) is composed of a series of elements fed using a transmission line that reverses the phase 180° at each element. (See the **Log Periodic Antennas** chapter.) In other words, the elements are connected to a transmission line that reverses connections left-to-right at each element. It is cumbersome to do so, but you could model such a transmission line using separate wires in *EZNEC* but it is a potentially confusing and a definitely painstaking process. Further, the accuracy of the resulting model is usually suspect, as shown by the Average Gain test.

It is far easier to use the TRANS LINES function from the *EZNEC* main window to accurately model an LPDA. See **Figure 8.20**, which shows the TRANS LINES window for the **9302A.EZ** 16-element LPDA. There are 15 transmission lines connecting the 16 elements, placed at the 50% point on each element, with a 200-Ω characteristic impedance and with Reversed connections.



No.	End 1 Specified Pos.		End 1 Act	End 2 Specified Pos.		End 2 Act	Length	Z0	VF	Rev/Norm
	Wire #	% From E1	% From E1	Wire #	% From E1	% From E1	(in)	(ohms)		
1	1	50	50	2	50	50	Actual dist	200	1	R
2	2	50	50	3	50	50	Actual dist	200	1	R
3	3	50	50	4	50	50	Actual dist	200	1	R
4	4	50	50	5	50	50	Actual dist	200	1	R
5	5	50	50	6	50	50	Actual dist	200	1	R
6	6	50	50	7	50	50	Actual dist	200	1	R
7	7	50	50	8	50	50	Actual dist	200	1	R
8	8	50	50	9	50	50	Actual dist	200	1	R
9	9	50	50	10	50	50	Actual dist	200	1	R
10	10	50	50	11	50	50	Actual dist	200	1	R
11	11	50	50	12	50	50	Actual dist	200	1	R
12	12	50	50	13	50	50	Actual dist	200	1	R
13	13	50	50	14	50	50	Actual dist	200	1	R
14	14	50	50	15	50	50	Actual dist	200	1	R
15	15	50	50	16	50	50	Actual dist	200	1	R

Figure 8.20 — Transmission-line data entry screen for the 9302A.EZ 16-element LPDA. Note that the transmission lines going between elements are "reversed," meaning that they are 180° out-of-phase at each element, a requirement for properly feeding an LPDA.

Fat Wires Connected to Skinny Wires

Another inherent limitation in the *NEC-2* computational core shows up when modeling many Yagis and some quads: popular amateur antennas.

Tapered Elements

As mentioned before, many Yagis are built using telescoping aluminum tubing. This technique saves weight and makes for a more flexible and usually stronger element, one that can survive wind and ice loading better than a single-diameter "monotaper" element design. Many vertical antennas are also constructed using telescoping aluminum tubing.

Unfortunately, native *NEC-2* doesn't model accurately such *tapered elements*, as they are commonly called. There is, however, a sophisticated and accurate workaround for such elements, called the *Leeson corrections*. Derived by Dave Leeson, W6NL, from pioneering work by Schelkunoff at Bell Labs, these corrections compute the diameter and length of an element that is electrically equivalent to a tapered element. This monotaper element is much easier to use in a program like *NEC-2*. (See the **HF Yagi and Quad Antennas** chapter for more information on tapered elements.)

EZNEC and other *NEC-2* programs can automatically invoke the Leeson corrections, providing that some basic conditions are met — and happily, these conditions are true for the telescoping aluminum-tubing elements commonly used as Yagi elements. *EZNEC* gives you the ability to disable or enable Leeson corrections, under the OPTION menu, under STEPPED DIAMETER CORRECTION, *EZNEC*'s name for the Leeson corrections. Open the modeling file **520-40H.EZ**, which contains tapered aluminum tubing elements and compare the results using and without using the Leeson corrections.

Table 8.6 lists the differences over the 20-meter band, with the 5-element Yagi at a height of 70 feet above flat ground. You can see that the non-Leeson corrected figures are very different from the corrected ones. At 14.3 MHz, the pattern for the non-corrected Yagi has degenerated to a F/R of 3.1 dB, while at 14.4 MHz, just outside the top of the amateur band, the pattern for the non-corrected antenna actually has reversed. Even at 14.2 MHz, the non-corrected antenna shows a low source impedance, while the corrected version exhibits smooth variations in gain, F/R and impedance across the whole band, just as the actual antenna exhibits.

Some Quads

Some types of cubical quads are made using a combination of aluminum tubing and wire elements, particularly in Europe where the "Swiss" quad has a wide following. Again, *NEC-2*-based programs don't handle such tubing/wire elements well. It is best to avoid modeling this type of antenna,

Table 8.6
5-element Yagi at 14.1739 MHz with Telescoping Aluminum Elements

	With Leeson Corrections			*Without Leeson Corrections*		
Freq (MHz)	*Source Impedance (Ω)*	*Gain (dBi)*	*F/R (dB)*	*Source Impedance (Ω)*	*Gain (dBi)*	*F/R (dB)*
14.0	23.2 – *j* 26.5	14.82	23.3	22.4 – *j* 12.7	14.92	23.1
14.1	22.7 – *j* 20.5	14.87	22.8	18.6 – *j* 12.5	14.70	21.6
14.2	22.8 – *j* 14.8	14.87	22.7	6.6 – *j* 4.6	14.01	16.2
14.3	22.5 – *j* 11.9	14.76	21.5	1.9 + *j* 10.6	10.61	3.1
14.4	14.5 – *j* 10.5	14.45	19.9	1.6 + *j* 23.7	11.15	–11.4

although there are some ways to attempt to get around the limitations, ways that are beyond the scope of this chapter.

8.2.8 NEAR-FIELD OUTPUTS

FCC regulations set limits on the maximum permissible exposure (MPE) allowed from the operation of radio transmitters. These limits are expressed in terms of the electric (V/m) and magnetic fields (A/m) close to an antenna. *NEC-2*-based programs can compute the electric and magnetic near fields and the FCC accepts such computations to demonstrate that an installation meets their regulatory requirements. See the section "RF Radiation and Electromagnetic Field Safety" in the **Antenna Fundamentals** chapter.

We'll continue to use the 5-element Yagi at 70 feet to demonstrate a near-field computation. Open **Ch8-520-40H.EZ** in *EZNEC* and choose SETUPS and then NEAR FIELD from the menu at the top of the main window. Let's calculate the E-field and H-field intensity for a power level of 1500 W (chosen using the OPTIONS, POWER LEVEL choices from the main menu) in the main beam at a fixed distance, say 50 feet, from the tower base. We'll do this at various heights, using 10-foot increments of height, in order to see the lobe structure of the Yagi at 70 feet height.

Table 8.7
E- and H-Field Intensities for 1500 W into 5-Element Yagi at 70 Feet on 14.2 MHz

Height (Feet)	*H-Field (A/m)*	*E-Field (V/m)*
0	0.04	4.1
10	0.03	13.8
20	0.04	20.6
30	0.06	22.6
40	0.08	25.8
50	0.10	33.8
60	0.12	41.5
70	0.12	44.3

Table 8.7 summarizes the total H- and E-field intensities as a function of height. As you might expect, the fields are strongest directly in line with the antenna at a height of 70 feet. At ground level, the total fields are well within the FCC limits for RF exposure for both fields. In fact, the fields are within the FCC limits if someone were to stand at the tower base, directly under the antenna.

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